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Thermal energy application on extrusion and nutritional characteristics of dog foods

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ABSTRACT

The aim of this study was to evaluate the effects of specific thermal energy (STE) application at the extrusion preconditioning stage on the processing parameters, starch gelatinization, kibble macrostructure, nutrient digestibility, feces characteristics, and palatability of a dog food formulation. Two experiments were conducted, and both used the same dog food recipe. In the first experiment, six amounts of STE were applied by changing steam infusion in the preconditioner to obtain the following discharge mass temperatures: 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, and 95 °C. After evaluating the processing and kibble characteristics, the diets were fed to 36 dogs (six dogs per diet), and nutrient digestibility was determined by total feces collection. Palatability comparisons were carried out with 36 dogs using the two-pan method. Results were analyzed by analysis of variance (ANOVA), and means evaluated by polynomial contrasts according to the STE application ($P < 0.05$). In the second experiment, three treatments were produced. The extruder was operated with preconditioner mass temperature of 45 °C, and the amperage documented. On the sequence, the preconditioner mass temperature was increased to 95 °C, and the reduction on amperage was recorded. The extruder feed rate was them increased until a motor amperage equivalent to that of treatment 45 °C was observed but keeping constant preconditioner mass temperature at 95 °C. Processing and kibble characteristics were evaluated. Results were analyzed by ANOVA with means separated by Tukey's test ($P < 0.05$). In experiment one, a quadratic reduction of specific mechanical energy (SME) implementation with increasing STE was verified ($P = 0.004$), with a linear increase in total specific energy application to mass ($P < 0.001$). Regarding the relationship of starch gelatinization with increasing STE, a quadratic increase after preconditioning and a linear increase in kibbles after drying were verified ($P < 0.001$). Kibble expansion increased (bulk density, expansion rate, specific length), and hardness decreased with increasing STE ($P < 0.001$). Apparent nutrient digestibility and food palatability did not change according to STE application. Feces dry matter increased ($P = 0.003$), but pH and fermentation product content did not change. In experiment two, increasing STE was able to substantially elevate the mass production of the extrusion system while keeping the

Abbreviations: BCFA, branched-chain fatty acids; CP, crude protein; DM, dry matter; GE, gross energy; OM, organic matter; RT, residency time of the mass at the preconditioner; SCFA, short-chain fatty acids; SG, starch gelatinization; SME, specific mechanical energy; STE, specific thermal energy; TSE, total specific energy; Temp, preconditioner temperature; T45, treatment with preconditioner mass temperature of 45 °C; T55, treatment with preconditioner mass temperature of 55 °C; T65, treatment with preconditioner mass temperature of 65 °C; T75, treatment with preconditioner mass temperature of 75 °C; T85, treatment with preconditioner mass temperature of 85 °C; T95, treatment with preconditioner mass temperature of 95 °C; $T95_{flow}$, treatment with preconditioner mass temperature of 95 °C and extruder mass flow corrected to achieve the same motor amperage of the treatment T45

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electric energy consumption constant. In conclusion, an increase in STE application decreased the SME required to process the food and increased the kibble expansion, starch gelatinization and *in vitro* digestibility of organic matter (OM), allowing a substantial increase in extruder productivity without increasing electric energy consumption, an important economic consideration for dog food production efficiency.

1. Introduction

Extrusion processing has been investigated and used to improve the nutritional quality of a variety of raw materials, producing high-quality cooked foods. Processes effects include enabling starch gelatinization, protein denaturation, inactivation of thermolabile anti-nutritional factors, and inactivation of pathogenic bacteria (Alonso et al., 2000), and creating kibbles of desirable shapes and textures. These transformations affect food digestibility and palatability by dogs, impacting both animal health and the commercial performance of the products. However, few published studies have evaluated methods to optimize energy input within processing conditions involved in the extrusion of dog foods (Monti et al., 2016).

Food extruders deliver specific mechanical energy (SME) *via* the main drive motor and specific thermal energy (STE) from direct steam and water injection during processing (Riaz, 2000). Together, these two energy sources promote extensive raw material transformations that are directly linked and are dependent on the total specific energy (TSE) applied to the mass (Riaz, 2000; Van Zuilichem et al., 2011). Although very few papers have reported the application of STE in the production of dog foods (Monti et al., 2016), authors evaluations of commercial single screw extrusion systems suggests that between 60% and 75% of the TSE applied corresponds to STE, and the remainder is SME. The authors were unable to find published studies that aimed to optimize the TSE and STE:SME ratios in the production of pet foods, that would facilitate achieve the better balance between raw material transformation and efficient use of energy saving production cost.

The extrusion process includes the steps of preconditioning, extrusion, cutting and drying, and each step serves a specific purpose in the cooking and shaping of the final product (Riaz, 2000). The preconditioner is an important part of the extrusion system and has been used in the pet food extrusion process since 1960 (Rokey et al., 2010). The primary role of the preconditioner is to preblend the ground raw materials with steam, water, and other liquids, preheating and partially cooking the ingredients entering the extruder (Levine, 2014). The preconditioner is the main site of STE application, although this energy can also be added at the extruder barrel. Starting the process of starch gelatinization, the preconditioner favors the internal hydration of food granules and the plasticization and sanitization of the mass, increasing extruder stability, and improving the quality of the final product (Guy, 2001; Gibson and Alavi, 2013). Better preconditioning results in lower SME application, which can reduce extruder barrel and screw component wear, increasing the lifespan of the equipment and decreasing the electric power consumption and the processing cost (Huber and Rokey, 1990; Riaz, 2000; Levine, 2014). In addition, proper preconditioning, in which the starting raw material receives adequate steam and water for a proper residence time, can significantly increase the extruder effective throughput (Guy, 2001), with a high impact on cost and efficiency.

Therefore, the objectives of the present study were to evaluate six amounts of STE application at the extruder preconditioner on the processing parameters, starch gelatinization, *in vitro* digestibility, kibble macrostructure, total tract apparent nutrient digestibility, fermentation products in feces, and palatability of a dog food formulation.

2. Material and methods

The study was conducted at the Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal, Brazil. All procedures with animals followed the ethical principles adopted by the Brazilian College of Animal Experimentation and were previously approved by the Ethics Committee on the Use of Animals (protocol number 018909/14).

2.1. Experimental design and food formulation

Two experiments were conducted. The first experiment evaluated six preconditioner temperatures during the extrusion of a dog food formulation. The second experiment compared the throughput and processing traits of a dog food processed at the lowest and highest preconditioner temperatures evaluated in the first experiment, adjusting the extruder feed rate to achieve the same amount of motor work (motor amperage).

