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Digestibility and energy value of wheat and triticale in pelleted diets for pigs

Abstract – The objective of this work was to assess the effect of pelleting on increments in the digestibility and energy values of diets and test-ingredients wheat and triticale for pigs. Two samples of wheat and three samples of triticale were evaluated in five metabolism experiments, with a total collection of feces and urine. In the study, 160 pigs from the MS115 x F1 cross, with an average initial weight of 52.5±4.72 kg were used. Eight pigs per treatment, corresponding to eight replicates, were housed in individual metabolic cages. The reference diet (RD) was based on corn-soybean meal, whereas, in the test-diets (TD), wheat or triticale replaced 40% of the RD. The following treatments were evaluated: meal RD (MRD), pelleted RD (PRD), meal TD (MTD), and pelleted TD (PTD). Pelleting enhances the energy value of swine diets formulated with corn-soybean or corn-wheat-soybean meal; however, this beneficial effect of pelleting is not observed in diets based on corn-triticale-soybean meal. Pelleting increases the digestibility of crude protein and the energy values of wheat by 7 and 4%, respectively, but does not alter the digestibility and energy values of triticale.

Index terms: *Sus scrofa domesticus*, *Triticosecale wittmack*, *Triticum aestivum*, metabolizable energy, pelleting.

Digestibilidade e valor energético do trigo e do triticale em dietas peletizadas para suínos

Resumo – O objetivo deste trabalho foi de avaliar o efeito da peletização sobre a digestibilidade e incrementos no valor energético das dietas e dos ingredientes-teste trigo e triticale para suínos. Foram avaliadas duas amostras de trigo e três de triticale em cinco experimentos de metabolismo com coleta total de fezes e urina. No estudo, foram utilizados 160 suínos cruza de MS115 X F1, com peso médio inicial de 52.5±4.72 kg. Oito suínos por tratamento, correspondendo a oito repetições, foram alojados individualmente em gaiolas de metabolismo. A dieta referência (DR) foi baseada em milho-farelo de soja, enquanto, nas dietas-teste (DT), o triticale ou o trigo substituiu 40% da DR. Foram avaliados os seguintes tratamentos: DR farelada (DRF), DR peletizada (DRP), DT farelada (DTF), e DT peletizada (DTP). A peletização aumenta o valor energético de dietas para suínos formuladas com milho-farelo de soja ou milho-trigo-farelo de soja; contudo, esse efeito benéfico da peletização não é observado em dietas à base de milho-triticale-farelo de soja. A peletização eleva a digestibilidade da proteína bruta e os valores energéticos do trigo em 7 e 4%, respectivamente, mas não altera a digestibilidade e os valores energéticos do triticale.

Termos para indexação: *Sus scrofa domesticus*, *Triticosecale wittmack*, *Triticum aestivum*, energia metabolizável, peletização.

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Introduction

Although wheat (*Triticum aestivum* L.) production in Brazil is primarily aimed to human consumption, it is among the cereal alternatives to corn (*Zea mays* L.) for feeding monogastric animals, due to its nutritional value, with energy content equivalent to 97% of the metabolizable energy of corn and 75% more protein in average values (Rostagno & Baalbino, 2024). For the 2025 harvest, the forecast of wheat production in Brazil is 9.12 million tons (Conab, 2025). On the other hand, triticale (*Triticosecale* Wittmack), a winter cereal obtained from the crossing of wheat and rye with characteristics of both, does not compete directly with human food and is very attractive for feeding monogastric animals due to its nutritional value. Nutritionally, triticale exhibits slightly higher levels of most nutritious compounds found in wheat and presents a greater similarity to wheat than to rye (Biel et al., 2020). The volume of triticale production in Brazil is low, with a forecast of 45.2 thousand tons in 2025 (Conab, 2025), however, it might expand.

Processing is an alternative to increase the nutritional value of feed ingredients, such as wheat and triticale, which reflects on pig (*Sus scrofa domesticus*) performance, profitability, and production. Pelleting, a hydrothermal processing method, has been used to increase density, reduce waste, powderiness, and segregation as well as to improve the efficiency of feed utilization for monogastric animals (Ball et al., 2015; Lancheros et al., 2020; Stas et al., 2024). During the pelleting process, due to steam conditioning and heat application gelatinization of a small fraction of the starch and partial denaturation of the proteins occur, which contribute to better quality of the pellets and increase starch and protein digestibility (Svihus & Zimonja, 2011; Rojas & Stein, 2017).

