Effects of Expander Operating Conditions on Nutrient Digestibility in Finishing Pigs[a]

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ABSTRACT : Five experiments were conducted using finishing pigs (PIC L326 sires × C15 dams) to examine the effects of expander operating conditions on nutrient digestibility in finishing pigs. The effects of different expanding conditions (0, 11.7, 24.4, 32.5 kg/cm^2) for corn-SBM based diets (Exp. 1), wheat meddlings diet (Exp. 2), sorghum-SBM based diets (Exp. 3) and wheat-SBM based diet (Exp. 4). Exp. 5 was conducted as a 2×4 factorial arrangement and factors examined were 2 soy products (raw soybean and SBM) and 4 expanding conditions (0, 14.1, 28.1, 42.2 kg/cm^2). In experiment 1, total production rates (p>0.10) were similar among treatments. The amount of fines decreased (cubic effect, p<0.001) as cone pressure was increased from 0 to 11.7 kg/cm^2, with smaller differences as cone pressure was further increased to 35.2 kg/cm^2. Nutrient digestibilities increased (p<0.02) as the feed was subjected to higher cone pressures. Digestibilities of DM, N, and GE were maximized at 24.4 kg/cm^2 cone pressure. The DE of the diet expanded at 24.4 and 35.2 kg/cm^2 increased by 172 and 109 kcal/kg, respectively, compared to the diet processed at 0 kg/cm^2 cone pressure. In experiment 2, total production and screened pellets production rates were similar among the processing treatments (p>0.21). The amount of fines decreased (quadratic effect, p<0.03) by 9 kg/h as cone pressure was increased from 0 to 11.7 kg/cm^2. Digestibilities of DM (p<0.02), N (p<0.001), and GE (p<0.002) were increased as cone pressure was increased from 0 to 35.2 kg/cm^2. DM, N, and GE digestibility in the pigs fed the midds-based diet increased by 8, 13, and 10%, respectively, at the highest processing cone pressure compared to the diets without any cone pressure. In experiment 3, the conditioned mash moistures for the treatments were numerically similar around 15% moisture. As the expander cone pressure was increased from 0 to 11.7 kg/cm^2, energy consumption for the pellet mill decreased (quadratic effect, p<0.004) from 14.1 to 12.0 kWh/t. Dry matter and gross energy digestibility increased (cubic effects, p<0.006) as cone pressure was increased from 0 to 35.2 kg/cm^2 with the largest improvement occurring as cone pressure was increased from 0 to 11.7 kg/cm^2. Nitrogen digestibility increased (cubic effect, p<0.001) from 78.3 to 81.0% as the feed was subjected to the higher cone pressures, with N digestibility being maximized at 24.4 kg/cm^2 cone pressure. The DE of the diet increased (cubic effect, p<0.001) by 225 kcal/kg as cone pressure was increased from 0 to 11.7 kg/cm^2. In experiment 4, pellet moisture decreased and moisture loss increased as cone pressure was increased from 0 to 35.2 kg/cm^2. Also, starch gelatinization of the wheat-based diets increased from 16.8 to 49.1% as the diets were processed at 0 and 35.2 kg/cm^2 cone pressure. Nutrient digestibilities were not affected (p>0.18) by any increase in cone pressure. In experiment 5, pellet moisture decreased as cone pressure was increased 0 to 35.2 kg/cm^2. The amount of moisture loss for the diets expanded at 42.2 kg/cm^2 was 3.0 and 3.8% for the SBM and raw soybean (RB) diets, respectively. Starch gelatinization for the SBM diets were 19% greater than the RB diets. The RB diets had lower DM, N and GE digestibilities as compared to the SBM diets. The DE of the RB diets were lower (p<0.02) than the SBM diets. DM (p<0.06), N (p<0.02), and GE (p<0.001) digestibilities of the dietary treatments increased as cone pressure was increased 0 to 42.2 kg/cm^2. *(Asian-Aus. J. Anim. Sci. 1999. Vol. 12, No. 3 : 400-410)*

Key Words : Expander, Processing Characteristics, Nutrient Digestibility, Finishing Pig

INTRODUCTION

Extrusion and expansion gelatinize cereal starch (Camire et al., 1990; Peisker, 1994b), increasing susceptibility to enzymatic hydrolysis (Chiang and Johnson, 1977). Other benefits of extrusion and expansion are feed sterilization, protein denaturation, increased fat stability, and decreased activity of anti-nutritional compounds (Peisker, 1994b). Early research (Deyoe et al., 1967) in broiler chicks fed expanded (dry extrusion) cereal grain diets resulted in no significant improvements in growth performance. In contrast, Sloan (1971) reported a trend for increased gain and improved feed conversion in the chicks fed diets of moist extruded corn and sorghum. More recently, Smith et al. (1995) reported increased growth and feed utilization in broiler chicks fed expanded and pelleted diets compared to chicks fed steam conditioned pelleted diets.