In the first experiment, the extrusion study followed a completely randomized design. Six different amounts of STE were applied by changing the steam infusion at the preconditioner to obtain the following discharge mass temperatures: 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, and 95 °C. After achieving stable production, processing data and food samples were taken approximately every 10 min. Each sample or recorded parameter were considered the experimental unit (treatment repetition), with four replications per treatment. The diets produced with these different amounts of STE were evaluated in dogs. The digestibility study was organized in a randomized complete block design with six diets, three blocks of 12 dogs each, and two dogs per diet in each block, totaling six dogs per diet. The blocking factor was period. The experimental unit was the individual dog.

In Experiment 2, only the extrusion characteristics were evaluated, and the diets were not tested on dogs. Three treatments were produced, to this the extruder was operated with preconditioner discharge mass temperature of 45 °C, and the motor amperage

documented. On the sequence, the preconditioner discharge mass temperature was increased by direct steam infusion to 95 °C, and the reduction on amperage was recorded. The extruder feed rate was them increased until a motor amperage equivalent to that of treatment 45 °C was observed but keeping constant preconditioner mass temperature at 95 °C. The experimental unit (repetition) was considered the processing data and food samples that were taken every 10 min along the extrusion process, for at least four replicates per food.

For both experiments, the same dog food (Table 1) formulated for maintenance was used, following the nutritional recommendations of FEDIAF (2014). The ingredients were mixed and ground in a hammer mill fitted with a 0.9 mm size screen sieve (Sistema Tigre de Mistura e Moagem, Tigre, Sao Paulo, Brazil), and a single production lot was used for both experiments. The mean geometric diameter of the raw material was determined according to Zanotto and Belaver (1996) and was 165 ± 1.6 µm.

2.2. Extrusion processing and experimental treatments

A single-screw extruder (MEX-250, Manzoni Industrial Ltda., Campinas, Sao Paulo, Brazil), with a 250 kg/h production capacity and a circular die with one opening of 8.0 mm in diameter were used to process all treatments. The extruder screw profile had five sections: first – single flight screw and no steam lock; second – single flight screw and small steam lock; third – double flight uncut screw and small steam lock; fourth – double flight uncut screw and medium steam lock; fifth – double flight cut cone screw. For both experiments, the operation conditions were set as follows: 45.5 rpm preconditioner shaft speed, 643 rpm extruder shaft speed, 1026 rpm cutting knife speed.

Table 1
Ingredients and analyzed chemical composition of the experimental diet for dogs used in Experiments 1 and 2.

Item	g/kg
Ingredient composition (as-fed basis)	
Corn, grain	557.1
Chicken by-product meal	300.0
Sugarcane fiber[a]	30.0
Common salt	5.0
Vitamin-mineral premix[b]	5.0
Potassium chloride	4.5
Choline chloride	2.0
Mold inhibitor[c]	1.0
Antioxidant[d]	0.4
Added by coating	
Chicken fat	85.0
Palatant enhancer[e]	10.0
Chemical composition, before coating (g/kg, DM-basis)	
Moisture	70.3
Ash	70.0
Crude protein	309.2
Crude fat	80.1
Crude fiber	29.4
Starch	473.1

[a] Vit2be Fiber, Dilumix Industrial Ltda., Leme, Brazil.

[b] Rovimix, DSM Produtos Nutricionais Brasil S.A., Jaguaré, Brazil. Added per kg of food: Vitamin A (encapsulated cross-linked beadlet), 18,750 IU; Vitamin D3 (encapsulated cross-linked beadlet), 1500 IU; Vitamin E (oil adsorbate, powder), 125 IU; Vitamin K3 (menadione nicotinamide bisulfite), 1,5 mg; Vitamin B1 (thiamine mononitrate), 5 mg; Vitamin B2 (riboflavin spray dried), 16.25 mg; Pantothenic Acid (calcium pantothenate, spray dried), 37.5 mg; Vitamin B6 (pyridoxine hydrochloride crystalline powder), 7.5 mg; Vitamin B12 (cobalamin crystalline powder), 45 mcg; Vitamin C (L-ascorbyl-2-phosphate), 0125 g; Nicotinic Acid (niacin, crystalline powder), 0.0625; Folic Acid (spray-dried powder), 0.75 mg; Biotin (spray-dried powder), 0.315 mg; Choline (choline hydrochloride, 60% powder), 0.625 g; Iron (iron sulphate), 0.1 g; Copper (cupper sulphate), 9.25 mg; Manganese (manganese sulphate), 6.25 mg; Zinc (zinc sulphate monohydrate), 0.15 g; Iodine (calcium iodate), 1.875 mg; Selenium (sodium selenite), 0.135 mg.

[c] Mold-Zap Citrus, Alltech do Brasil Agroindustrial Ltda., Araucária, Brazil.

[d] Banox, Alltech do Brasil Agroindustrial Ltda., Araucária, Brazil.

[e] D'TECH 10 L, Palatabilizante Líquido, SPF do Brasil Indústria e Comércio Ltda., Descalvado, Brazil.

In the Experiment 1, STE was added to the preconditioner through direct steam injection. Steam was collected from a central line, cleaned of residual water by a separation valve, and had it pressure reduced from 8 bars to 2 bars. The injection on extruder preconditioner was controlled by a manual valve, read by an automatic flow meter system. Six different amounts of steam were injected that produced six different preconditioner discharge mass temperatures, constituting the following experimental treatments: T45, mass temperature of 45 °C; T55, mass temperature of 55 °C; T65, mass temperature of 65 °C; T75 mass temperature of 75 °C; T85, mass temperature of 85 °C; and T95, mass temperature of 95 °C. No steam was infused at the extruder barrel. To compensate for the different moisture concentrations added to the mass, the treatments with lower steam application had more water added during preconditioning to achieve similar in-barrel moisture content. Water addition at the extruder barrel was kept constant for all treatments, approximately 3.5% of the raw material feed rate.

Experiment 2 used the same operation conditions as used in experiment 1, with two amounts of STE added to the preconditioner to obtain discharge mass temperatures of 45 °C and 95 °C. In sequence, the reduction in extruder motor amperage after the increase in STE application was recorded, and the extruder feed rate was increased until the same motor amperage registered for the 45 °C treatment was observed. The procedure resulted in three experimental treatments in experiment 2: T45, preconditioner mass temperature of 45 °C; T95, preconditioner mass temperature of 95 °C; $T95_{flow}$, preconditioner mass temperature of 95 °C and increased extruder product flow rate. To compensate for the different moisture concentrations added to the mass during processing, the treatments with lower steam application had more water added to the preconditioner to achieve similar in-barrel moisture content. Water addition at the extruder barrel was kept constant (3.5% of the raw material feed rate).