Rojas et al. (2016) stated that pelleting pig diets containing different ingredients and different fiber levels increased the digestibility of dry matter (DM) and energy and the energy values depending on the fiber content. However, recent study results are contradictory, since some reported that pelleting wheat-based diets increased the digestibility of some dietary components, digestible energy, and metabolizable energy values (Ball et al., 2015; Yang et al., 2017), whereas others showed that these effects were absent (Liermann et al., 2015).

Therefore, the effect of pelleting on the nutritional value of wheat and wheat-based diets for pigs is neither consistent nor well established. Additionally, in Brazil, it is produced spring type varieties, developed for baking or green fodder, which are different in composition and physical characteristics from the types evaluated in the mentioned studies, consequently affecting the response to pelleting. Furthermore, no studies about the effect of pelleting on the nutritional value of triticale-based diets for pigs were found.

The objective of this work was to assess the effect of pelleting on increments in the digestibility and energy values of diets and test-ingredients wheat and triticale for pigs.

Materials and Methods

The protocol used in this study (No. 18/2018) was approved by the Animal Ethics Committee (CEUA/CNPSA), following the Ethical Principles of Animal Experimentation of Federal Council of Veterinary Medicine (CFMV) (Resolution 879/2008) adopted by the Brazilian College of Animal Experimentation (COBEA) and in accordance with the technical guidance of National Council for the Control of Animal Experimentation (CONCEA) No. 8/2016.

Five metabolism experiments were carried out, of which two with samples of wheat and three with samples of triticale: Experiment 1 used 'BRS Belajoia' wheat (Sample 1); Experiment 2, 'BRS Belajoia' wheat (Sample 2); Experiment 3, 'BRS Surubim' triticale (Sample 3); Experiment 4, 'BRS Zênite' triticale (Sample 4); Experiment 5, 'BRS Saturno' triticale (Sample 5). Metabolism experiments followed the methodology of total collection of feces and urine as described by Sakomura & Rostagno (2016).

The reference diet (RD) of all experiments was based on corn-soybean meal and was formulated to meet the nutritional requirements (Table 1) of barrows with 50 to 70 kg (Rostagno, 2017). The test-diets (TD) consisted of wheat or triticale samples, which replaced 40% of the RD. In each experiment, the following treatments were evaluated: meal RD (MRD), pelleted RD (PRD), meal TD (MTD), and pelleted TD (PTD). The cereals were ground in a hammer mill through a 4 mm sieve. The diets were subjected to steam-pelleting in an experimental flat die pellet mill (Engmaq, Peritiba, SC, Brazil) with steam at 80°C, 40 s retention in the conditioner, and a 5 mm matrix. Binders, fat, molasses, preservatives, enzymes, or others were not included during the pelletizing process.

In the experiment, 160 pigs from the MS115 x F1 cross with average initial weight of 52.5±4.72 kg were used. Eight pigs, corresponding to eight replicates, per treatment were housed in individual metabolic cages of Pekas model. The metabolism room was air-conditioned at 24°C. Pigs were allotted to the treatments according to initial weight (block) in a randomized block design.

During the first seven days of the experiment, the pigs adapted to the cages and diets, consequently, the daily feed intake could be determined. Thereafter, in the five following days, feces and urine of the animals were collected. The individual voluntary daily feed intake in the adaptation period was recorded for each block and used to determine the daily amount of feed offered in the collection period as follows: the constant of metabolic weight (CMW) of the lightest pig in each block was calculated by CMW = feed intake/metabolic weight, that is, grams of feed per kilo of metabolic weight; and the daily amount of feed offered to each pig was obtained by daily feed = CMW × metabolic weight. Therefore, all pigs in the same block received the same amount of feed per kilogram of metabolic weight.

The daily amount of feed was divided into two meals, offered at 7h30 and 14h, and water was offered ad libitum after each meal. Ferric oxide was used as a fecal marker in the proportion of 0.5%, to indicate the beginning and the end of the fecal collection that was conducted twice a day and stored in plastic bags. The urine was collected in plastic buckets, containing a 20 mL 1:1 solution of distilled water and concentrated HCl, 12 N reagent grade. Every morning, the volume of urine collected was measured and an aliquot of 20% was obtained and stored in refrigerator, at 2°C, while feces were stored in a freezer, at -8°C.

Table 1. Ingredient composition (as-fed basis) of reference diet used in the metabolism experiments with pigs.