However, limited research is available about the effects of expander processing conditions on nutrient digestibility in finishing pig diets. Hancock et al. (1992) reported improved digestibility and feeding value of corn, sorghum, wheat, and barley by extruding cereal grains in finishing pig diets. Peisker (1994a) reported improved rates of gain in nursery pigs fed diets with 30% expanded wheat bran and a complete expanded diet compared to an untreated starter diet. In contrast, Hongtrakul et al. (1996) reported reduced ADG and improved efficiencies of gain in segregated early-weaned pigs fed expanded simple and complex diets. Johnston et al. (1996) reported that finishing pigs fed expanded diets in mash or pelleted form had improved efficiencies of gain compared to long- or short-term conditioning. Thus, there are few published reports elucidating the effects of expander conditions on nutrient digestibility in pigs. For the experiments reported herein, cone pressure was

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increased to determine the effects of expander processing conditions on processing characteristics and nutrient digestibility in finishing pigs fed expanded diets.

MATERIALS AND METHODS

1. Digestibility experiments

1) General

Five experiments were conducted using finishing pigs (PIC L326 sires × C15 dams). The pigs were allotted to pens based on weight, sex, and ancestry in a complete randomized block design. The pigs were housed in a modified open front finishing facility in 1.83 m × 4.88 m pens with half slatted and half solid concrete flooring. Each pen had a nipple waterer and two-hole self-feeder to allow *ad libitum* consumption of feed and water. The diets (tables 1 and 2) were formulated to meet or exceed NRC (1988) levels for all nutrients.

Table 1. Diet composition for Exp. 1, 2, 3, and 4 (as fed basis)[a]

Ingredient, %	Exp. 1[a]	Exp. 2[b]	Exp. 3[c]	Exp. 4[c]
Corn	80.28	41.35	-	-
Wheat middlings	-	50.00	-	-
Grain sorghum	-	-	70.14	-
Hard red winter wheat	-	-	-	78.10
Soybean meal, 46.5% CP	15.43	4.81	25.48	17.49
Monocalcium phosphate	1.07	-	0.89	0.70
Soybean oil	1.00	1.00	1.00	1.00
Limestone	1.03	1.47	1.04	1.17
Salt	0.30	0.30	0.30	0.30
Lysine · HCl	0.24	0.33	0.22	0.33
Vitamin premix	0.19[d]	0.19[d]	0.25[e]	0.25[e]
Mineral premix	0.10[f]	0.10[f]	0.15[g]	0.15[g]
DL-Methionine	0.01	0.05	0.13	0.06
L-Threonine	0.02	0.07	0.07	0.12
Antibiotic[h]	0.13	0.13	0.13	0.13
Chromic oxide[i]	0.20	0.20	0.20	0.20

[a] Formulated to contain 0.85% lysine, 0.65% Ca, 0.55% P and 3.46 Mcal of DE/kg.
[b] Formulated to contain 0.85% lysine, 0.65% Ca, 0.55% P and 3.25 Mcal of DE/kg.
[c] Formulated to contain 1.10% lysine, 0.65% Ca, 0.55% P and 3.37 Mcal of DE/kg.
[d] Supplied per kilogram of diet; 8,260 IU of vitamin A, 826 IU of vitamin D_3, 33 IU of vitamin E, 3.3 mg of vitamin K (as menadione), 6.2 mg of riboflavin, 21.5 mg of pantothenic acid (as d-calcium pantothenate), 37.2 mg of niacin, 124 mg of choline and 0.03 mg of vitamin B_{12}.
[e] Supplied per kilogram of diet; 11,013 IU of vitamin A, 1,101 IU of vitamin D_3, 44.1 IU of vitamin E, 4.4 mg of vitamin K (as menadione), 8.3 mg of riboflavin, 28.6 mg of pantothenic acid (as d-calcium pantothenate), 49.9 mg of niacin, 165.2 mg of choline and 0.03 mg of vitamin B_{12}.
[f] Supplied per kilogram of diet; 110 mg of Fe, 110 mg of Zn, 26.4 mg of Mn, 11 mg of Cu, 0.2 mg of I and 0.2 mg of Se.
[g] Supplied per kilogram of diet; 165 mg of Fe, 165 mg of Zn, 39.6 mg of Mn, 16.5 mg of Cu, 0.3 mg of I and 0.3 mg of Se.
[h] Provided per kilogram of diet; 110 mg of tylosin.
[i] Used as an indigestible marker.