In both studies, the treatments were administered sequentially with no stop-start cycle. After achieved the target processing conditions for a specific treatment, a minimum of 30 min of a stable processing condition was observed, and the following parameters were recorded every 10 min: feed screw speed (rpm); preconditioner shaft speed (rpm); preconditioner steam flow (kg/h); preconditioner water flow (kg/h); preconditioner water temperature (ºC); preconditioner discharge mass temperature (ºC); extruder shaft speed (rpm); motor load (A); extruder water flow (kg/h); extruder water temperature (ºC); cutting knife speed (rpm); mass temperature before the extruder die (ºC); mass pressure before the extruder die (MPa); steam pressure (psig); ambient temperature (ºC); air moisture (%). Kibble bulk density after extrusion and after drying (g/L) was recorded at each sampling time (measured as the weight of food corresponding to a 1 L volume). The mass flow rate from the extruder was measured directly in a bucket at each sampling time. At each observation time, food samples were collected from the preconditioner, from the extruder and from the dryer. Food samples were stored at -20 °C for further analysis. After extrusion, the kibbles were dried in a forced air dryer at 105 °C for approximately 20 min.

2.3. Specific mechanical energy and specific thermal energy calculations

The SME (kW-h/ton) was calculated for each treatment repetition (experimental unit) using the following equation (Riaz, 2000):

$$SME = \frac{(\sqrt{3} \times Voltage \times (At - Av) \times cosFi) \div 1000) \times 1000}{M}$$

where: Voltage = 220 V; At = torque load working amperage (A); Av = no torque load working amperage (A); cosFi = power factor; M = mass flow rate from extruder (kg/h).

The STE (kW-h/ton) in the preconditioner and extruder was calculated by mass and energy balance equations according to Riaz (2000). The feed, water and steam total input and output mass amounts were determined. These mass values and the corresponding specific heat values from each component of the system were used to calculate the amount of heat produced, as described below.

- Preconditioner mass balance equation:

$$M_{raw} + M_w + M_S = M_{sl} + M_{pc}$$

- Extruder mass balance equation:

$$M_{pc} + M_w = M_{sl} + M_f$$

where: M_{raw} = raw material mass; M_w = water mass; M_s = steam mass; M_{sl} = steam loss mass; M_{pc} = preconditioner mass flow rate; M_f = final mass flow rate from extruder.

-Preconditioner energy balance:

$$Q_R + Q_W + Q_S = Q_{Pc} + Q_{SL} + Q_{HL} + \Sigma_{\Delta h}$$

- Extruder energy balance:

$$Q_{Pc} + Q_W + Q_{sme} + Q_{barrel} = Q_{ex} + Q_{SL} + \Sigma_{\Delta h}$$

Where: Q_R = Raw material heat capacity; Q_W = Water input heat capacity; Q_S = Steam input heat capacity; Q_{SL} = Steam loss heat capacity; Q_{HL} = Preconditioner heat loss by convection; Q_{Pc} = Preconditioner product heat capacity; Q_{sme} = Mechanical energy amount; Q_{Barrel} = Extruder heat loss by convection; Q_{ex} = Extruder product heat capacity; Q_{te} = Thermal energy amount; $\Sigma_{\Delta h}$ = Reaction energy.

The amount of heat (Q) was obtained from the formula:

$$Q = m.c.T$$

where: m = mass; c = specific heat capacity; T = temperature.

The TSE (kW-h/ton) was obtained by the summation of SME and STE.

2.4. Residence time in the preconditioner measurement

The mass residence time in the preconditioner was evaluated in both experiments. For the measurement, the conditions of operation of the preconditioner were kept the same as those verified during the extrusion of the treatments (raw material feed rate, steam and water injection, preconditioner shaft speed). Before collecting samples to determine the residence time, the preconditioner was operated stably for 20 min. After that, the system was stopped, and all material inside the preconditioner cylinder was quantitatively collected and weighed. The residence time was determined as the preconditioner product flow rate (kg/s) divided by the total amount of product (kg) retained in the preconditioner by the following equation:

Residence time (seconds) = preconditioner product flow rate (kg/s) / total amount of product retained into the preconditioner (kg).

2.5. Kibble macrostructure, starch gelatinization and in vitro digestibility of the organic matter

Hardness was analyzed in 20 kibbles using a texture analyzer (TAX/T2I, Stable Micro Systems, Godalming, UK) equipped with a load cell of 50 kgf, and a guillotine probe. First kibbles were stabilized at the same moisture in an oven (Quimis, Diadema, Brazil) at 35 °C during 24 h. For each treatment, the length, diameter and mass of 40 extrudates were measured using a caliper, and the data were used to obtain the radial expansion ratio, specific length and piece density, as described by Karkle et al. (2012). The die diameter used was 8.0 mm.

Samples were collected from the preconditioner and from the dryer for each treatment replication for the measurement of starch gelatinization, which was determined by the amyloglucosidase method (Sá et al., 2013). For each treatment replication, the *in vitro* digestibility of organic matter (OM) was determined as described by Hervera et al. (2007) in samples collected after the dryer. The incubation conditions simulate two steps of the digestion process, digestion in the stomach and in the small intestine, using an enzymatic system with pepsin and pancreatin, respectively.

2.6. Digestibility protocol

This evaluation was conducted only on experiment one. Thirty-six Beagle dogs aged 3.6 ± 2.2 years old and weighing 11.3 ± 1.5 kg were used. The health of the animals was confirmed prior to the start of the study. The total tract apparent digestibility tests were carried out through the quantitative collection of feces without urine collection according to FEDIAF (2014) recommendations. Dogs were allowed a 10-d diet adaptation phase, after which a 5-d total feces collection was conducted to determine nutrient and energy total tract apparent digestibility. During the adaptation period, dogs were housed in 1.5 × 4.0 m kennels with a solarium and were released daily into a collective playground for exercise and socialization. During the fecal collection period, dogs were individually housed in 1 × 1 × 1 m stainless steel metabolic cages. Animals were fed twice daily (10h00 a.m. and 16h00 p.m.) in amounts sufficient to satisfy their metabolizable energy requirements (ME, kcal/d = 110 × Body Weight$^{0.75}$), as recommended by the NRC (2006). Feces were quantitatively collected, weighed at each feeding time, and immediately frozen at −20 °C. The fecal score was determined using the system described by Carciofi et al. (2008): 0 = watery liquid that can be poured; 1 = soft, unformed; 2 = soft, malformed stool that assumes the shape of its container; 3 = soft, formed, and moist stool that retains its shape; 4 = well-formed and consistent stool that does not adhere to the floor; and 5 = hard, dry pellets, which are small and hard masses.

2.7. Chemical analyses

At the end of the collection period in experiment one, feces were thawed, homogenized and pooled by dog. All feces samples were dried using a forced-air oven (MA035, Marconi, Piracicaba, Brazil) at 55 °C for 72 h. Diets and dried feces were ground in a cutting mill (MA680, Marconi, Piracicaba, Brazil) fitted with a 1 mm screen sieve and analyzed (AOAC, 1995) for dry matter (DM) (method 934.01), total fat was assessed using the acid-hydrolyzed fat assay (method 954.02), and ash content by muffle furnace incineration (method 942.05). Crude protein (CP) was determined using a LECO nitrogen/protein analyzer (FP-528, LECO Corporation, Saint Joseph, USA) (method 990.03), organic matter (OM) was calculated as DM minus ash, and gross energy (GE) was determined in a bomb calorimeter (IKA C2000 Basic, IKA-Werke GmbH & Co. KG, Staufen, Germany). Starch content was determined according to the method of Hendrix (1993). All analyses were carried out in duplicate and repeated when the coefficient of variation was higher than 5%.