Ingredient	%
Corn	76.291
Soybean meal	20.314
Dicalcium phosphate	1.456
Limestone	0.775
Salt	0.474
L-Lysine HCl 78.8%	0.303
DL-Methionine 99%	0.044
L-Threonine 98%	0.043
Vitamin-mineral premix(1)	0.300
Total	100.000

(1)Supplied per kg of diet: Cu, 85.050 mg as copper sulphate; Fe, 90.450 mg as ion sulphate; Zn, 80.550 mg as zinc oxide; Mn, 30.300 mg as manganese sulfate; I, 0.830 mg as calcium iodate; Se, 0.200 mg as sodium selenite; vitamin A, 6,750 IU; vitamin D_3, 1,350 IU; vitamin E, 15.000 IU; vitamin K_3, 0.900 mg; folic acid, 0.342 mg; pantothenic acid, 9.040 mg; biotin, 0.090 mg; niacin, 16.790 g; vitamin B_1, 1.010 mg; vitamin B_{12}, 16.870 mcg; vitamin B_2, 2.830 mg; vitamin B_6, 1.120 mg; choline, 0.050 g; ethoxyquin, 0.750 mg.

At the end of the collection period, the pool of feces and urine from each experimental unit were homogenized, and a sample of each pool was collected. A sample of 500 g of feces from each experimental unit was collected, dried in a forced-air oven at 55°C for 48 hours, and ground in a Willey type knife mill, Star FT-50 model (Fortinox, Piracicaba, SP, Brazil) with a 1-mm aperture strainer. Nitrogen balance (NB), coefficients of apparent digestibility of dry matter (CADDM), organic matter (CADOM), crude protein (CADCP), digestible energy (DE), metabolizable energy (ME), and N-corrected ME (ME_n) were calculated according to Sakomura & Rostagno (2016). The apparent biological value of protein (ABVP), which is based on the percentage of N ingested (Ni), was calculated as follows: ABVP = (NB/N_i) × 100.

Wheat and triticale samples were analyzed according to the procedures of the Association of Official Analytical Chemists (AOAC), Latimer Jr. (2016) for DM content (Method 967.03), ash (Method 942.05), CP as total N by Dumas (Method 981.10) and the result was multiplied by 6.25, and crude fiber (CF) (Method 962.09). Ether extract (EE) was analyzed according to American Oil Chemists Society (AOCS, 2017), using a TX-10 extractor (ANKOM Technology, Macedon, NY, USA). Gross energy (GE) was analyzed by calorimetry, using an AC500 isoperibol calorimeter (Leco Corporation, St. Joseph, MI, USA).

Hemicellulose (HEM) was estimated by the difference between NDF and ADF. According to the Compêndio Brasileiro de Alimentação Animal (Guia…, 2023), the following were analyzed: acid detergent fiber (ADF) (Method 2021.019), neutral detergent fiber (NDF) (Method 2021.020), cellulose (CEL) (Method 2021.032), starch (Method 996.11), and total sugars (TS) (Method 939.03). Bulk weight (BW) and thousand kernel weight (TKW) were determined by ISTA (2008).

The geometric mean diameter (GMD) of the particles was determined by sieving (ASAE, 2008).

Diets and feces were analyzed for DM, CP, and GE as described for wheat and triticale samples, while urine was analyzed for N, using Kjeldahl method, and GE. For GE analysis, a 5-mL aliquot of urine was transferred to Fisherbrand polystyrene beakers (Thermo Fisher Scientific, Waltham, MA, USA), dried in a forced-air oven at 50°C for 24 hours. The GE was determined using the same bomb calorimeter used for wheat and triticale samples.

Fines percentage (FP) and pellet durability index (PDI) were measured according to the methodology described by the American Society of Agricultural and Biological Engineers as ASAE Standard S269.5 (ASAE, 2012). A 600 g sample of pelleted feed was sieved for 1 min through a Tyler No. 5 4 mm sieve (Telastem Peneiras para Análises LTDA, São Paulo, SP, Brazil) to determine the FP. After sieving, a sample of 500 g of unbroken pellets were revolved at 50 rpm in a closed cylinder for 10 min of a PDI tester, which consisted of 5 rotating boxes, 30 cm in height and 12.5x12.5 cm in base. Pellet durability index was recorded as the proportion of unbroken pellets remained on the sieve after revolving, as follows: PDI = [(Weight of unbroken pellets after revolving)/ Weight of sample prior to revolving)] × 100.

Statistical analyses were conducted using the GLM procedure of the SAS (SAS Institute Inc., Cary, NC, USA), considering the animal as the experimental unit. The normal distribution assumption was tested using Shapiro-Wilk’s, Kolmogorov-Smirnov’s, Anderson-Darling’s, and Cramér-von Mises’s tests. The assumptions for analysis of variance were tested using residual graph analysis. The digestibility and energy value of the diets were analyzed separately for each experiment. The analysis of ingredient data was grouped by cereal. Diet means were compared using the following contrasts: MRD vs PRD; and MTD vs PTD. Feedstuffs means were compared using the F test. Differences were considered significant at 5% probability and statistical tendencies were considered at 10% probability.

