R. Bras. Zootec., 54:e20240158, 2025
https://doi.org/10.37496/rbz5420240158

Non-ruminants
Full-length research article

Revista Brasileira de Zootecnia

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

The effect of thermal processing on pre-starter diets based on corn or sorghum for male broiler chicks

Regina Fialho de Sousa[1], **Fabyola Barros de Carvalho**[1*], **Igo Gomes Guimarães**[2], **Marcos Barcellos Café**[1], **Heloísa Helena de Carvalho Mello**[1], **José Henrique Stringhini**[1], **Emmanuel Arnhold**[1], **Nadja Susana Mogyca Leandro**[1]

[1] Universidade Federal de Goiás, Escola de Veterinária e Zootecnia, Goiânia, GO, Brasil.
[2] Universidade Federal de Jataí, Instituto de Ciências Agrárias, Jataí, GO, Brasil.

***Corresponding author:**
fabyola_carvalho@ufg.br

Received: October 10, 2024
Accepted: June 29, 2025

How to cite: Sousa, R. F.; Carvalho, F. B.; Guimarães, I. G.; Café, M. B.; Mello, H. H. C.; Stringhini, J. H.; Arnhold, E. and Leandro, N. S. M. 2025. The effect of thermal processing on pre-starter diets based on corn or sorghum for male broiler chicks. Revista Brasileira de Zootecnia 54:e20240158.
https://doi.org/10.37496/rbz5420240158

Editor:
Ines Andretta

ABSTRACT - This study aimed to evaluate the effects of thermal processing and different carbohydrate sources on performance, development of digestive organs, and pancreatic enzyme activity in broiler chicks during the pre-starter phase. The experiment was conducted in a completely randomized design with a 2 × 2 factorial arrangement (pelleting or extrusion processing, and corn or sorghum) and included six replicates of 15 chicks each. The experimental diets were provided only during the pre-starter period (1–7 d). From 8 to 21 days of age, all chicks received a corn-soybean meat mash diet. At 7 days of age, chicks fed corn-based pelleted diets showed the best performance. When the feed was extruded, the best performance at 14 and 21 days old was observed with the sorghum-based diet. Chicks fed pelleted diets showed greater duodenum, jejunum, and ileum weights. Regarding carbohydrate sources, sorghum-fed chicks showed greater pancreas, jejunum, and ileum weights. Broiler chicks fed corn-based extruded diets exhibited higher pancreatic amylase activity. Extruded sorghum-based diets improved duodenum and jejunum villus development, whereas pelleted corn-based diets enhanced duodenal villus development. Although extruded sorghum diets did not affect digestive organ development, they improved duodenum and jejunum villus morphology, resulting in better performance up to 21 days of age. However, the corn-based extruded feed provided increased production of the pancreatic amylase enzyme. Sorghum-based feed, regardless of thermal processing, improved the development of digestive tract organs.

Keywords: amylase, enzyme activity, extrusion, pelleting, starch, villi

1. Introduction

Broiler chick feeding strategies should be designed to promote gastrointestinal tract development during the pre-starter phase, thereby increasing the effectiveness of digestive secretions (Vieira and Pophal, 2000), and improving nutrient digestion and absorption during a period of intense physiological adaptation optimizing chick performance (Uni and Ferket, 2004).

The main reason to use mash feeds in the poultry industry is directly related to feeding costs. However, these feeds are not subjected to technological processing methods that could optimize nutrient digestibility. Pelleting and extrusion are feed processing methods that expose the feed to heat and pressure, altering the starch structure through gelatinization. Additionally, these processes increase protein availability and reduce antinutritional factors effects (Boroojeni et al., 2016; Massuquetto et al., 2018). These modifications enhance nutrient absorption, resulting in better performance, such as greater weight gain and improved feed conversion (Iravani et al., 2024).

Several studies in poultry have compared mash with thermally processed feeds, showing that pelleted diets improve broiler digestibility and performance (Abdollahi et al., 2011; Abdollahi et al., 2013; Boroojeni et al., 2014; Teixeira Netto et al., 2019; Avazkhanloo et al., 2020). However, results on the use of extruded feeds in poultry production are still quite divergent in the literature, which motivates a direct comparison with pelleted feeds.

Pelleting and extrusion are widely used in the feed industry to improve the utilization of raw materials. Sorghum is a carbohydrate-rich grain used as an energy source that can replace corn in broiler diets without affecting the growth performance (Garcia et al., 2013), and it contains higher levels of crude protein, starch and fiber content compared with corn (Rostagno et al., 2011). However, sorghum metabolizability is generally reduced because starch is encapsulated by a protein matrix composed of glutelin and kafirin, which limits amylase action (Selle et al., 2018). Additionally, kafirin is resistant to pepsin digestion, which further impairs starch utilization (Wong et al., 2010).

A previous study reported an increase in the *in vitro* digestibility of sorghum starch after extrusion (Al-Rabadi et al., 2011). Furthermore, studies in poultry and other species have demonstrated better nutrient utilization when sorghum is subjected to thermal processing (Svihus et al., 2005). Therefore, investigating the effects of pelleting and/or extrusion of sorghum is relevant to evaluate its influence on digestive physiology and chick growth.