2.8. Fecal pH and fermentation products

For experiment one, fresh fecal samples (collected and processed within 15 min of elimination) were collected on three consecutive days to measure pH, short-chain fatty acids (SCFA), branched-chain fatty acids (BCFA), lactic acid and ammonia. Fecal pH was measured in a pH meter (DM20, Digimed Analítica Ltda., São Paulo, Brazil) immediately after collection by mixing 2 g of fresh

feces with 6 ml of ultrapure water (1:3 w/v). For SCFA and BCFA analyses, 10 g of feces was mixed in 30 ml of formic acid solution at 4.2 N (1:3 w/v) and precipitated at 4 °C for 72 h, and the supernatant was centrifuged three times (5000 G at 15 °C for 15 min). The analyses were performed by gas chromatography (GC-2014, Shimadzu Corporation, Kyoto, Japan) according to Erwin et al. (1961). Lactic acid was measured according to Pryce (1969) by mixing 3 g of feces with 9 ml of ultrapure water (1:3 w/v) and subsequent evaluation with a colorimetric method (Spectrophotometer Quick-Lab, Drake, Sao José do Rio Preto, Brazil). The concentration of ammonia was assessed in the extracts prepared for SCFA and BCFA analysis according to Vieira (1980). The extracts were thawed at room temperature, diluted with ultrapure water (2:13 v/v), and then ammonia distilled in a nitrogen system (Tecnal TE-036/1, Tecnal, Piracicaba, Brazil).

2.9. Food palatability test

Food preference comparisons were performed only in the first experiment at Panellis Latin America (Descalvado, Sao Paulo, Brazil) using a panel of qualified dogs. Three preference tests were performed: T45 *versus* T75, T45 *versus* T95, and T75 *versus* T95. The first choice (first product consumed) and the preferred product (product consumed in greater amount) were determined using the two-pan method (Griffin, 2003). For the study, 36 adult dogs of different breeds, individually housed, were used. Dogs were tested in two consecutive meals. In the morning, after 12 h of fasting, the animals received the first meal in two pans, each containing one of the experimental foods, and were allowed to eat for 30 min. The position of the food bowls was changed at the evening meal. The amount of food offered in each bowl surpassed the consumption capacity of the animal to ensure that there would be leftovers to measure. After 30 min, the bowls were removed, the remains weighed, and the consumption calculated by taking the difference in amount offered and amount remained. Due to the differences in body weight, the results were calculated as the relative consumption of each diet, and the mean intake of the two meals was compared.

2.10. Statistical analysis

The results of the extrusion parameters were analyzed in a complete randomized design with four replications per treatment (sampling time). In Experiment 1, data were submitted to ANOVA, and when differences were found by F test, polynomial contrasts were used to compare means according to the preconditioner mass temperature. Data on apparent digestibility and feces parameters in Experiment 1 were submitted to ANOVA in a completely randomized block design with three blocks (period) and two repetitions (dogs) per block, totaling six dogs per treatment. The sums of squares in the models were separated on diet and block effects, and when differences were found by F test, means were compared by polynomial contrasts according to preconditioner mass temperature. In Experiment 2, data were submitted to ANOVA, and when differences were found by F test, the means were compared by Tukey's test. All data were found to comply with the assumptions of the analysis of variance and were analyzed using the PROC MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). For the palatability study, the first preference was evaluated through the Chi^2 test, and for

Table 2
Processing traits and starch gelatinization at the preconditioner for a dog food formulation extruded using different specific thermal energy applications (Experiment 1).

Item	Treatments[a]						SEM[b]	*P*-values	Contrast[c]	
	T45	T55	T65	T75	T85	T95			Linear	Quad
Preconditioner										
Discharge mass temperature (°C)	43.5	54.3	64.5	75.7	86.0	93.0	2.82	–	–	–
Discharge mass moisture (%)	20.5	20.7	20.8	21.5	21.6	22.5	0.15	< 0.001	0.0002	0.218
Product flow rate (kg/h)	192.1	185.9	189.3	193.6	191.2	195.5	0.88	0.234	–	–
Starch gelatinization (%)	25.0	26.1	28.0	28.9	31.1	33.6	0.48	< 0.001	< 0.001	0.013
Extruder										
Motor amperage (A)	42.5	41.3	39.3	38.3	36.5	36.5	0.36	< 0.001	< 0.001	< 0.001
Mass pressure before die (MPa)	5.03	5.08	4.83	4.33	3.85	3.75	0.09	< 0.001	< 0.001	0.047
Mass temperature before die (°C)	112.5	115.5	119.0	122.3	123.4	125.5	0.75	< 0.001	< 0.001	0.004
Product flow rate (kg/h)	195.5	190.3	189.5	192.8	194.5	192.0	0.68	0.111	–	–
Bulk density (g/L)	472.8	481.8	462.3	447.8	433.0	409.5	4.18	< 0.001	< 0.001	0.007
In-barrel moisture (%)	23.5	23.8	23.8	24.4	24.6	25.4	0.14	< 0.001	< 0.001	0.249
Energy Balance (kW-h/ton)										
Specific mechanical energy (SME)	18.5	16.9	14.2	12.5	9.6	10.8	0.52	< 0.001	< 0.001	0.004
Specific thermal energy (STE)	19.6	23.7	35.2	44.0	47.2	64.7	2.67	< 0.001	< 0.001	0.326
Total specific energy (TSE)	38.1	40.6	49.3	56.5	56.9	75.5	2.28	< 0.001	< 0.001	0.161
STE/SME ratio	1.1	1.4	2.5	3.5	4.9	6.1	0.30	< 0.001	< 0.001	0.219

[a] T45 = preconditioner mass temperature of 45 °C; T55 = preconditioner mass temperature of 55 °C; T65 = preconditioner mass temperature of 65 °C; T75 = preconditioner mass temperature of 75 °C; T85 = preconditioner mass temperature of 85 °C; T95 = preconditioner mass temperature of 95 °C.

[b] SEM = standard error of the mean (n = 24).

[c] Linear or quadratic effect of preconditioner discharge mass temperature.

the food intake rate, the Student's *t*-test was applied. Values of $P < 0.05$ were considered significant.