Results and Discussion

The PDI of the diets varied between 83 and 94% among experiments and FP was low in all diets, except for the PRD diet of Experiment 5, which presented the highest FP (7.56%) and PDI below 70% (Table 2). Diets containing 40% wheat or triticale (PTD) showed higher PDI than the RD diets based on corn-soybean meal (PRD) in all experiments; however, the greatest differences were observed in the experiments with triticale.

Despite being the same cultivar, the two wheat samples presented differences in chemical composition and BW (Table 3). Sample 2 was influenced by a period of drought, probably causing higher CP and fiber contents, lower starch content, and lower BW. The triticale samples showed little variation in chemical composition.

The ABVP increased ($p<0.05$) in the PTD of Experiment 2 with wheat Sample 2 (Table 4) and Experiment 4 with triticale Sample 4 (Table 5), but not in the other diets of all experiments. The CADDM, CADOM, and CADCP increased ($p<0.05$) when pelleting the RD of Experiment 1 and TD containing wheat in Experiments 1 and 2. Furthermore, pelleting resulted in increased ($p<0.001$) DE, ME, and ME_n of the RD, as well as TD of all experiments, except in Experiment 4.

As for the test feedstuffs, pelleting increased ($p<0.05$) the NB, ABVP, CADCP, DE, ME, and ME_n, besides tending to increase ($p<0.10$) the CADDM and CADCP of wheat (Table 6). On the other hand, pelleting did not affect ($p>0.05$) the N balance, ABVP, digestibility coefficients, and energy values of triticale, showing only an increasing trend ($p<0.10$) in the ME_n value.

The FP observed in all diets in this study was higher than that observed by Ball et al. (2015), who reported only 1% of FP in pelleted diets based on wheat-barley-soybean meal. However, those authors used a 1.7 mm sieve to determine the FP, whereas, in this study, a 4.0 mm sieve was utilized. The PDI values of all diets from Experiments 1 and 2 and TD from Experiments 3 and 4 are comparable to those obtained by Moradi et al. (2019). Additionally, pelleted wheat-based diets and the PDI of RD of Experiments 3 and 4 are comparable to those obtained by the same authors in pelleted corn-based diets. However, Behnke (2019) found higher PDI values than those observed in this study both for corn-based diets and diets containing varied proportions of wheat.

Pelleting increased the ME_n of TD containing wheat at an average of 161 kcal kg^{-1} (4.4%) and the ME_n of

TD containing triticale at an average of 83 kcal kg^{-1} (2.2%). The increase in the ME_n of test feedstuffs due to pelleting was of 147 kcal kg^{-1} (4%) for wheat and only 55 kcal kg^{-1} for triticale.

The enhancement of crude protein digestibility in pelleted wheat-based diets may be partially explained by changes in the three-dimensional structure of the proteins (Lancheros et al., 2020), since the steam pelletization process results in the destruction of tertiary structure of proteins (Svihus & Zimonja, 2011). A relevant factor that could potentially cause different responses to pelleting between wheat and triticale is the difference in the protein composition of these two cereals. Triticale protein has a higher proportion of water-soluble proteins, such as albumin and globulins, and a lower proportion of gluten-forming proteins, as glutenins and gliadins, compared to wheat (Navarro-Contreras et al., 2014). These proteins have different

Table 2. Chemical composition and gross energy (dry matter basis) analyzed in the experimental swine diets and pellet quality parameters.