The pigs were fed a diet with 0.20% chromic oxide (Cr_2O_3) to allow calculation of apparent digestibilities of DM, N, and GE using the indirect ratio method. In each study, a grab sample of feces was collected at 1800 h on d 4 and 0600 h on d 5 and pooled within pen. The fecal samples were oven dried at 50℃ for 5 d. Feed and fecal samples were analyzed for DM, and N according to AOAC (1990). Gross energy was determined using an oxygen bomb calorimeter (Parr Co., Oxygen Bomb Calorimeter, Model No. 13031, Moline, IL). Chromium concentration was determined by atomic absorption spectrometry (Varian Techtron, Model No. 1475, Springvale, Australia) using the procedure described by Williams et al. (1962).

Table 2. Diet composition for Exp. 5 (as-fed basis)[a]

Ingredient, %	Soybean meal	Raw soybeans
Corn	75.01	72.89
Soybean meal, 46.5% CP	18.54	-
Raw soybean	-	23.94
Soybean oil	3.24	-
Monocalcium phosphate	1.05	0.95
Limestone	1.02	1.04
Salt	0.30	0.30
Lysine · HCl	0.20	0.23
Vitamin premix[b]	0.19	0.19
Mineral premix[c]	0.10	0.10
DL-Methionine	0.02	0.03
Antibiotic[d]	0.13	0.13
Chromic oxide[e]	0.20	0.20

[a] Formulated to contain 15% CP, 0.9% lysine, 0.65% Ca, 0.55% P and 3.56 Mcal of DE/kg.
[b] Supplied per kilogram of diet; 8,260 IU of vitamin A, 826 IU of vitamin D_3, 33 IU of vitamin E, 3.3 mg of vitamin K (as menadione), 6.2 mg of riboflavin, 21.5 mg of pantothenic acid (as d-calcium pantothenate), 37.2 mg of niacin, 124 mg of choline and 0.03 mg of vitamin B_{12}.
[c] Supplied per kilogram of diet; 110 mg of Fe, 110 mg of Zn, 26.4 mg of Mn, 11 mg of Cu, 0.2 mg of I and 0.2 mg of Se.
[d] Provided per kilogram of diet; 110 mg of tylosin.
[e] Used as an indigestible marker.

2) Feed preparation.

Feed for all experiments was processed through a 100 hp expander (Model OE15.2, Amandus Kahl, Hamburg, Germany) and pelleted with a 30 hp California Pellet Mill® (Crawfordsville, IN) 1000 series "Master HD" model pellet mill. Production rates for the dietary treatments within an experiment were held constant at approximately 900 kg/h. All cereal grains (i.e., corn, sorghum, and wheat) were hammer mill ground through a 3.2 mm screen. The diets were steam conditioned, expanded, and pelleted using a die that was 38 mm thick with 4.8 mm diameter holes. Pellets were cooled using forced ambient air in a double pass cooler. Pellets were screened to determine whole pellet production rate and the amount of fines produced. Electrical energy consumption was measured on the main drive motor for the expander and pellet mill using a recording amp-volt meter (Model DMI, Amprobe Instrument, Lynbrook, NY). Pellet quality (PDI) was measured on the cooled pellets using the standard determination for pellet durability index S269.3 (ASAE, 1987) and a modified procedure using five 13 mm hexagonal nuts added with the pellets. Processing treatments were replicated three times for each experiment.

Samples (approx. 300 g) were taken after the preconditioner (i.e., between the conditioner and expander) and pellet mill to allow for moisture determination in the conditioned mash and pellets. Mash moisture was determined after conditioning using AACC Method 44-19 (AACC, 1983). Pellet moisture was determined before cooling using AACC Method 44-45A (AACC, 1983). The degree of cook (i.e., starch gelatinization) was determined using a modified enzymatic procedure on the pellet samples after drying at 50℃ in a forced air oven for 36 h. Urease activity was determined on the pellet samples for Exp. 5 using AACC method for urease activity (AACC, 1983).