3. Results

3.1. Extrusion traits (Experiment 1)

During the extrusions, preconditioner discharge mass temperatures close to the target temperatures for the treatments were obtained (Table 2). The mean residence time of the mass at the preconditioner was 182.7 s. The product flow rate did not change among treatments ($P = 0.234$). Despite the procedures adopted to control the preconditioner mass moisture, a two-percentage point increase was verified with the increase in STE application ($P < 0.001$). With the increase in STE application at the preconditioner, the starch gelatinization (SG) of the mass showed a quadratic increase ($P = 0.013$). The starch gelatinization increased by 8.5 percentage points and could be described as a function of the preconditioner temperature (Temp) as follows: SG after preconditioner, % = 23.8 – (0.38 * Temp) + (0.002 * Temp^2); $r^2 = 0.96$; $P < 0.001$.

The extruder motor amperage and the pressure of the mass before the die reduced quadratically with the increase in preconditioner temperature ($P < 0.001$). The reduction in motor amperage as a function of preconditioner temperature could be described as motor amperage, A = 53.5 – (0.29 * Temp) + (0.001 * Temp^2); $r^2 = 0.97$; $P < 0.001$. The mass pressure as a function of preconditioner temperature was described as follows: Mass pressure, MPa = 5.23 + (0.011 * Temp) – (0.0003 * Temp^2); $r^2 = 0.89$; $P < 0.001$. The temperature of the mass before the die, on the other hand, increased with the increase in STE application (mass temperature, ºC = 90.05 + (0.61 * Temp) – (0.002 * Temp^2); $r^2 = 0.97$; $P < 0.001$). The derivation of this equation resulted in a maximum temperature of extrusion with a preconditioner temperature of 123 °C, but as this temperature is not feasible, it is possible to conclude that the maximum temperature of extrusion was not achievable for these operation conditions or this equipment. The extruder product flow rate was similar between treatments ($P = 0.111$). Following the increase in preconditioner mass moisture, the mass in-barrel moisture increased linearly ($P < 0.001$), but the change was numerically small.

In energy balance calculations, the SME application reduced quadratically with the increase in preconditioner temperature (SME, kW-h/ton = 36.5 – (0.49 * Temp) + (0.002 * Temp^2); $r^2 = 0.93$; $P < 0.001$). The STE application increased linearly ($P < 0.001$) from 19.6 kW-h/ton for the T45 treatment to 64.7 kW-h/ton for the T95 treatment. Therefore, a linear increase in TSE and STE/SME ratio was observed ($P < 0.001$).

3.2. Kibble macrostructure, starch gelatinization and in vitro digestibility (Experiment 1)

Significant effects of preconditioner temperature were observed for all analyzed kibble characteristics (Table 3). The bulk density decreased linearly ($P < 0.001$) with the increase in STE application, from 444 g/L for T45 to 355 g/L for T95. The hardness and piece density decreased quadratically ($P < 0.001$), and the expansion rate increased quadratically with increasing preconditioner temperature ($P < 0.001$).

The starch gelatinization (SG, % = 52.19 + (0.35 * Temp); $r^2 = 0.96$; $P < 0.001$) and the *in vitro* digestibility of the OM (*in vitro* digestibility, % = 81.13 + (0.106 * Temp); $r^2 = 0.76$; $P < 0.001$) increased linearly with the increase in the preconditioner temperature. These parameters also increased linearly considering the increase in TSE application to the mass ($P < 0.001$).

3.3. Nutrient intake and total tract apparent nutrient digestibility (Experiment 1)

To study digestibility, after drying, the diets were coated with poultry fat and liquid palatant, as described in Table 1. Their final chemical compositions were similar (Table 4), except for a slightly lower fat content for diet T75. The nutrient intake during the

Table 3
Kibble macrostructure, starch gelatinization, and *in vitro* digestibility of a dog food formulation extruded with different specific thermal energy applications (Experiment 1). Values reported are of the kibbles after the drier step.

Item	Treatments[a]						SEM[b]	P-values	Contrast[c]	
	T45	T55	T65	T75	T85	T95			Linear	Quad
Bulk density (g/L)	444.3	426.3	405.5	391.0	376.8	355.0	4.93	< 0.001	< 0.001	0.780
Hardness (N)	50.9	44.1	39.2	37.2	36.3	35.3	1.2	< 0.001	< 0.001	0.001
Expansion rate	2.1	2.2	2.4	2.5	2.5	2.6	0.04	< 0.001	< 0.001	< 0.001
Piece density (g/cm^3)	0.55	0.51	0.49	0.47	0.46	0.43	0.01	< 0.001	< 0.001	0.013
Specific length (cm/g)	1.84	1.84	1.82	1.79	1.81	1.87	0.02	< 0.001	0.788	< 0.001
Starch gelatinization (%)	68.9	72.2	77.8	80.1	85.3	89.3	1.16	< 0.001	< 0.001	0.753
In vitro digestibility of the OM (%)	84.8	85.6	86.1	86.2	86.3	86.9	0.12	< 0.001	< 0.001	0.118

[a] T45 = preconditioner mass temperature of 45 °C; T55 = preconditioner mass temperature of 55 °C; T65 = preconditioner mass temperature of 65 °C; T75 = preconditioner mass temperature of 75 °C; T85 = preconditioner mass temperature of 85 °C; T95 = preconditioner mass temperature of 95 °C.

[b] SEM = standard error of the mean ($n = 24$).

[c] Linear or quadratic effect of preconditioner discharge mass temperature.

Table 4
Analyzed chemical composition of a dog food formulation extruded with different specific thermal energy applications (Experiment 1). Values are after coating with chicken fat and palatant enhancer.

Item	Treatments[a]					
	T45	T55	T65	T75	T85	T95
Chemical composition (g/kg, DM-basis)						
Moisture	79.8	77.5	71.8	79.6	73.2	74.6
Ash	68.2	69.0	69.1	70.7	70.8	71.1
Crude Protein	274.9	273.6	276.3	285.8	278.6	281.7
Crude fat	161.1	153.4	159.1	146.1	163.9	161.3
Starch	398.6	419.0	399.2	412.5	394.8	395.3

[a] T45 = preconditioner mass temperature of 45 °C; T55 = preconditioner mass temperature of 55 °C; T65 = preconditioner mass temperature of 65 °C; T75 = preconditioner mass temperature of 75 °C; T85 = preconditioner mass temperature of 85 °C; T95 = preconditioner mass temperature of 95 °C.

digestibility experiment was similar for all treatments (Table 5). The coefficient of total tract apparent digestibility of DM, OM, CP, fat, and GE was also unaffected by increasing the STE application ($P > 0.05$). A quadratic reduction in starch digestibility was verified with the increase in STE application ($P < 0.001$), but this reduction was small, only 0.1%.

3.4. Fecal characteristics and fermentation products (Experiment 1)

Fecal DM increased linearly with the increase in preconditioner mass temperature ($P = 0.003$; Table 6). The other evaluated feces parameters were similar among all dogs fed the experimental diets. The fermentation products in feces were also unaffected by increasing the preconditioner mass temperature. Although a diet effect for lactate fecal concentration was verified by the F test ($P = 0.018$), the polynomial comparisons did not find differences among diets.