Chemical composition (dry matter basis)	MRD[1]	PRD	MTD	PTD
Experiment 1: Wheat (*Triticum aestivum*) Sample 1				
Ash (%)	5.07	4.79	4.27	3.60
Organic matter (%)	94.93	95.21	95.73	96.40
Crude protein (%)	15.62	16.21	16.01	15.49
Gross energy (kcal kg^{-1})	4,350	4,426	4,391	4,435
Fines percentage (FP, %)	-	1.99	-	1.06
Pellet durability index (PDI, %)	-	90.20	-	92.56
Experiment 2: Wheat (*Triticum aestivum*) Sample 2				
Ash (%)	5.18	4.94	4.00	3.80
Organic matter (%)	94.82	95.06	96.00	96.20
Crude protein (%)	17.82	18.65	17.94	18.37
Gross energy (kcal kg^{-1})	4,413	4,471	4,458	4,495
Fines percentage (FP, %)	-	3.02	-	4.62
Pellet durability index (PDI, %)	-	91.06	-	93.89
Experiment 3: Triticale (*Triticosecale wittmack)* Sample 3				
Ash (%)	5.43	5.22	4.07	4.01
Organic matter (%)	94.57	94.78	95.93	95.99
Crude protein (%)	18.56	18.03	17.71	17.30
Gross energy (kcal kg^{-1})	4,348	4,493	4,397	4,463
Fines percentage (FP, %)	-	2.01	-	1.36
Pellet durability index (PDI, %)	-	85.0	-	91.1
Experiment 4: Triticale (*Triticosecale wittmack)* Sample 4				
Ash (%)	5.46	5.01	4.16	4.10
Organic matter (%)	94.54	94.99	95.84	95.90
Crude protein (%)	19.84	20.31	17.50	17.44
Gross energy (kcal kg^{-1})	4,394	4,393	4,418	4,423
Fines percentage (FP, %)	-	2.58	-	1.36
Pellet durability index (PDI, %)	-	87.73	-	93.2
Experiment 5: Triticale (*Triticosecale wittmack)* Sample 5				
Ash (%)	5.47	5.83	3.97	4.09
Organic matter (%)	94.53	94.17	96.03	95.91
Crude protein (%)	20.03	20.68	18.19	18.37
Gross energy (kcal kg^{-1})	4,609	4,654	4,587	4,656
Fines percentage (FP, %)	-	7.56	-	3.04
Pellet durability index (PDI, %)	-	67.6	-	83.2

[1]MRD, meal reference diet; PRD, pelleted reference diet; MTD, meal test-diet; PTD, pelleted test-diet.

Table 3. Energy and nutrient composition (dry matter basis) and physical characteristics of wheat and triticale samples.

Composition[1] (dry matter basis)	Wheat		Triticale		
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Organic matter (%)	98.19	98.01	97.92	98.00	98.05
Ash (%)	1.81	1.99	2.08	2.00	1.95
Crude protein (%)	16.22	18.21	14.43	15.12	14.60
Ether extract (%)	2.44	1.87	2.04	1.57	1.72
Crude fiber (%)	1.96	3.08	2.49	2.38	2.84
ADF (%)	2.72	3.10	3.52	2.68	3.37
NDF (%)	23.38	26.29	15.81	15.00	15.33
Hemicellulose (%)	20.66	23.19	12.29	12.32	11.96
Cellulose (%)	1.66	1.99	2.67	1.92	2.55
Starch (%)	65.90	63.83	70.93	73.87	72.70
Total sugars (%)	73.22	70.93	76.72	80.39	79.89
Gross energy (kcal kg^{-1})	4,399.00	4,453.00	4369	4453	4514
BW (kg hL^{-1})	79.30	75.80	77.00	78.05	75.45
TKW (g)	32.76	34.47	41.50	35.00	37.40
GMD (µm)	806.00	666.00	690.00	778.00	752.00

[1]ADF, acid detergent fiber; NDF, neutral detergent fiber; BW, bulk weight; TKW, thousand kernel weight; GMD, geometric mean diameter.

Table 4. Effect of pelleting on nitrogen balance, digestibility, and energy values (mean±standard deviation) of reference diets and test-diets with 40% wheat (*Triticum aestivum*)[1].