Therefore, the aim of this study was to evaluate the effect of using sorghum or corn in the pelleting and extrusion process on the performance and development of the digestive organs of male chickens in the pre-starter phase to add information to the bulk of literature on the effects of thermal processing methods on growth and digestive development in the initial stages of broiler production.

2. Material and methods

The experiment was conducted in the poultry facility of the Escola de Medicina Veterinária e Zootecnia of the Universidade Federal de Goiás, in Goiânia, Brazil (16°35'48.3" S and 49°17'08.8" W). Research on animals was conducted according to the ethics committee on animal use of the Universidade Federal de Goiás (Protocol No. 039/16).

This experiment is part of a series of studies on the effects of thermal processing and carbohydrate sources on poultry nutrition. A previous study was published using post-hatch feed (Sousa et al., 2021b). The present study is a follow-up evaluating the effects on pre-starter diets.

A total of 360 male Cobb 500 chicks (38 ± 0.73 g) were allocated in a completely randomized design with a 2 × 2 factorial arrangement (processing method: pelleting or extrusion; carbohydrate source: corn- or sorghum-based diets). The study comprised four treatments, each with six replicates of 15 chicks.

Chicks were housed in metallic battery cages (0.30 × 0.74 × 0.79 m) equipped with linear feeders and drinkers. The temperature inside the experimental shed, controlled using gas brooders and curtains, was monitored daily with two thermohygrometers placed inside the shed. Average values of temperature and relative humidity were 32.75 ± 1.35 °C and 46.85 ± 5.30% from 1 to 7 d, 30.08 ± 1.04 °C and 48.50 ± 4.60% from 8 to 14 d, and 27.25 ± 0.75 °C and 61.20 ± 5.25% from 15 to 21 d.

The sorghum and corn were ground through a 0.5 mm sieve and were formulated according to the nutritional recommendations of Rostagno et al. (2011) for the pre-starter phase (Table 1).

Table 1 - Composition of experimental diets (g/kg) for broiler chicks in the post-hatch phase

Item	Corn	Sorghum
Ingredient (g/kg)		
Corn	533	-
Soybean meal	391	376
Sorghum	-	531
Calcitic limestone	8.70	8.70
Dicalcium phosphate	19.4	19.4
L-Lysine	2.10	2.50
DL-Methionine	2.10	2.30
L-Threonine	0.900	1.30
Soybean oil	23.0	38.6
Sodium bicarbonate	1.90	1.80
Common salt	3.80	3.80
Mineral-vitamin premix[1]	1.00	1.00
Starch	13.0	13.0
Calculated composition		
EM (MJ/kg)	12.3	12.3
Crude protein (g/kg)	222	222
Calcium (g/kg)	9.20	9.20
Available phosphorus (g/kg)	4.70	4.70
Digestible lysine (g/kg)	13.2	13.1
Digestible methionine (g/kg)	5.10	5.10
Digestible methionine + cysteine (g/kg)	8.10	7.90
Digestible threonine (g/kg)	8.50	8.50
Digestible tryptophan (g/kg)	2.50	2.70
Digestible arginine (g/kg)	14.2	13.6
Potassium (g/kg)	8.70	8.70
Sodium (g/kg)	2.20	2.20
Chloride (g/kg)	2.80	2.70

[1] Mineral and vitamin supplement - guaranteed levels per kilogram of product: 3,125,000 IU vitamin A; 550,000 IU vitamin D3; 3,750 mg vitamin E; 625 mg vitamin K3; 250 mg vitamin B1; 1,125 mg vitamin B2; 250 mg vitamin B6; 3,750 mg vitamin B12; 9,500 mg niacin; 1,500 mg anticoccidial; 3,750 mg calcium pantothenate; 125 mg folic acid; 350,000 mg DL-methionine; 150,000 mg choline chloride (50%); 50 mg selenium; 2,500 mg antioxidant; 1,000 g manganese; 150,000 mg zinc; 100,000 mg iron; 16,000 mg copper; 1,500 mg iodine; vehicle qsp.

The rations were extruded in an experimental extruder (model EX30, Exteec), with a 3.1 mm hole matrix, 23% humidity and 150 °C temperature. For pelletization, the matrix used was 2.0 mm, 23% humidity and 56 °C temperature. After processing, diets were disintegrated for supply to day-old chicks, providing the following mean geometric diameter (MGD): pelleted corn diet (498.59 μm), pelleted sorghum diet (442.48 μm) and extruded corn diet (348.99 μm), extruded sorghum diet (396.81 μm), (Zanotto and Bellaver, 1996). Experimental diets were provided until 7 days of age, after which all birds received a single pre-starter mash diet (MGD = 712.77 μm) with the same composition. Feed and water were provided *ad libitum* throughout the experiment.

Feed intake, feed conversion ratio (FCR), and livability were measured at 7, 14, and 21 d of age. Feed intake was calculated as feed offered minus feed refusals per replicate. Birds were weighed weekly to calculate weight gain, and FCR was determined as the ratio between feed intake and weight gain. Mortality was recorded and subtracted from 100% to calculate livability.

At 7 days of age, 12 chicks per treatment were euthanized by cervical dislocation for organ collection. The gizzard, liver (with gallbladder), small intestine, large intestine, and pancreas were weighed to calculate their relative weight (%) in relation to body weight.