3.5. Food palatability test (Experiment 1)

Before the palatability comparisons, foods were coated with 85 g/kg of poultry fat and 10 g/kg of a standard liquid palatant for dogs (2D'Tech 2 L, Palatabilizante Líquido, SPF do Brasil Indústria e Comércio Ltda., Descalvado, Brazil). The palatability study did not find many differences in dog preferences. The dog's first choice was higher for the T45 (77% of the first food intake) than the T95 food (23%; $P < 0.01$), but the intake ratio was similar, 63% T45 and 37% T95 ($P > 0.05$). The intake ratio was similar for T45 and T75 (48% and 52%, respectively) and for T75 and T95 (59% and 41%, respectively).

Table 5
Nutrient intake and total tract apparent nutrient digestibility of a dog food formulation extruded with different specific thermal energy applications (Experiment 1).

Item	Treatments[a]						SEM [b]	P-values	Contrast[c]	
	T45	T55	T65	T75	T85	T95			Linear	Quad
Nutrient intake (g/dog/d)										
Dry matter	161.9	168.5	166.6	175.5	154.5	158.8	2.73	0.310	–	–
Organic matter	163.9	170.2	167.3	177.7	155.7	159.9	2.78	0.268	–	–
Crude fat	28.4	29.4	28.9	30.8	26.9	27.6	0.48	0.260	–	–
Crude protein	48.4	50.2	49.4	52.4	45.8	47.2	0.82	0.269	–	–
Starch	70.1	72.8	71.6	76.0	65.5	68.4	1.19	0.270	–	–
Coefficient of total tract apparent digestibility										
Dry matter	0.830	0.838	0.830	0.840	0.840	0.828	0.22	0.434	–	–
Organic matter	0.865	0.872	0.866	0.873	0.874	0.864	0.17	0.377	–	–
Crude fat	0.941	0.939	0.939	0.932	0.934	0.933	0.11	0.069	–	–
Crude protein	0.885	0.893	0.893	0.898	0.900	0.897	0.17	0.080	–	–
Starch	0.998	0.999	0.998	0.998	0.997	0.997	0.01	< 0.001	< 0.001	< 0.001
Gross Energy	0.874	0.882	0.877	0.883	0.885	0.875	0.17	0.331	–	–

[a] T45 = preconditioner mass temperature of 45 °C; T55 = preconditioner mass temperature of 55 °C; T65 = preconditioner mass temperature of 65 °C; T75 = preconditioner mass temperature of 75 °C; T85 = preconditioner mass temperature of 85 °C; T95 = preconditioner mass temperature of 95 °C.
[b] SEM = standard error of the mean ($n = 36$).
[c] Linear or quadratic effect of preconditioner discharge mass temperature.

Table 6
Fecal characteristics and fermentation products for dogs fed a food formulation extruded with different specific thermal energy applications (Experiment 1).

Item	Treatments[a]						SEM[b]	P-values	Contrast[c]	
	T45	T55	T65	T75	T85	T95			Linear	Quad
Fecal characteristics										
DM (g/kg)	397.4	399.3	412.3	390.1	432.3	428.5	0.50	0.008	0.003	0.262
Score[d]	3.9	3.9	4.0	3.9	4.0	4.0	0.01	0.374	–	–
pH	6.6	6.4	6.4	6.5	6.5	6.7	0.03	0.061	–	–
*Fermentation products (*mMol/kg *of DM)*										
Acetic acid	229.8	265.1	286.7	245.9	226.7	224.0	7.62	0.103	–	–
Propionic acid	122.1	138.5	147.0	115.9	117.0	110.2	4.28	0.053	–	–
Butyric acid	49.5	53.3	58.2	64.8	48.6	50.3	2.30	0.270	–	–
Total short-chain fatty acids	401.4	456.9	491.9	426.6	392.3	384.5	12.56	0.093	–	–
Isobutyric acid	7.6	7.7	8.2	8.0	7.1	8.6	0.24	0.620	–	–
Isovaleric acid	11.1	11.4	11.6	11.9	10.5	12.7	0.35	0.590	–	–
Valeric acid	0.02	0.03	0.02	0.02	0.02	0.02	0.00	0.339	–	–
Total branched-chain fatty acids	18.7	19.2	19.8	20.0	17.6	21.3	0.58	0.611	–	–
Total volatile fatty acids	420.1	476.0	511.8	446.6	409.9	405.8	12.87	0.110	–	–
Ammonia	116.6	146.2	140.9	131.3	117.8	114.0	5.32	0.177	–	–
Lactate	8.6	8.3	9.4	8.3	8.0	8.2	0.15	0.018	0.101	0.192

[a] T45 = preconditioner mass temperature of 45 °C; T55 = preconditioner mass temperature of 55 °C; T65 = preconditioner mass temperature of 65 °C; T75 = preconditioner mass temperature of 75 °C; T85 = preconditioner mass temperature of 85 °C; T95 = preconditioner mass temperature of 95 °C.

[b] SEM = standard error of the mean (n = 36).

[c] Linear or quadratic effect of preconditioner discharge mass temperature.

[d] According to the following system: 0 = watery liquid, which can be poured; 1 = soft, unformed; 2 = soft, malformed stool, which assumes shape of container; 3 = soft, formed, and moist, which retains shape; 4 = well-formed and consistent stool, which does not adhere to the floor; and 5 = hard, dry pellets, which are small and a hard mass.

Table 7
Processing traits, kibble macrostructure, starch gelatinization, and *in vitro* digestibility of a dog food formulation extruded with different specific thermal energy applications and product flow rate (Experiment 2).

Item	Treatments[1]			SEM[2]	P-values
	T45	T95	$T95_{flow}$		
Preconditioner					
Discharge mass temperature (ºC)	45.0	94.5	95.0	8.84	–
Discharge mass moisture (%)	20.5 [b]	22.5 [a]	20.7 [b]	0.37	0.006
Starch gelatinization (%)	25.1 [c]	33.8 [a]	30.8 [b]	1.38	< 0.001
Extruder					
Motor amperage (A)	42.4 [a]	37.1 [b]	42.2 [a]	0.95	< 0.001
Mass pressure before die (MPa)	5.1 [a]	3.7 [b]	5.1 [a]	0.26	< 0.001
Mass temperature before die (ºC)	112.3 [c]	125.3 [b]	130.3 [a]	2.86	< 0.001
Product flow rate (kg/h)	195.0 [b]	189.7 [c]	294.3 [a]	18.13	< 0.001
Bulk density (g/L)	477.0 [a]	407.7 [b]	390.3 [b]	14.44	< 0.002
In-barrel moisture (%)	23.5 [b]	25.4 [a]	22.7 [c]	0.45	< 0.001
Energy Balance (kW-h/ton)					
Specific mechanical energy	18.5 [a]	10.8 [b]	11.3 [b]	1.33	< 0.001
Specific thermal energy	18.5 [c]	64.7 [a]	44.8 [b]	7.21	< 0.001
Total specific energy	37.0 [c]	75.5 [a]	56.1 [b]	6.01	< 0.001
STE/SME ratio	1.0 [b]	6.1 [a]	4.0 [a]	0.81	< 0.001
Kibble macrostructure (after dryer)					
Expansion rate	2.1 [c]	2.6 [b]	3.1 [a]	0.05	< 0.001
Piece density (g/cm^3)	0.56 [a]	0.43 [b]	0.43 [b]	0.01	< 0.001
Specific length (cm/g)	1.9 [a]	1.9 [a]	1.6 [b]	0.02	< 0.001
Starch gelatinization (%)	69.2 [c]	89.4 [a]	84.5 [b]	3.25	< 0.001
In vitro digestibility of the OM (%)	84.9 [b]	86.8 [a]	83.5 [c]	0.53	< 0.001