Variable	Diet				p-value		
	MRD[1]	PRD	MTD	PTD	Diets	MRD vs PRD	MTD vs PTD
			Experiment 1 – Sample 1				
Initial weight (kg)	53.84±1.37	53.56±1.72	53.33±2.00	52.51±2.03	0.893	0.777	0.812
Final weight (kg)	58.23±1.70	58.44±1.83	57.27±2.20	56.54±2.00	0.592	0.848	0.632
Feed intake (kg)	8.761±0.183	8.719±0.200	8.633±0.258	8.613±0.253	0.862	0.731	0.808
N balance (g)	102.75±3.96	102.24±4.04	81.72±9.08	80.21±2.11	0.006	0.940	0.797
ABVP (%)	53.22±1.59	52.34±2.23	41.87±3.73	43.43±1.04	0.002	0.770	0.401
CADDM (%)	85.85±0.35	88.72±0.24	86.30±0.14	88.51±0.44	0.001	0.001	0.001
CADOM (%)	87.40±0.34	90.18±0.21	87.61±0.12	89.82±0.39	0.001	0.001	0.001
CADCP (%)	82.27±0.86	86.64±0.47	81.62±0.68	86.28±0.74	0.001	0.001	0.001
DE (kcal kg^{-1} DM)	3,715±18	3,948±10	3,749±10	3,931±22	0.001	0.001	0.001
ME (kcal kg^{-1} DM)	3,632±15	3,870±16	3,658±17	3,841±19	0.001	0.001	0.001
ME_n (kcal kg^{-1} DM)	3,559±15	3,796±16	3,599±16	3,782±18	0.001	0.001	0.001
			Experiment 2 – Sample 2				
Initial weight (kg)	54.29±1.92	54.96±1.59	54.29±1.62	54.60±1.27	0.935	0.869	0.633
Final weight (kg)	59.05±1.94	59.95±1.40	58.21±1.59	58.99±1.08	0.277	0.544	0.325
Feed intake (kg)	8.471±0.196	8.830±0.189	8.638±0.185	8.679±0.168	0.707	0.311	0.587
N balance (g)	110.21±4.35	122.68±4.70	91.85±2.36	102.66±2.69	0.001	0.023	0.017
ABVP (%)	51.98±1.94	53.38±1.72	42.19±0.79	46.14±1.00	0.001	0.236	0.030
CADDM (%)	90.51±0.50	90.91±0.56	89.04±0.74	90.78±0.43	0.077	0.372	0.037
CADOM (%)	91.99±0.49	92.46±0.51	90.31±0.70	92.06±0.38	0.033	0.310	0.028
CADCP (%)	88.58±0.48	89.18±0.79	87.28±1.19	90.15±0.55	0.035	0.232	0.007
DE (kcal kg^{-1} DM)	3,999±20	4,091±24	3,959±35	4,096±19	0.001	0.008	0.001
ME (kcal kg^{-1} DM)	3,854±22	3,963±26	3,820±34	3,966±21	0.001	0.002	0.001
ME_n (kcal kg^{-1} DM)	3,773±21	3,876±25	3,754±33	3,892±21	0.001	0.003	0.001

[1]MRD, meal reference diet; PRD, pelleted reference diet; MTD, meal test-diet; PTD, pelleted test-diet; ABVP, apparent biological value of protein; CADD, coefficient of apparent digestibility of dry matter; CADOM, coefficient of apparent digestibility of organic matter; CADCP, coefficient of apparent digestibility of crude protein; DE, digestible energy; ME, metabolizable energy; ME_n, N-corrected ME.

amino acid composition and different properties. Gluten-forming proteins, for instance, are rich in digestion-resistant proline and glutamine (Moehs et al., 2019), which may lead to distinct reactions to the pelleting process.

Starch gelatinization is another factor that may impact the digestibility and energy values of diets and cereals as a result of the pelleting process. Although the starch gelatinization is generally limited during the pelleting process, studies have reported values

Table 5. Effect of pelleting on nitrogen balance, digestibility, and energy values (mean±standard deviation) of reference diets and test-diets with 40% triticale (*Triticosecale wittmack*).