3) Experiment 1

A total of 32 finishing pigs (four gilts and four barrows per pen) with an average initial BW of 72 kg was used in a 15-d digestibility assay. The diets (table 1) were corn-soybean meal-based and formulated to 0.85% lysine and 3.46 Mcal of DE/kg. The dietary treatments were conditioned to 71℃, expanded at 0, 11.7, 24.4, and 35.2 kg/cm^2 cone pressure, and pelleted. The dietary treatments were fed for three consecutive (i.e., three replicates) 5-d periods. The dietary treatments were randomized within a replicate providing that a pen received a dietary treatment only once throughout the experiment. Feeders were weighed on d 0, 5, 10, and 15 to determine ADFI.

4) Experiment 2.

A total of 32 pigs (four gilts and four barrows per pen with an average initial BW of 72 kg) was used in a 15-d digestibility assay. The diets contained 50% wheat middlings and formulated to 0.85% lysine and 3.25 Mcal of DE/kg. The dietary treatments were processed and allocated to pens as in Exp. 1. Feeders were weighed on d 0, 5, 10, and 15 to allow calculation of ADFI.

5) Experiment 3.

A total of 136 pigs (17 gilts or 17 barrows per pen) with an average initial BW of 42 kg was used in a 10-d digestibility assay. The diets were sorghum-soybean meal-based and formulated to 1.1% lysine and 3.37 Mcal of DE/kg. The dietary treatments were processed as in Exp. 1. The dietary treatments were fed for two consecutive (i.e., four replicates) 5-d periods. The dietary treatments were randomized within a replicate providing that a pen received a dietary treatment only once throughout the experiment. Feeders were weighed on d 0, 5, and 10 to determine ADFI.

6) Experiment 4.

A total of 136 pigs (17 gilts and 17 barrows per pen) with an average initial BW of 42 kg was used in a 10-d digestibility assay. The diets were wheat-soybean meal-based and formulated to 1.1% lysine and 3.37 Mcal of DE/kg. The dietary treatments were processed and allocated to pens as in Exp. 3. Feeders were weighed on d 0, 5, and 10 to allow calculation of ADFI.

7) Experiment 5.

A total of 64 pigs (four gilts and four barrows per pen) with an average initial BW of 86 kg was used in a 15-d digestibility assay. The pigs were fed raw soybean (RB)- or soybean meal (SBM)-based diets (table 2) that were formulated to same crude protein and energy concentrations at 15% and 3.56 Mcal of DE/kg, respectively. The dietary treatments were conditioned to 77℃, expanded at 0, 14.1, 28.1, and 42.2 kg/cm^2 cone pressure, and pelleted. The dietary treatments were fed for three consecutive (i.e., three replicates) 5-d periods. The dietary treatments were randomized and allocated as in Exp. 1. Feeders were weighed on d 0, 5, 10, and 15 to determine ADFI.

2. Statistical analyses

All response criteria were analyzed as a randomized complete block design, using the GLM procedures of SAS (1985). The results of three replicates of processing data were used to determine the response to increasing cone pressure. Replicate and treatment were defined as the sources of variation and pen was the experimental unit for the digestibility assay. Polynomial regression was used to characterize the response to cone pressure. For Exp. 5, a 2 × 4 factorial arrangement of treatments was used with the main effects of formulation (raw vs soybean meal) and expander cone pressure. Polynomial regression was used to characterize the response of processing characteristics and nutrient digestibility as cone pressure was increased, and to identify any interactions among the formulation and cone pressure treatments.

RESULTS AND DISCUSSION

1. Experiment 1

1) Processing characteristics

Total production rates (p>0.10) were similar among treatments (table 3). The amount of fines decreased (cubic effect, p<0.001) as cone pressure was increased from 0 to 11.7 kg/cm^2, with smaller differences as cone pressure was further increased to 35.2 kg/cm^2. Increasing cone pressure resulted in increased specific and gross energy consumption (quadratic effects, p<0.002) for the expander, with the greatest numerical increase in energy consumption occurring as cone pressure was increased from 24.4 to 35.2 kg/cm^2. In contrast, specific and gross energy consumption for the pellet mill decreased