To determine pancreatic amylase and lipase activity, the pancreas was frozen in liquid nitrogen (−196 °C). Subsequently, the sample was solubilized in 1 mL of distilled water. The samples were centrifuged at 2,000 × *g* for 10 min at 5 °C. The supernatant was used to determine the activity of the lipase and amylase enzymes (Sousa et al., 2021b).

At 7 days of age, intestinal histomorphometry was evaluated using six chicks per treatment. Chicks were euthanized by cervical dislocation, and 2-cm fragments of the duodenum and jejunum were collected from each bird. Samples were fixed in 10% formalin and dehydrated in 70% alcohol, cleared in xylene, and embedded in paraffin (Luna et al., 1968). Sections were cut using a microtome and stained with hematoxylin–eosin. Images were captured with a camera attached to an optical microscope and analyzed using an image analysis system (Carl Zeiss). Villus height and crypt depth were measured, with 10 villi and 10 crypts per slide used as replicates. Additionally, absorptive area was calculated according to Kisielinski et al. (2002), as the ratio of the villus-enhanced surface area to a smooth surface.

The data were tested for homogeneity and normality, and outliers were removed. Analysis of variance (ANOVA) was performed using the R statistical software (version 3.5.3) and, when necessary, the means were compared using the Tukey's test at 5% significance level. The proposed mathematical model was as follows:

$$Y_{ijk} = \mu + a_i + b_j + (ab)_{ij} + \varepsilon_{ijk}, \quad (1)$$

in which Y_{ijk} = value observed in type of ingredient factor i (i = 1, 2), thermal processing factor j (j = 1, 2), and replicate k (k = 1, 2, 3, 4); μ = overall mean of the experiment; a_i = fixed effect of factor i (i = 1, 2); b_j = fixed effect of factor j (j = 1, 2); $(ab)_{ij}$ = fixed effect of the interaction between factor i (i = 1, 2) and factor j (j = 1, 2); and ε_{ijk} = random error in factor i (i = 1, 2), level j (j = 1, 2), and replicate k (k = 1, 2, 3, 4).

3. Results

The results showed that when the feed was extruded, the chicks performed best when fed sorghum-based feed. Conversely, pelleted corn-based feed positively influenced the chicks' performance (Table 2).

When the feed was extruded, the chicks performed best with the sorghum-based feed (Table 3). However, carbohydrate source did not affect the chicks' performance at 14 days when fed a pelleted diet. Thermal pelleting was more suitable for corn-based feed, providing better results for the chicks than extruded feed.

As previously observed, chicks performed best when fed extruded sorghum-based diets. However, chicks fed corn-based pelleted feed had increased feed intake (Table 4).

Table 2 - Performance of chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet from 1 to 7 days of age

Variable	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
BW	Corn	101Bb	131Aa	116	1.88	0.011	<0.001	<0.001
	Sorghum	128Aa	119Bb	123	1.88			
	Average	115	125					
	SEM	1.88	1.88					
FI	Corn	112B	124	118	3.24	0.030	0.67	0.033
	Sorghum	132A	124	128	2.90			
	Average	122	124					
	SEM	2.78	3.35					
FCR	Corn	1.78Aa	1.35Bb	1.57	0.022	0.11	<0.001	<0.001
	Sorghum	1.44Bb	1.58Aa	1.51	0.023			
	Average	1.61	1.47					
	SEM	0.020	0.025					

BW - body weight (g); FI - feed intake (g/bird/period); FCR - feed per unit gain (g feed/g gain); EXT - extruded; PEL - pelleted; SEM - standard error of the mean; Ing - ingredient; Proc - thermal processing.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test (P<0.05).

Broiler chicks fed pelleted diets had greater duodenum, jejunum, and ileum weights (Table 5). Regarding carbohydrate sources, chicks fed sorghum-based diets had greater pancreas, jejunum, and ileum weights (P<0.05). Chicks fed sorghum-based pelleted feed had heavier intestine than those fed corn-based pelleted or sorghum-based extruded feed.

Pancreatic lipase activity was not affected by the factors studied (Table 6). However, amylase activity was higher in chicks fed corn-based extruded diets (P<0.05).

Chicks fed corn-based extruded feed exhibited reduced villus height and absorptive area. In contrast, chicks fed corn-based pelleted feed exhibited the highest values for villus height and crypt depth. An independent effect of the factors was observed for the duodenal villus–crypt ratio (P<0.05), with the highest values observed in the chicks fed pelleted diets (Table 7).

Table 3 - Performance of chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet from 1 to 14 days of age

Variable	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
BW	Corn	239Bb	276Aa	257	3.98	0.025	0.030	<0.001
	Sorghum	277Aa	267Aa	272	4.24			
	Average	258	271					
	SEM	4.40	3.79					
FI	Corn	357Bb	407Aa	382	8.41	0.066	0.530	0.004
	Sorghum	424Aa	390Aa	407	9.32			
	Average	390	399					
	SEM	9.32	8.41					
FCR	Corn	1.64	1.47	1.55	0.032	0.39	0.043	0.23
	Sorghum	1.62	1.57	1.60	0.035			
	Average	1.63a	1.52b					
	SEM	0.033	0.034					

BW - body weight (g); FI - feed intake (g/bird/period); FCR - feed per unit gain (g feed/g gain); EXT - extruded; PEL - pelleted; SEM - standard error of the mean; Ing - ingredient; Proc - thermal processing.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test (P<0.05).