Variable	Diet				p-value		
	MRD[(1)]	PRD	MTD	PTD	Diets	MRD vs PRD	MTD vs PTD
Experiment 3 – Sample 3							
Initial weight (kg)	53.88±1.47	54.98±1.23	54.33±1.51	54.66±1.91	0.441	0.133	0.697
Final weight (kg)	58.98±1.60	60.78±1.12	59.29±1.37	59.76±1.90	0.195	0.059	0.831
Feed intake (kg)	8.824±0.078	8.963±0.015	8.878±0.034	8.846±0.103	0.442	0.144	0.658
N balance (g)	134.99±5.53	131.80±2.79	115.43±2.35	108.89±4.05	0.001	0.514	0.254
ABVP (%)	58.84±2.22	59.87±1.26	52.57±1.08	51.92±1.66	0.001	0.585	0.889
CADDM (%)	88.69±0.46	89.48±0.40	88.75±0.25	89.59±0.54	0.376	0.182	0.258
CADOM (%)	90.19±0.47	90.95±0.40	90.07±0.24	90.92±0.52	0.342	0.180	0.253
CADCP (%)	86.82±0.74	86.55±0.72	86.49±0.50	88.02±0.77	0.596	0.775	0.227
DE (kcal kg^{-1} DM)	3,832±22	4,038±20	3,870±13	3,999±26	0.001	0.001	0.001
ME (kcal kg^{-1} DM)	3,730±29	3,930±25	3,743±14	3,868±25	0.001	0.001	0.004
ME_n (kcal kg^{-1} DM)	3,634±27	3,836±25	3,661±13	3,790±24	0.001	0.001	0.003
Experiment 4 – Sample 4							
Initial weight (kg)	52.61±1.87	52.85±2.11	51.36±1.85	52.65±1.76	0.103	0.709	0.053
Final weight (kg)	58.05±1.83	58.18±1.95	56.30±1.83	57.63±1.57	0.091	0.873	0.101
Feed intake (kg)	8.682±0.178	8.619±0.225	8.531±0.200	8.691±0.184	0.354	0.526	0.116
N balance (g)	134.65±3.67	129.65±4.72	105.48±2.75	99.72±2.43	0.001	0.198	0.141
ABVP (%)	56.17±1.19	54.16±0.89	50.98±0.62	48.04±0.66	0.001	0.112	0.025
CADDM (%)	88.83±0.32	89.41±0.37	89.47±0.35	89.37±0.40	0.666	0.323	0.869
CADOM (%)	90.44±0.29	91.09±0.37	90.61±0.35	90.68±0.39	0.688	0.254	0.900
CADCP (%)	87.12±0.60	87.71±0.72	86.98±0.52	86.10±0.86	0.530	0.591	0.426
DE (kcal kg^{-1} DM)	3,875±15	3,921±22	3,913±17	3,930±21	0.314	0.148	0.569
ME (kcal kg^{-1} DM)	3,789±18	3,833±24	3,834±16	3,842±16	0.304	0.157	0.770
ME_n (kcal kg^{-1} DM)	3,692±17	3,737±24	3,756±16	3,769±16	0.076	0.140	0.648
Experiment 5 – Sample 5							
Initial weight (kg)	58.10±1.39	57.53±1.09	57.43±1.47	57.76±1.16	0.696	0.356	0.585
Final weight (kg)	63.18±1.20	62.21±1.08	61.99±1.61	62.04±1.27	0.249	0.152	0.939
Feed intake (kg)	9.254±0.075	9.169±0.059	9.143±0.057	9.206±0.082	0.692	0.391	0.526
N balance (g)	125.62±4.61	124.42±4.42	110.49±3.60	107.65±2.15	0.001	0.796	0.540
ABVP (%)	49.59±1.71	48.55±1.88	48.57±1.66	47.16±1.08	0.658	0.593	0.470
CADDM (%)	89.45±0.48	89.23±0.24	89.26±0.26	89.28±0.28	0.970	0.659	0.975
CADOM (%)	91.05±0.45	91.08±0.24	90.48±0.26	90.64±0.26	0.497	0.936	0.724
CADCP (%)	87.67±0.78	87.92±0.49	87.30±0.51	87.25±0.68	0.860	0.787	0.958
DE (kcal kg^{-1} DM)	4,134±22	4,203±12	4,090±11	4,179±16	0.001	0.008	0.001
ME (kcal kg^{-1} DM)	4,032±18	4,100±18	3,983±8	4,088±24	0.002	0.026	0.001
ME_n (kcal kg^{-1} DM)	3,946±19	4,013±20	3,906±6	4,012±23	0.002	0.028	0.001

[(1)]MRD, meal reference diet; PRD, pelleted reference diet; MTD, meal test-diet; PTD, pelleted test-diet; ABVP, apparent biological value of protein; CADD, coefficient of apparent digestibility of dry matter; CADOM, coefficient of apparent digestibility of organic matter; CADCP,coefficient of apparent digestibility of crude protein; DE, digestible energy; ME, metabolizable energy; ME_n, N-corrected ME.

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up to 21% under varying conditions of temperature, conditioning time, and diet composition (Zimonja & Svihus, 2009; Lewis et al., 2015).

Differences in starch structure and alpha-amylase inhibitory activity may also influence varied responses of wheat and triticale to pelleting, since they affect the degree of gelatinization and viscosity, among other starch properties. Wheat starch is characterized by a larger proportion of small granules (B-granules) with a higher amylose content compared to triticale starch (Ao & Jane, 2007). Consequently, starches composed of smaller diameter granules, such as those of wheat, are considered more susceptible to a higher degree of gelatinization at lower temperatures during pelleting (Zimonja & Svihus, 2009).

Triticale starch is characterized by a predominance of short branched-chain amylopectin, while wheat starch, in contrast, contains a lower proportion of short branched-chain amylopectin, a lower rate of amylolysis (Naguleswaran et al., 2014), and a slightly higher amylose content (Ao & Jane, 2007). Starch granules with a high amylose content exhibit high retrogradation, elevated levels of resistant starch, and limited water absorption during cooking. In contrast, starch granules rich in amylopectin show high peak viscosity and low susceptibility to retrogradation (Magallanes-Cruz et al., 2017). Supporting this effect of amylose, Ma et al. (2020) demonstrated that a higher amylose proportion in cereals reduces starch digestibility and energy availability for broilers.