[a,b,c]Mean values in the same row not sharing a common superscript differ ($P < 0.05$).

[1] T45 = preconditioner mass temperature of 45 °C; T95 = preconditioner mass temperature of 95 °C; $T95_{flow}$ = preconditioner mass temperature of 95 °C and extruder mass flow corrected to achieve the same motor amperage of the treatment T45.

[2] SEM = standard error of the mean (n =16).

3.6. Extrusion traits, kibble macrostructure, starch gelatinization and in vitro digestibility (Experiment 2)

After increasing the STE application, the temperature of the preconditioner mass increased from 45 °C to 95 °C. This was followed by a significant reduction of extruder motor amperage ($P < 0.01$) (Table 7). The motor amperage was increased by increasing the product flow rate from approximately 195 kg/h for treatments T45 and T95 to 294.3 kg/h for treatment $T95_{flow}$ ($P < 0.01$). The mean residence time of the mass in the preconditioner was reduced to 120.4 s in treatment $T95_{flow}$. The preconditioner mass moistures were similar between T45 and $T95_{flow}$ but higher for T95 ($P < 0.05$). Starch gelatinization after the preconditioner was higher for T95, intermediate for $T95_{flow}$ and lower for T45 ($P < 0.05$).

The mass pressure before the extruder die was higher for T45 and $T95_{flow}$ than for T95 ($P < 0.05$), and the temperature of extrusion was higher for $T95_{flow}$, intermediate for T95, and lower for T45 ($P < 0.05$). The SME applied to the mass was similar in $T95_{flow}$ and T95, with lower values than for T45 ($P < 0.05$). This was justified because although the motor amperage was higher for $T95_{flow}$ than for T95, the product flow rate was also higher, resulting in similar SME application between these two treatments. The same occurred for thermal energy; although more steam was infused in $T95_{flow}$, the higher product flow rate of this treatment resulted in lower STE application in comparison with the T95 ($P < 0.05$). Therefore, TSE was higher for T95, intermediate for $T95_{flow}$, and lower for T45 ($P < 0.05$).

The starch gelatinization followed the TSE application, with higher values for T95, intermediary values for $T95_{flow}$, and lower values for T45 ($P < 0.05$). The *in vitro* digestibility of OM, however, was higher for T95 than for $T95_{flow}$ and T45 ($P < 0.05$), which presented similar values. The kibble expansion rate and kibble bulk density were higher for $T95_{flow}$, intermediate for T95, and lower for T45 ($P < 0.05$). The greater expansion of the kibbles in treatments $T95_{flow}$ and T95 in comparison with treatment T45 can be explained by the higher TSE, temperature of extrusion and starch gelatinization of these two treatments. However, the greater expansion of the kibbles of $T95_{flow}$ in comparison with those of T95 can be explained by the lower extruder open area of treatment $T95_{flow}$ (171 mm^2/ton/h compared to 262 mm^2/ton/h for T95). This greater restriction of mass flow induced a higher temperature and pressure of the mass before the die ($P < 0.05$), favoring water vaporization and kibble expansion after extruder.

4. Discussion

Important changes in extrusion parameters were verified after the increase in STE implementation (or preconditioner temperature). The SME decreased by 7.7 kW-h/ton, approximately 58%. The inverse relationship between STE and SME implementation is known (Riaz, 2000) and is associated with a potentially relevant reduction in processing cost due to a direct decrease in electric energy consumption and a decrease in equipment wear (Streit, 2015). The reduction in SME application can be explained by an increase in mass fluidity, reducing the resistance to flow. When the preconditioner temperature was higher, the supplementary STE (and higher TSE implementation) probably promoted better internal hydration of the food particles and induced greater starch gelatinization in the preconditioner. The starch gelatinization was 8.6 percentage points higher with the greater STE application. The higher starch gelatinization reduced the mechanical energy required to deform and push forward the mass on the extruder barrel and the shear stress (Moscicki and Wójtowicz, 2011). This is reinforced by the reduction of the pressure of the mass before the die with the increase in STE application, showing that the mass resistance to flow was lower.

Possible confounding factors for the reduction in SME application and mass pressure were the die open area and the mass in-barrel moisture, critical parameters for understanding and comparing the extrusion conditions (Riaz, 2000). The product flow rate and consequently die open area did not change. The in-barrel moisture increased with the increase in preconditioner temperature, and its relationship with the SME application was significant ($r^2 = 0.35$; $P = 0.014$). Water is a fluidizing agent, and the moisture increase probably contributed, along with the higher TSE input, to the observed reduction in SME application (Suknark et al., 1998; Pansawat et al., 2008). This increase in moisture content was not expected and occurred despite the measures taken to avoid moisture variation during the extruder operation. Nevertheless, the results obtained confirm that a better preconditioning of raw materials results in lower SME application during the extrusion of dog foods.

In the present study, it was possible to verify that kibble formation can be greatly improved by preconditioning the raw material (Riaz, 2001). Most published studies about kibble formation and quality evaluated the impact of SME application, specifically altering moisture content, extruder screw speed, or die open area (Iwe et al., 2001; Pansawat et al., 2008). All studies in this area, however, were conducted for extruded human snacks or breakfast cereals, and none were found for dog foods. SME is more relevant for breakfast cereals and starch-based formulations than for pet food recipes, for which thermal energy assumes greater relevance due to the high protein, fat, and fiber contents (Monti et al., 2016). In the present study, the kibble bulk density was reduced by 63 g/L, or approximately 14%, and the kibble expansion increased by 23% after the greater STE application and higher preconditioner temperature. It is interesting to observe that the increase in kibble expansion occurred even with the observed reduction in SME application and mass pressure, highlighting that STE and TSE implementation are important parameters to consider when studying and comparing different extrusion conditions for dog foods. It is probable that the increase in kibble expansion can be attributed to the higher starch gelatinization verified after greater STE application; the mass of molten gelatinized starch is more easily deformed by the water vaporization when mass exit from the extruder occurs, creating a larger inner cell structure in the kibbles (Guy, 2001).