Table 3. Effects of cone pressure on processing characteristics in corn based diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
Production rate, kg/h								
Overall	936	906	932	904	13	-[b]	-	0.10
Fines	87	30	39	25	1	0.001	0.001	0.001
Screened pellets	849	876	893	879	12	0.10	0.14	-
Screened pellets electrical energy consumption, kWh/t								
Pellet mill								
Idle	9.4	8.7	8.7	8.7	0.2	0.03	0.04	-
Specific	7.5	3.9	3.4	4.1	0.1	0.001	0.001	0.03
Gross	16.9	12.6	12.1	12.8	0.1	0.001	0.001	0.006
Expander								
Idle	29.5	28.1	29.7	28.8	0.8	-	-	-
Specific	0.05	10.7	36.3	64.6	1.4	0.001	0.001	0.09
Gross	30.0	38.8	66.0	93.4	1.8	0.001	0.002	0.07
Total gross	46.9	51.4	78.0	106.2	1.9	0.001	0.001	0.05
Overall production electrical energy consumption, kWh/t								
Pellet mill								
Idle	8.5	8.4	8.5	8.5	0.1	-	-	-
Specific	6.8	3.8	3.2	4.0	0.1	0.001	0.001	0.11
Gross	15.3	12.2	11.7	12.5	0.2	0.001	0.001	0.09
Expander								
Idle	26.8	27.1	28.4	28.0	0.7	-	-	-
Specific	0.4	10.4	34.8	62.8	1.3	0.001	0.001	0.11
Gross	27.2	37.5	63.2	90.8	1.7	0.001	0.002	0.12
Total gross	42.5	49.7	74.9	103.3	1.7	0.001	0.001	0.09
Pellet durability index, %								
Standard	68.5	90.7	93.3	95.5	0.3	0.001	0.001	0.001
Modified	44.7	85.2	92.0	94.7	0.3	0.001	0.001	0.001

[a] Three replicates/treatment. [b] Dashes indicate p>0.15.

(quadratic effect, p<0.002) as cone pressure was increased, with the majority of this effect being realized as cone pressure was increased from 0 to 11.7 kg/cm². Pellet durability increased (cubic effect, p<0.001) as cone pressure was increased from 0 to 11.7 kg/cm² with smaller differences being realized in pellet quality as cone pressure was further increased to 35.2 kg/cm².

2) Nutrient digestibility

Nutrient digestibilities increased (p<0.02) as the feed was subjected to higher cone pressures (table 4). Digestibilities of DM, N, and GE were maximized at 24.4 kg/cm² cone pressure. The DE of the diet expanded at 24.4 and 35.2 kg/cm² increased by 172 and 109 kcal/kg, respectively, compared to the diet processed at

Table 4. Effects of cone pressure on nutrient digestibility in corn-based diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
ADFI, g	3,245	2,714	2,825	2,807	117	0.07	0.08	-[b]
DM digesibility, %	81.4	84.3	86.5	85.9	0.8	0.05	0.07	-
N digestibility, %	77.5	81.1	83.8	82.8	0.5	0.001	0.003	-
GE digestibility, %	82.5	85.3	87.2	86.5	0.9	0.02	0.10	-
DE of diet, kcal/kg	3,236	3,267	3,392	3,325	34	0.04	-	0.11
Starch gelatinization, %	32.0	44.3	48.9	49.9	-	-	-	-

[a] A total of 36 pigs (eight pigs/pen with an average initial BW of 72 kg) and three replicates/treatment.

[b] Dashes indicate p>0.15.

Table 5. Effects of cone pressure on processing characteristics in high fiber diets (wheat middlings)

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
Production rate, kg/h								
Overall	900	883	889	879	9	-[b]	-	-
Fines	47	36	38	42	3	-	0.03	-
Screened pellets	853	847	851	837	9	-	-	-
Screened pellets electrical energy consumption, kWh/t								
Pellet mill								
Idle	8.8	8.9	8.8	8.9	0.1	-	-	-
Specific	5.8	3.1	2.6	2.7	0.1	0.001	0.001	0.03
Gross	14.6	12.0	11.4	11.6	0.2	0.001	0.001	-
Expander								
Idle	29.4	28.9	29.1	30.1	0.5	-	-	-
Specific	0.3	9.8	21.1	39.3	2.5	0.001	0.13	-
Gross	29.7	38.7	50.2	69.4	2.5	0.001	0.09	-
Total gross	44.3	50.7	61.6	81.0	2.5	0.001	0.05	-
Overall production electrical energy consumption, kWh/t								
Pellet mill								
Idle	8.4	8.5	8.4	8.5	0.1	-	-	-
Specific	5.5	3.0	2.5	2.5	0.1	0.001	0.001	0.03
Gross	13.9	11.5	10.9	11.0	0.2	0.001	0.001	-
Expander								
Idle	27.8	27.8	27.9	28.7	0.5	-	-	-
Specific	0.3	9.4	20.2	37.5	2.4	0.001	0.14	-
Gross	28.1	37.2	48.1	66.2	2.5	0.001	0.12	-
Total gross	42.0	48.7	59.0	77.2	2.5	0.001	0.06	-
Pellet durability index, %								
Standard	84.2	89.1	87.0	89.2	1.1	0.05	-	0.09
Modified	73.0	83.9	76.7	87.6	4.6	0.13	-	0.13

[a] Three replicates/treatment. [b] Dashes indicate p>0.15.