Table 4 - Performance of chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet from 1 to 21 days of age

Variable	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
BW	Corn	698Ba	755Aa	727	14.36	0.013	0.53	0.042
	Sorghum	797Aa	766Aa	782	14.36			
	Average	748	761					
	SEM	14.36	14.36					
FI	Corn	829Bb	924Aa	876	15.11	0.33	0.65	<0.001
	Sorghum	936Aa	859Bb	897	14.47			
	Average	882	892					
	SEM	14.47	15.11					
FCR	Corn	1.23	1.18	1.20A	0.013	0.024	0.037	0.66
	Sorghum	1.17	1.14	1.16B	0.012			
	Average	1.20a	1.16b					
	SEM	0.012	0.014					

BW - body weight (g); FI - feed intake (g/bird/period); FCR - feed per unit gain (g feed/g gain); EXT - extruded; PEL - pelleted; SEM - standard error of the mean; Ing - ingredient; Proc - thermal processing.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test (P<0.05).

The extrusion process induced an increase in villi height of the 7-day-old chicks fed sorghum-based feed, as well as a greater crypt depth (P<0.05).

Table 5 - Relative weight (%) of the digestive organs of 7-day-old chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet

Variable (%)	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
Gizzard	Corn	3.52	3.36	3.44	0.067	0.95	0.37	0.48
	Sorghum	3.46	3.44	3.44	0.067			
	Average	3.48	3.40					
	SEM	0.067	0.067					
Pancreas	Corn	0.460	0.530	0.490B	0.015	0.013	0.17	0.12
	Sorghum	0.560	0.560	0.560A	0.018			
	Average	0.510	0.540					
	SEM	0.016	0.017					
Liver	Corn	4.26	4.52	4.40	0.117	0.45	0.69	0.057
	Sorghum	4.46	4.10	4.27	0.101			
	Average	4.36	4.30					
	SEM	0.106	0.113					
Duodenum	Corn	2.47	2.74	2.60	0.068	0.37	0.032	0.550
	Sorghum	2.44	2.60	2.52	0.058			
	Average	2.46b	2.67a					
	SEM	0.065	0.061					
Jejunum	Corn	2.93	3.71	3.32B	0.074	<0.001	<0.001	0.480
	Sorghum	3.40	4.03	3.72A	0.074			
	Average	3.17b	3.87a					
	SEM	0.074	0.075					
Ileum	Corn	2.11	2.70	2.40B	0.067	<0.001	<0.001	0.93
	Sorghum	2.62	3.22	2.92A	0.067			
	Average	2.36b	2.96a					
	SEM	0.067	0.067					
Large intestine	Corn	1.32	1.34B	1.33	0.051	0.002	0.023	0.037
	Sorghum	1.42b	1.79Aa	1.60	0.057			
	Average	1.37	1.56					
	SEM	0.051	0.057					

EXT - extruded; PEL - pelleted; SEM - standard error of the mean; Ing - ingredient; Proc - thermal processing.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test (P<0.05).

Table 6 - The specific activity (U/mg protein) of the amylase and pancreatic lipase of 7-day-old chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet

Variable (U/mg of protein)	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
Amylase	Corn	50.9Aa	25.5b	41.8	1.67	<0.001	0.019	<0.001
	Sorghum	31.0B	32.6	28.2	1.77			
	Average	38.2	31.8					
	SEM	1.67	1.77					
Lipase	Corn	0.801	0.616	0.709	0.052	0.097	0.280	0.170
	Sorghum	0.568	0.592	0.580	0.050			
	Average	0.680	0.600					
	SEM	0.045	0.056					

EXT - extruded; PEL - pelleted; Ing - ingredient; Proc - thermal processing; SEM - standard error of the mean.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test (P<0.05).

Table 7 - Histomorphometrically measurements of the duodenum and jejunum of 7-day-old chicks fed corn- or sorghum-based pre-starter (extruded or pelleted) diet

Variable	Ing	Thermal processing		Average	SEM	P-value		
		EXT	PEL			Ing	Proc	Ing × Proc
			Duodenum					
HV	Corn	757Bb	939Aa	848	27.49	0.57	0.31	<0.001
	Sorghum	880Aa	774Bb	827	22.76			
	Average	818	856					
	SEM	24.14	26.29					
DC	Corn	92.8b	146Aa	119	9.84	0.44	0.43	0.006
	Sorghum	125	93.1B	109	9.04			
	Average	109	120					
	SEM	9.842	9.842					
AA	Corn	10.6Bb	14.3a	12.5	0.020	0.27	0.14	0.007
	Sorghum	14.0A	12.7	13.4	0.020			
	Average	12.3	13.5					
	SEM	0.020	0.020					
			Jejunum					
HV	Corn	664B	694	679	22.7	0.22	0.12	0.022
	Sorghum	787Aa	653b	720	22.7			
	Average	725	673					
	SEM	22.67	22.67					
DC	Corn	114	107	116	4.78	0.63	0.11	0.037
	Sorghum	130a	117b	118	3.78			
	Average	122	112					
	SEM	3.99	4.12					
AA	Corn	11.6	11.0	11.3	0.070	0.60	0.41	0.80
	Sorghum	12.4	11.3	11.8	0.070			
	Average	12.0	11.2					
	SEM	0.070	0.070					

HV - height of villus (µm), DC - depth of crypt (µm); AA - absorptive area; EXT - extruded; PEL - pelleted; SEM - standard error of the mean; Ing - ingredient; Proc - thermal processing.
Averages with the same lowercase letter in the rows and uppercase in the columns do not differ statistically according to Tukey's test ($P<0.05$).