The starch gelatinization after drying, an important aspect of extrusion processing efficiency, increased by 20.4 percentage points, or almost 23%. Although less pronounced, this increase also resulted in higher *in vitro* digestibility of OM. The mass temperature before the die increased more than 10 °C after the higher STE application, probably contributing to the higher starch gelatinization. The temperature and pressure of the mass during extrusion are usually directly linked to the SME application and mass resistance to flow (Riaz, 2000; Pansawat et al., 2008). However, in the present study, the SME and mass pressure before the die were reduced.

Therefore, the increase in mass temperature can be attributed to the supplementary STE application and the consequent higher mass temperature at extruder barrel entry. Therefore, the higher starch gelatinization after drying is probably the result of the increased starch cooking in the preconditioner, the higher temperature of extrusion, and the greater TSE application to the product. The better preconditioning of the raw material created conditions that favored starch gelatinization, which occurred with less SME application. Considering that the same production lot was used for all diets, the increase in OM *in vitro* digestibility can be mainly attributed to an increased cooking efficiency.

The diets all presented similar total tract apparent nutrient digestibilities in dogs. Considering the verified increase in starch gelatinization, this was unexpected. The effect of starch gelatinization on nutrient digestibility of extruded diets for dogs is little studied in the available literature. Most publications about kibble diet digestibility do not report the starch gelatinization of the foods, and information about how much starch gelatinization is necessary to obtain proper digestibility for dogs is not available (Bazolli et al., 2015). In the study with dog food formulations based on rice, corn, and sorghum, Bazolli et al. (2015) verified that for a corn-based formulation, the apparent total tract nutrient digestibility was similar for diets with 73.8% and 79.9% starch gelatinization. Therefore, it is possible that modest cooking is sufficient to achieve adequate digestibility of a dog food when corn is the cereal source. A methodological limitation of the present study is the measurement of the total tract apparent digestibility of the nutrients. Nutrients not digested and absorbed in the small intestine can be fermented in the colon and not recovered in feces (Silvio et al., 2000). Greater fermentation in the colon induces higher fecal output, increased fecal moisture, the production of soft feces, a reduction in fecal pH, and/or an increase in short-chain fatty acids (Kawauchi et al., 2011). In the present study, fecal moisture was greater for the lower STE treatments; however, no alterations in fecal score, pH or fermentation product content could be detected, making it unclear if the lower STE application resulted in higher OM fermentation in the colon.

The method used to study *in vitro* OM digestibility has been validated in dogs (Hervera et al., 2007). As an enzymatic method, the obtained results increased with the increase in starch gelatinization, which is also an enzymatic method. The lack of relationship between the *in vitro* OM digestibility and the *in vivo* digestibility in dogs may be explained by some factors, including the following: the numerically small differences in *in vitro* digestibilities among diets; the addition by coating of 8.5% of poultry fat to diets before testing the *in vivo* digestibility, changing the compositions; and the *in vitro* method's failure to consider OM fermentation in the colon.

The implications of SME or STE application during extrusion on the palatability of dog foods have been explored by some studies. Dunsford et al. (2002) evaluated different SME and STE applications and verified that dogs preferred a more terminally cooked product. However, Trivedi and Benning (2003) observed the opposite response, with dogs selecting a diet prepared with higher SME. The results of the present study were also different, as the dogs did not show preferences among foods across a large range of STE/SME ratios (from 1.1 to 6.1). Palatability is a complex characteristic involving several aspects related to the ingredients used and processing parameters, including food texture, shape, size, taste, and flavor (Trivedi et al., 2000). Therefore, it is difficult to perform direct comparisons focusing only on energy input among studies, as the ingredient base, palatant enhancer, and final kibble structure, including hardness, size, moisture, and shape, might be different.

In overall, the lack of effect of processing characteristics on food intake, digestibility, and feces formation and fermentation products were not expected, bringing to question of which are the most relevant parameters that impact animal responses to food. Raw material source and quality, and diet chemical composition are known important factors, and related to food processing the raw material particle size was shown be relevant for proper food digestibility (Bazolli et al., 2015). However, the better raw material particle size, hardware and software operation conditions, energy application, starch gelatinization, and kibble characteristics to achieve good responses on animals are still to be determined.

Experiment 2 was designed to evaluate the effects of STE on motor amperage and extruder productivity, complementing the outcomes of Experiment 1. After stable production was achieved with preconditioner discharge mass temperatures of 45 °C and 95 °C, the extruder feed rate was increased until the extruder motor amperage was restored to the level observed for the treatment at 45 °C, resulting in an increase of 99.3 kg/h, or approximately 51%, on extruder output mass. This means that supplementing STE at the preconditioner was able to substantially elevate the production of the extrusion system while keeping the electric energy consumption constant, a very important economic consideration for dog food production efficiency (Huber and Rokey, 1990; Rokey et al., 2010; Levine, 2014).

Whit the increase in productivity, the STE and TSE application was reduced proportionally to the higher throughput mass. In addition, the higher mass flow through the extrusion system reduced the mass residence time in the preconditioner and the extruder open area by altering the relationship between mass flow and die opening (Moscicki and Wójtowicz, 2011). Therefore, the starch gelatinization after drying decreased, although the reduction was quantitatively small. However, the kibble expansion was even higher for $T95_{flow}$ than for T95, explained by the combination of high STE application at the preconditioner and the lower extruder open area, which created shear and resulted in higher mass pressure and temperature before the extruder die. Consequently, kibble formation remained adequate or was even slightly better on the $T95_{flow}$.

The interpretation of the data obtained on the present study requires some considerations. All results from extrusion processing are very dependent on the equipment used, hardware and software conditions adopted, and may differ among extruder equipment brands and models. The tested recipe was simple, based on corn and chicken by-product meal and caution is needed to extrapolate results to different formulations. Altering the protein, fiber, and fat content of the recipe the outcomes might be different, as the chemical composition of the mass have important implications on energy transferences and flowability on extruder barrel (Guy, 2001; Monti et al., 2016). The starch source used was corn, and starch from other cereals, and even from legumes or tubers shows different responses during extrusion (Guy, 2001), altering the implications of the different STE applications tested on the present study. Howsoever, the results described in the present study started a database to better understand processing requirements of dog foods, substantiating future studies with different equipment designs, raw materials, and software operation conditions.

5. Conclusions

The increase in STE application by direct steam injection at the preconditioner decreased the SME required to gelatinize the starch and to shape and structure the kibbles of a dog food recipe. Higher STE application resulted in increased TSE application, starch gelatinization, kibble expansion, and *in vitro* digestibility of the organic matter. Apparent nutrient digestibility and palatability for dogs, however, were unaffected. The supplementary STE made possible a substantial increase in extruder productivity without elevating electric energy consumption, an important economic consideration for dog food production efficiency.

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