0 kg/cm² cone pressure (i.e., conventional pellet conditioning). This increase in energy availability of the expanded diets at higher pressures indicate that the carbohydrate portion of the diets were more readily susceptible to enzymatic hydrolysis. Indeed, starch gelatinization of the diet increased from 32 to 50% as cone pressure was increased from 0 to 35.2 kg/cm².

2. Experiment 2

1) Processing characteristics

Total production and screened pellets production rates (table 5) were similar among the processing treatments ($p>0.21$). The amount of fines decreased (quadratic effect, $p<0.03$) by 9 kg/h as cone pressure was increased from 0 to 11.7 kg/cm². As in Exp. 1, increasing cone pressure resulted in increased ($p<0.001$) gross and specific energy consumption for the expander and a decrease ($p<0.001$) in pellet mill energy consumption. Standard pellet durability increased as cone pressure was increased ($p<0.05$), however, after simulated handling (i.e., modified PDI) pellet durability was numerically increased ($p>0.13$) as cone pressure was increased from 0 to 35.2 kg/cm².

2) Nutrient digestibility

Digestibilities of DM ($p<0.02$), N ($p<0.001$), and GE ($p<0.002$) were increased as cone pressure was increased from 0 to 35.2 kg/cm² (table 6). DM, N, and GE digestibility in the pigs fed the midds-based diet increased by 8, 13, and 10%, respectively, at the highest processing cone pressure compared to the diets without any cone pressure. The DE of the diet increased ($p<0.02$) by 331 kcal/kg (a 12% increase in diet DE) as cone pressure was increased from 0 to 35.2 kg/cm². Suggesting that the majority of the response resulted from the increased utilization of dietary crude fiber. This is in agreement with Peisker (1994a), who reported a 19% increase in crude fiber digestibility of expanded diets containing wheat bran when fed to nursery pigs. Furthermore, starch gelatinization also increased as cone pressure was increased and was the highest in the diet processed at 35.2 kg/cm² cone pressure.

3. Experiment 3

1) Processing characteristics

The conditioned mash moistures (table 7) for the treatments were numerically similar around 15%

Table 6. Effects of cone pressure on nutrient digestibility in high fiber diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
ADFI, g	2,814	2,583	3,204	2,541	225	-[b]	-	0.08
DM digesibility, %	70.0	72.6	72.4	75.6	1.2	0.02	-	-
N digestibility, %	69.2	74.5	77.1	78.3	1.2	0.001	-	-
GE digestibility, %	69.8	73.8	74.5	77.0	0.9	0.002	-	-
DE of diet, kcal/kg	2,789	2,968	2,990	3,120	37	0.01	-	-
Starch gelatinization,%	33.8	51.7	51.9	69.9	-	-	-	-

[a] A total of 36 pigs (eight pigs/pen with an average initial BW of 72 kg) and three replicates/treatment.
[b] Dashes indicate p>0.15.

Table 7. Effects of cone pressure on diet characteristics in sorghum-based diets

Item	Cone pressure, kg/cm²			
	0	11.7	24.4	35.2
Conditioned mash moisture, %	15.0	15.1	15.0	14.6
Pellet moisture, %	14.8	14.2	13.2	12.0
Moisture loss, %	0.2	0.9	1.8	2.6
Starch gelatinization, %	26.0	37.3	41.9	61.7

moisture. However, pellet moisture decreased as cone pressure was increased, indicating that as expander cone pressure was increased the feed was subjected to higher internal barrel pressures. Thus, as the feed exited the expander cone a greater pressure drop was realized, resulting in a larger amount of moisture flash (i.e., vaporization of moisture). Indeed, the amount of moisture loss for the diet expanded at 35.2 kg/cm^2 was 2.6% compared to only 0.2% for the diet with no added cone pressure. As a result of the increased cone pressure