4. Discussion

In this study, we aimed to enhance the performance of broiler chicks by utilizing different carbohydrate sources and thermal processes in pre-starter diets. The results revealed that extrusion improved chick performance in the starter phase when the diet was based on sorghum. Extrusion involves higher temperatures and pressures, leading to increased starch gelatinization (Abdollahi et al., 2010; Abdollahi et al., 2011; Liu et al., 2013; Massuquetto et al., 2018) and improved nutrient metabolizability (Freitas et al., 2005; García et al., 2008; Al-Marzooqi and Wiseman, 2009; Massuquetto et al., 2018; Teixeira Netto et al., 2019; Avazkhanloo et al., 2020). These findings are therefore consistent with previous research. However, for corn-based pre-starter diet, the pelleting process, which involves lower temperatures (56 °C), induced an improved chick performance up to 21 days of age. Similarly, a recent study reported that pelleting at 75 °C resulted in greater weight gain in chicks at 10 days of age, but this advantage was not maintained at 24 days, when compared with processing at 65 °C (Salahshour et al., 2023).

The interaction between feed raw materials and thermal processing conditions causes chemical reactions and nutrient changes, influencing the final physicochemical structure of the feed. In this study, we observed that extrusion conditions with high temperatures (150 °C), associated with the nutritional composition of corn, adversely affected chick performance. This result can be attributed to the decrease in nutrient availability resulting from the high extrusion temperature. Wang et al. (2023), when evaluating the digestibility of cassava starch in chickens, also concluded that a high conditioning temperature is not favorable for broiler feed production.

It is essential to monitor thermal processing to avoid several negative effects, such as the loss of thermolabile nutrients, such as vitamins (Skřivan et al., 2012); decreased availability of amino acids (Al-Marzooqi and Wiseman, 2009; Liu et al., 2013; Boroojeni et al., 2014), especially lysine, which is complexed through the Maillard reaction in the presence of reducing sugars (Hendriks et al., 1994); and the production of resistant starch (Abdollahi et al., 2010; Abdollahi et al., 2011; Liu et al., 2013). Retrograded starch, also known as resistant starch, arises when gelatinized starch undergoes chain restructuring, establishing covalent bonds that are not accessible to digestive enzymes (Wang et al., 2015). Furthermore, the negative consequences of high extrusion temperatures can result in reduced nutrient metabolization (Freitas et al., 2005; González-Alvarado et al., 2007; Abdollahi et al., 2010; Abdollahi et al., 2011; Abdollahi et al., 2013), which may be the explain, in this experiment, the lower growth performance observed in chicks fed extruded corn feed.

Previous studies on thermal processing have shown varied effects on broiler performance (García et al., 2008; Abdollahi et al., 2011; Abdollahi et al., 2013; Amerah et al., 2013; Boroojeni et al., 2014; Massuquetto et al., 2018; Teixeira Netto et al., 2019). These variations can be attributed to differences in starch sources (González-Alvarado et al., 2007; García et al., 2008; Al-Marzooqi and Wiseman, 2009; Abdollahi et al., 2010; Al-Rabadi et al., 2011; Abdollahi et al., 2013) and thermal processing conditions, such as mash conditioning time (Silversides and Bedford, 1999), moisture level (Al-Marzooqi and Wiseman, 2009), and temperature (Freitas et al., 2005; Abdollahi et al., 2010; Abdollahi et al., 2011; Al-Rabadi et al., 2011; Amerah et al., 2013; Liu et al., 2013; Boroojeni et al., 2014; Massuquetto et al., 2018; Sousa et al., 2021a).

Chicks fed pelleted diets in the pre-starter phase showed increased development of digestive organs, resulting in improved feed conversion up to 21 days of age. Similarly, a previous study from our group using pelleted or extruded diets in post-hatch feeding observed the same trend for these parameters (Sousa et al., 2021b). Although we observed consistent results in our trials, there are limited studies in the literature evaluating the same parameters which makes it difficult to draw broader conclusions.

At 7 d of age, greater relative weights of the jejunum, ileum, small intestine, and pancreas were found for chicks fed sorghum-based diets, regardless of the thermal processing method. Sorghum starch is digested more slowly and remains in the digestive tract for a longer time (Pasquali et al., 2017). The inclusion of slowly digestible starch in the diet has been shown to improve protein and energy utilization in broilers (Weurding et al., 2003). Studies such as Abdollahi et al. (2010) and Manyelo et al. (2019) which included sorghum in starter diets, also reported higher relative weights of digestive tract organs.

Amylase reached its highest activity in chicks fed corn-based extruded diets. Compared with conditioning temperatures of 75 °C and 60 °C, a temperature of 90 °C was effective in increasing the concentration of resistant starch in the diet (Abdollahi et al., 2010). Therefore, the extrusion temperature used in this study (150 °C) may have caused structural changes in corn starch, leading to the formation of resistant starch that is not easily digested by digestive enzymes and, consequently, causing an increase in pancreatic amylase activity. The increased production of pancreatic amylase may be an adaptive response of the organism to the presence of low-digestibility substances such as resistant starch. This finding is in line with those observed in the post-hatch phase by our group (Sousa et al., 2021b), showing a higher concentration of amylase in chicks fed corn-based extruded diets.