Beyond the amylose/amylopectin ratio, amylopectin chain length also influences starch digestibility. Longer amylopectin chains can form extended double helices and strengthen inter-segment hydrogen bonds, resulting in a more stable structure and increased resistant starch content, while shorter amylopectin branches disrupt crystalline stability (Lv et al., 2021). Therefore, a greater proportion of small starch granules with high amylose content and long amylopectin chains in wheat contributes to lower starch digestibility; however, pelleting may enhance digestibility by increasing the susceptibility of small granules to gelatinization, which may increase the energy levels of pelleted wheat.

Furthermore, triticale exhibits lower alpha-amylase inhibitory activity compared to wheat (Burgos-Hernández et al., 1999), displaying up to 50% higher alpha-amylase activity (Dennett et al., 2013) and reduced starch viscosity (Navarro-Contreras et al., 2014). In wheat, pelleting could partially inactivate alpha-amylase inhibitors, potentially increasing starch digestibility and energy values (Zimonja & Svihus, 2009). Possibly, these variations in protein and starch structure, as well as properties between wheat and triticale, contribute to the observed differences in pelleting responses of the two cereals.

The observed increases in digestibility coefficients and energy values following pelleting align with findings from other studies. Researchers have reported improvements in digestibility coefficients of some components of the diet and increased DE and ME values with pelleted wheat-barley (Ball et al., 2015), wheat (Yang et al., 2017), corn-DDGS (Rojas et al., 2016), and corn-soybean meal (Teixeira Netto et al., 2019) diets. Notably, Teixeira Netto et al. (2019) observed these enhancements only at pelleting temperatures equal or above 80°C, consistent with temperature used

Table 6. Effect of pelleting on nitrogen balance, digestibility, and energy values (mean ± standard deviation) of wheat (joint analysis of Experiments 1 and 2) and triticale (joint analysis of Experiments 3, 4, and 5).

Variable[1]	Diet processing		p-value
	Meal	Pelleted	
	Wheat (*Triticum aestivum*)		
N balance (g)	22.25±3.50	27.72±1.70	0.001
ABVP (%)	26.25±3.98	33.01±1.85	0.001
CADDM (%)	86.90±1.04	89.48±0.80	0.082
CADOM (%)	87.83±0.98	90.45±0.71	0.069
CADCP (%)	83.31±1.91	88.86±1.33	0.009
DE (kcal kg^{-1} DM)	3,857±51	4,011±43	0.025
ME (kcal kg^{-1} DM)	3,738±51	3,890±42	0.021
ME_n (kcal kg^{-1} DM)	3,697±50	3,844±39	0.026
	Triticale (*Triticosecale wittmack*)		
N balance (g)	31.80±1.26	30.12±1.25	0.427
ABVP (%)	44.36±1.70	41.52±1.67	0.319
CADDM (%)	89.42±0.43	89.46±0.56	0.854
CADOM (%)	90.13±0.41	90.29±0.54	0.702
CADCP (%)	86.50±0.71	86.56±1.19	0.795
DE (kcal kg^{-1} DM)	3,974±21	4,013±35	0.211
ME (kcal kg^{-1} DM)	3,858±23	3,907±39	0.144
ME_n (kcal kg^{-1} DM)	3,801±23	3,856±38	0.105

[1]ABVP, apparent biological value of protein; CADD, coefficient of apparent digestibility of dry matter; CADOM, coefficient of apparent digestibility of organic matter; CADCP, coefficient of apparent digestibility of crude protein; DE, digestible energy; ME, metabolizable energy; ME_n, N-corrected ME.

in the present study. On the other hand, Liermann et al. (2015) found no significant effect of pelleting on the digestibility or energy values in diets based on wheat-barley-rye-triticale-wheat bran, regardless the ingredient particle size.

The observed increase in protein digestibility due to pelleting of the 40% wheat diet corroborates the findings of Yang et al. (2017), but contrasts with the results from Ball et al. (2015) and Liermann et al. (2015). Despite this and the other studies cited using same test feedstuff, the factors underlying the divergent responses observed on CP digestibility remain unclear, since the information provided in most of these studies on the processing parameters were incomplete. However, in all the studies cited that did not show an increase in CP digestibility, the conditioning temperature in the pelleting process was below 75°C. The variability observed in the responses to pelleting in different studies is certainly influenced by variations in processing parameters, such as degree of grinding, temperature, retention time, pressure, pellet diameter, among others; diet composition, as combination of different cereals and protein sources; and variations in fiber, starch, and ether extract content.

Conclusions

1. Pelleting enhances the energy value of swine diets formulated with corn-soybean meal or corn-wheat-soybean meal; however, this beneficial effect of pelleting is not observed in diets based on corn-triticale-soybean meal.

2. Pelleting increases the digestibility of crude protein and the energy values of wheat by 7 and 4%, respectively, but it does not alter the digestibility and energy values of triticale.

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