Table 8. Effects of cone pressure on processing characteristics in sorghum-based diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
Production rate, kg/h								
Overall	940	982	966	962	15	-[b]	-	-
Fines	28	11	8	7	6	-	-	-
Screened pellets	912	971	958	955	15	-	0.08	-
Screened pellets electrical energy consumption, kWh/t								
Pellet mill								
Idle	7.7	7.7	7.5	7.5	0.1	-	-	-
Specific	6.8	4.4	3.7	5.0	0.4	0.02	0.003	-
Gross	14.5	12.1	11.2	12.5	0.3	0.004	0.001	-
Expander								
Idle	26.1	25.4	25.0	25.4	0.5	-	-	-
Specific	0.2	10.1	17.4	37.3	0.7	0.001	0.001	0.003
Gross	26.3	35.5	42.4	62.7	0.6	0.001	0.001	0.001
Total gross	40.8	47.6	53.6	75.2	0.6	0.001	0.001	0.001
Overall production electrical energy consumption, kWh/t								
Pellet mill								
Idle	7.5	7.6	7.5	7.4	0.1	-	-	-
Specific	6.6	4.4	3.6	4.9	0.4	0.02	0.004	-
Gross	14.1	12.0	11.1	12.3	0.3	0.006	0.002	-
Expander								
Idle	25.3	25.1	24.8	25.0	0.5	-	-	-
Specific	0.2	10.0	17.2	36.5	0.7	0.001	0.001	0.003
Gross	25.5	35.1	42.0	61.5	0.5	0.001	0.001	0.001
Total gross	39.6	47.1	53.1	73.8	0.5	0.001	0.001	0.001
Pellet durability index, %								
Standard	77.2	90.6	92.8	90.8	3.2	0.04	0.06	-
Modified	60.6	84.5	90.2	87.6	6.0	0.03	0.07	-

[a] Three replicates/treatment. [b] Dashes indicate p>0.15.

Table 9. Effects of cone pressure on nutrient digestibility in sorghum-based diets[a]

Item	Cone pressure, kg/cm^2				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
ADFI, g	1,754	1,664	1,644	1,619	62	0.15	-[b]	-
DM digesibility, %	85.5	87.1	86.2	86.2	0.3	-	0.006	0.006
N digestibility, %	78.3	80.3	81.0	80.3	0.6	0.01	0.02	-
GE digestibility, %	85.5	87.8	86.5	86.6	0.3	0.09	0.001	0.001
DE of diet, kcal/kg	3,339	3,564	3,426	3,462	11	0.01	0.001	0.001

[a] A total of 136 pigs (17 pigs/pen with an average initial BW of 42 kg) and four replicates/treatment.

[b] Dashes indicate p>0.15.

and moisture flash, starch gelatinization increased from 26 to 61.7% as cone pressure was increased from 0 to 35.2 kg/cm^2.

The overall and fines production rates (table 8) were not affected (p>0.16) by cone pressure, however, there was a trend (p<0.08) for a reduction in the amount of whole pellets produced as cone pressure was increased from 0 to 11.7 kg/cm^2. Gross and specific energy required for the expander increased (cubic effects, p<0.003) as cone pressure was increased from 0 to 35.2 kg/cm^2. The majority of this increase in energy consumption was realized as cone pressure was increased from 24.4 to 35.2 kg/cm^2. As the expander cone pressure was increased from 0 to 11.7 kg/cm^2, energy consumption for the pellet mill decreased (quadratic effect, p<0.004) from 14.1 to 12.0 kWh/t. A marked improvement in pellet durability (quadratic effect, p<0.04) resulted when cone pressure was increased from 0 to 11.7 kg/cm^2, with small numerical differences as cone pressure was further increased to 35.2 kg/cm^2.

2) Nutrient digestibility

Feed intakes were similar (p>0.15) among the sorghum-based dietary treatments (table 9). Dry matter and gross energy digestibility increased (cubic effects, p<0.006) as cone pressure was increased from 0 to 35.2 kg/cm^2 with the largest improvement occurring as cone pressure was increased from 0 to 11.7 kg/cm^2. Nitrogen digestibility increased (cubic effect, p<0.001) from 78.3 to 81.0% as the feed was subjected to the higher cone pressures, with N digestibility being maximized at 24.4 kg/cm^2 cone pressure. The DE of the diet increased (cubic effect, p<0.001) by 225 kcal/kg as cone pressure was increased from 0 to 11.7 kg/cm^2.

4. Experiment 4

1) Processing characteristics

Pellet moisture (table 10) decreased and moisture loss increased as cone pressure was increased from 0 to 35.2 kg/cm^2. Also, starch gelatinization of the wheat-based diets increased from 16.8 to 49.1% as the diets were processed at 0 and 35.2 kg/cm^2 cone pressure.

Overall production rates (table 11) varied little among the processing treatments (p>0.24).