Depending on the type of starch (Abdollahi et al., 2011) and temperature (Liu et al., 2013), the starch retrogradation process may intensify. In this study, the type of carbohydrate used influenced extrusion, since the extruded sorghum diets did not increase the enzymatic activity of the chicks. One possibility is that sorghum starch may be less thermolabile than corn starch, resulting in less formation of non-digestible compounds, such as resistant starch (Abdollahi et al., 2010). Sorghum contains the protein kafirin in the endosperm that can impair the effects of temperature and moisture inside the granule, hindering the swelling and gelatinization of starch (Selle et al., 2018). Therefore, a study by Al-Rabadi et al. (2011) showed that the *in vitro* digestibility of sorghum starch increased from temperatures of 100 to 140 °C.

Finally, our results showed that the sorghum-based extruded diets does not significantly alter the development of digestive organs but improves the quality of the duodenum and jejunum villi, resulting in better performance in chicks up to 21 days of age. Conversely, corn-based extruded feed promotes increased production of the pancreatic amylase enzyme. Regardless of the type of carbohydrate used, the pelleting process enhanced the development of digestive organs and the quality of intestinal villi. However, when corn is used in this process, the chicks exhibit improved performance in the initial phase. Sorghum-based feed, regardless of thermal processing, improves digestive tract organ development and feed conversion at 21 days of age. These results indicate that probably the type of starch in these carbohydrates sources plays a significant role in the early stages of broilers development, and these changes lasted for at least 21 days. Although some speculative statements were used in this study because we did not analysed the formation of resistant starch and the decrease in amino acid availability, these effects have been previously demonstrated (Al-Marzooqi and Wiseman, 2009; Liu et al., 2013; Boroojeni et al., 2014). Additionally, a limitation of our study, as well as in several poultry studies, is the lack of correction of vitamin content in the premix mixture for feeds submitted to these thermal processing methods as it is performed when formulating vitamin supplements for pets and aquaculture feeds. Further studies should address these issues in order to provide a better understanding of the changes that occurr in feed after the thermal processing is applied.

5. Conclusions

Our results clearly indicated that the type of carbohydrate source (starch type) and thermal processing method interactively affected chick growth and gut development. These changes appear to persist from the pre-starter phase to 21 days of age. The extrusion process seems to provide better results when diets are based on sorghum, whereas the pelleting process yields, the best outcomes are observed for corn as the carbohydrate source. However, the extrusion process remains underexplored in the nutrition of chicks in the pre-starter phase, and several aspects remain to be clarified, such as the ideal temperature and moisture levels for high-starch diets and the specific characteristics of diets used in poultry farming.

Data availability

The data that support the results of this study are available from the corresponding author upon reasonable request.

Author contributions

Conceptualization: Carvalho, F. B.; Guimarães, I. G.; Mello, H. H. C.; Stringhini, J. H. and Leandro, N. S. M. **Data curation:** Mello, H. H. C. and Arnhold, E. **Formal analysis:** Mello, H. H. C.; Arnhold, E. and Leandro, N. S. M. **Investigation:** Sousa, R. F. **Methodology:** Sousa, R. F.; Carvalho, F. B. and Guimarães, I. G. **Project administration:** Sousa, R. F. and Carvalho, F. B. **Resources:** Stringhini, J. H. **Supervision:** Café, M. B. and Leandro, N. S. M. **Validation:** Café, M. B. **Visualization:** Café, M. B. **Writing – original draft:** Sousa, R. F.; Carvalho, F. B.; Guimarães, I. G.; Stringhini, J. H. and Leandro, N. S. M. **Writing – review & editing:** Sousa, R. F.; Carvalho, F. B.; Guimarães, I. G.; Stringhini, J. H. and Leandro, N. S. M.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

Thanks to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq; 459664/2014-0), Brazil, for funding this research.

References

Abdollahi, M. R.; Ravindran, V.; Wester, T. J.; Ravindran, G. and Thomas, D. V. 2010. Influence of conditioning temperature on performance, apparent metabolisable energy, ileal digestibility of starch and nitrogen and the quality of pellets, in broiler starters fed maize-and sorghum-based diets. Animal Feed Science and Technology 162:106-115. https://doi.org/10.1016/j.anifeedsci.2010.08.017

Abdollahi, M.; Ravindran, V.; Wester, T.; Ravindran, G. and Thomas, D. 2011. Influence of feed form and conditioning temperature on performance, apparent metabolisable energy and ileal digestibility of starch and nitrogen in broiler starters fed wheat-based diet. Animal Feed Science and Technology 168:88-99. https://doi.org/10.1016/j.anifeedsci.2011.03.014

Abdollahi, M. R.; Ravindran, V. and Svihus, B. 2013. Pelleting of broiler diets: An overview with emphasis on pellet quality and nutritional value. Animal Feed Science and Technology 179:1-23. https://doi.org/10.1016/j.anifeedsci.2012.10.011

Al-Marzooqi, W. and Wiseman, J. 2009. Effect of extrusion under controlled temperature and moisture conditions on ileal apparent amino acid and starch digestibility in peas determined with young broilers. Animal Feed Science and Technology 153:113-130. https://doi.org/10.1016/j.anifeedsci.2009.05.004

Al-Rabadi, G. J.; Torley, P. J.; Williams, B. A.; Bryden, W. L. and Gidley, M. J. 2011. Effect of extrusion temperature and pre-extrusion particle size on starch digestion kinetics in barley and sorghum grain extrudates. Animal Feed Science and Technology 168:267-279. https://doi.org/10.1016/j.anifeedsci.2011.04.097

Amerah, A. M.; Quiles, A.; Medel, P.; Sánchez, J.; Lehtinen, M. J. and Gracia, M. I. 2013. Effect of pelleting temperature and probiotic supplementation on growth performance and immune function of broilers fed maize/soy-based diets. Animal Feed Science and Technology 180:55-63. https://doi.org/10.1016/j.anifeedsci.2013.01.002

Avazkhanloo, M.; Shahir, M. H.; Khalaji, S. and Anarkooli, I. J. 2020. Flaxseed extrusion and expansion coupled with enzyme and pelleting changed protein and lipid molecular structure of flaxseed and improved digestive enzymes activity, intestinal morphology, breast muscle fatty acids and performance of broiler chickens. Animal Feed Science and Technology 260:114341. https://doi.org/10.1016/j.anifeedsci.2019.114341

Boroojeni, F. G.; Mader, A.; Knorr, F.; Ruhnke, I.; Röhe, I.; Hafeez, A.; Männer, K. and Zentek, J. 2014. The effects of different thermal treatments and organic acid levels on nutrient digestibility in broilers. Poultry Science 93:1159-1171. https://doi.org/10.3382/ps.2013-03563

Boroojeni, F. G.; Svihus, B.; von Reichenbach, H. G. and Zentek, J. 2016. The effects of hydrothermal processing on feed hygiene, nutrient availability, intestinal microbiota and morphology in poultry—A review. Animal Feed Science and Technology 220:187-215. https://doi.org/10.1016/j.anifeedsci.2016.07.010

Freitas, E. R.; Sakomura, N. K.; Neme, R. and Barbosa, N. A. A. 2005. Valor nutricional do milho termicamente processado, usado na ração pré-inicial para frangos de corte. Arquivo Brasileiro de Medicina Veterinária e Zootecnia 57:510-517.

García, M.; Lázaro, R.; Latorre, M. A.; Gracia, M. I. and Mateos, G. G. 2008. Influence of enzyme supplementation and heat processing of barley on digestive traits and productive performance of broilers. Poultry Science 87:940-948. https://doi.org/10.3382/ps.2007-00266

Garcia, R. G.; Mendes, A. A.; Almeida Paz, I. C. L.; Komiyama, C. M.; Caldara, F. R.; Nääs, I. A. and Mariano, W. S. 2013. Implications of the use of sorghum in broiler production. Brazilian Journal of Poultry Science 15:257-262. https://doi.org/10.1590/S1516-635X2013000300013

González-Alvarado, J. M.; Jiménez-Moreno, E.; Lázaro, R. and Mateos, G. G. 2007. Effect of type of cereal, heat processing of the cereal, and inclusion of fiber in the diet on productive performance and digestive traits of broilers. Poultry Science 86:1705-1715. https://doi.org/10.1093/ps/86.8.1705

Hendriks, W. H.; Moughan, P. J.; Boer, H. and van der Poel, A. F. B. 1994. Effects of extrusion on the dye-binding, fluorodinitrobenzene-reactive and total lysine content of soyabean meal and peas. Animal Feed Science and Technology 48:99-109. https://doi.org/10.1016/0377-8401(94)90114-7

Iravani, S.; Aziz-Aliabadi, F. and Vakili, R. 2024. Feed processing: a review of the impacts of conditioning time and temperature on feed quality and broilers performance. World's Poultry Science Journal 80:657-679. https://doi.org/10.1080/00439339.2024.2341276

Kisielinski, K.; Willis, S.; Prescher, A.; Klosterhalfen, B. and Schumpelick, V. 2002. A simple new method to calculate small intestine absorptive surface in the rat. Clinical and Experimental Medicine 2:131-135. https://doi.org/10.1007/s102380200018

Liu, S. Y.; Selle, P. H. and Cowieson, A. J. 2013. Influence of white-and red-sorghum varieties and hydrothermal component of steam-pelleting on digestibility coefficients of amino acids and kinetics of amino acids, nitrogen and starch digestion in diets for broiler chickens. Animal Feed Science and Technology 186:53-63. https://doi.org/10.1016/j.anifeedsci.2013.08.006

Luna, L. G. 1968. Manual of histology staining methods of the Armed Forces Institute of Pathology. 3rd ed. McGraw Hill, New York. 258p.

Manyelo, T. G.; Ng' ambi, J. W.; Norris, D. and Mabelebele, M. 2019. Substitution of *Zea mays* by *Sorghum bicolor* on performance and gut histo-morphology of Ross 308 broiler chickens aged 1–42 d. Journal of Applied Poultry Research 28:647-657. https://doi.org/10.3382/japr/pfz015

Massuquetto, A.; Durau, J. F.; Schramm, V. G.; Netto, M. V. T.; Krabbe, E. L. and Maiorka, A. 2018. Influence of feed form and conditioning time on pellet quality, performance and ileal nutrient digestibility in broilers. Journal of Applied Poultry Research 27:51-58. https://doi.org/10.3382/japr/pfx039

Pasquali, G. A. M.; Fascina, V. B.; Silva, A. L.; Aoyagi, M. M.; Muro, E. M.; Serpa, P. G.; Berto, D. A.; Saldanha, E. S. P. B. and Sartori, J. R. 2017. Maize replacement with sorghum and a combination of protease, xylanase, and phytase on performance, nutrient utilization, litter moisture, and digestive organ size in broiler chicken. Canadian Journal of Animal Science 97:328-337. https://doi.org/10.1139/cjas-2016-0133

Rostagno, H. S.; Albino, L. F. T.; Donzele, J. L.; Gomes, P. C.; Oliveira, R. F.; Lopes, D. C.; Ferreira, A. S.; Barreto, S. L. T. and Euclides, R. F. 2011. Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais. 3.ed. UFV, DZO, Viçosa, MG.

Salahshour, A.; Vakili, R. and Hesabi Nameghi, A. 2023. Effect of different conditioning temperatures and times on the pellet quality, performance, intestinal morphology, ileal microbial population, and apparent metabolizable energy in broiler chickens. Brazilian Journal of Poultry Science 25:1-10. https://doi.org/10.1590/1806-9061-2023-1801

Selle, P. H.; Moss, A. F.; Truong, H. H.; Khoddami, A.; Cadogan, D. J.; Godwin, I. D. and Liu, S. Y. 2018. Outlook: Sorghum as a feed grain for Australian chicken-meat production. Animal Nutrition 4:17-30. https://doi.org/10.1016/j.aninu.2017.08.007

Silversides, F. G. and Bedford, M. R. 1999. Effect of pelleting temperature on the recovery and efficacy of a xylanase enzyme in wheat-based diets. Poultry Science 78:1184-1190. https://doi.org/10.1093/ps/78.8.1184

Skřivan, M.; Englmaierová, M.; Bubancová, I. and Dlouhá, G. 2012. The stability of vitamin C and other vitamins in the diets of breeding hens. Animal Feed Science and Technology 177:253-258. https://doi.org/10.1016/j.anifeedsci.2012.06.010

Sousa, R. F.; Leandro, N. S. M.; Carvalho, F. B.; Stringhini, J. H.; Café, M. C.; Jardim Filho, R. M. and Rezende, P. M. 2021a. Pre-starter feed thermally processed to feed broiler chicks. Revista Brasileira de Saúde e Produção Animal 22:e2122102021. https://doi.org/10.1590/S1519-99402122102021

Sousa, R. F.; Carvalho, F. B.; Guimarães, I. G.; Café, M. C.; Stringhini, J. H.; Ulhôa, C. J.; Oliveira, H. and Leandro., N. S. M. 2021b. The effect of hydrothermal processing on the performance of broiler chicks fed corn or sorghum-based diets. Animal Feed Science and Technology 277:114953. https://doi.org/10.1016/j.anifeedsci.2021.114953

Svihus, B.; Uhlen, A. K. and Harstad, O. M. 2005. Effect of starch granule structure, associated components and processing on nutritive value of cereal starch: A review. Animal Feed Science and Technology 122:303-320. https://doi.org/10.1016/j.anifeedsci.2005.02.025

Teixeira Netto, T.; Massuquetto, A.; Krabbe, E. L.; Surek, D.; Oliveira, S. G. and Maiorka, A. 2019. Effect of conditioning temperature on pellet quality, diet digestibility, and broiler performance. Journal of Applied Poultry Research 28:963-973. https://doi.org/10.3382/japr/pfz056

Uni, Z. and Ferket, R. P. 2004. Methods for early nutrition and their potential. World's Poultry Science Journal 60:101-111. https://doi.org/10.1079/WPS20038

Vieira, S. L. and Pophal, S. 2000. Nutrição pós-eclosão de frangos de corte. Brazilian Journal of Poultry Science 2:189-199. https://doi.org/10.1590/S1516-635X2000000300001

Wang, S.; Li, C.; Copeland, L.; Niu, Q. and Wang, S. 2015. Starch retrogradation: A comprehensive review. Comprehensive Reviews in Food Science and Food Safety 14:568-585. https://doi.org/10.1111/1541-4337.12143

Wang, X.; Du, B.; Nian, F.; Ru, Y.; Sun, L.; Qin, S. and Tang, D. 2023. Effects of processing methods and conditioning temperatures on the cassava starch digestibility and growth performance of broilers. Animals 13:e1373. https://doi.org/10.3390/ani13081373

Weurding, R. E.; Enting, H. and Verstegen, M. W. A. 2003. The effect of site of starch digestion on performance of broiler chickens. Animal Feed Science and Technology 110:175-184. https://doi.org/10.1016/S0377-8401(03)00219-0

Wong, J. H.; Marx, D. B.; Wilson, J. D.; Buchanan, B. B.; Lemaux, P. G. and Pedersen, J. F. 2010. Principal component analysis and biochemical characterization of protein and starch reveal primary targets for improving sorghum grain. Plant Science 179:598-611. https://doi.org/10.1016/j.plantsci.2010.08.020

Zanotto, D. L. and Bellaver, C. 1996. Método de determinação da granulometria de ingredientes para uso em rações de suínos e aves. Comunicado Técnico, 215. EMBRAPA-CNPSA, Concórdia.