The production of fines decreased (quadratic effect, p<0.04) from 8 to 4 kg/h as cone pressure was increased from 0 to 24.4 kg/cm^2, however, the amount of fines increased as cone pressure was further increased to 35.2 kg/cm^2. Again, energy consumption for the expander increased (cubic effect, p<0.02) as cone pressure was increased from 0 to 35.2 kg/cm^2, with a plateau being reached as cone pressure was increased from 11.7 to 24.4 kg/cm^2 and increased at a greater rate as cone pressure was increased to 35.2 kg/cm^2. Pellet mill energy consumption decreased (cubic effect, p<0.05) as cone pressure was increased from 0 to 24.4 kg/cm^2 and then increased as cone pressure was further increased to 35.2 kg/cm^2. Both standard and modified pellet durabilities improved (quadratic effects, p<0.001) as cone pressure was increased from 0 to 11.7 kg/cm^2 with fewer differences being realized as cone pressure was further increased to 35.2 kg/cm^2.

Table 10. Effects of cone pressure on diet characteristics in wheat-based diets

Item	Cone pressure, kg/cm^2			
	0	11.7	24.4	35.2
Conditioned mash moisture, %	13.5	13.4	13.2	13.3
Pellet moisture, %	13.3	12.9	11.9	10.8
Moisture loss, %	0.2	0.5	1.3	2.5
Starch gelatinization, %	16.8	28.7	31.5	49.1

2) Nutrient digestibility

Feed intakes (table 12) of the wheat-based diets were similar (p>0.50). Nutrient digestibilities were not affected (p>0.18) by any increase in cone pressure. In fact, DM, N and GE digestibilities were increasing the highest in pigs fed the diet without any cone pressure suggesting that the wheat based diets are already highly digestible for finishing pigs. This is in agreement with the results reported by Hancock et al. (1992), who reported no differences in DM or N nutrient digestibility in extruded wheat-based diets compared to a ground wheat diet.

5. Experiment 5

1) Processing characteristics

The conditioned mash moistures for both dietary

Table 11. Effects of cone pressure on processing characteristics in wheat-based diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
Production rate, kg/h								
Overall	971	997	969	965	16	-[b]	-	-
Fines	8	7	4	12	2	-	0.04	-
Screened pellets	963	990	965	953	16	-	-	-
Screened pellets electrical energy consumption, kWh/t								
Pellet mill								
Idle	8.5	8.6	8.5	8.5	0.1	-	-	-
Specific	8.2	3.5	3.1	4.0	0.3	0.001	0.001	0.05
Gross	16.7	12.1	11.6	12.5	0.3	0.001	0.001	0.10
Expander								
Idle	25.4	25.6	25.1	24.4	0.3	0.07	-	-
Specific	0.2	9.6	16.4	35.8	0.5	0.001	0.001	0.001
Gross	25.6	35.2	41.5	60.2	0.7	0.001	0.001	0.003
Total gross	42.3	47.3	53.1	72.7	0.8	0.001	0.001	0.02
Overall production electrical energy consumption, kWh/t								
Pellet mill								
Idle	8.2	8.2	8.2	8.3	0.1	-	-	-
Specific	8.1	3.4	3.0	3.9	0.3	0.001	0.001	0.05
Gross	16.3	11.6	11.2	12.2	0.3	0.001	0.001	0.05
Expander								
Idle	25.1	25.4	25.0	24.7	0.3	-	-	-
Specific	0.2	9.6	16.3	35.4	0.6	0.001	0.001	0.002
Gross	25.3	35.0	41.3	60.1	0.7	0.001	0.001	0.005
Total gross	41.6	46.6	52.5	72.3	0.8	0.001	0.001	0.02
Pellet durability index, %								
Standard	92.6	95.3	95.5	94.5	0.3	0.004	0.001	-
Modified	88.5	91.9	93.3	92.5	0.2	0.001	0.001	-

[a] Three replicates/treatment. [b] Dashes indicate p>0.15.

Table 12. Effects of cone pressure on nutrient digestibility in wheat-based diets[a]

Item	Cone pressure, kg/cm²				SE	Probability, p<		
	0	11.7	24.4	35.2		Linear	Quadratic	Cubic
ADFI, g	1,695	1,649	1,692	1,664	51	-[b]	-	-
DM digesibility, %	85.7	84.5	85.1	85.2	0.6	-	-	-
N digestibility, %	83.7	83.2	83.5	83.8	0.7	-	-	-
GE digestibility, %	85.8	84.6	85.1	85.6	0.7	-	-	-
DE of diet, kcal/kg	3,389	3,329	3,345	3,362	23	-	-	-

[a] A total of 136 pigs (17 pigs/pen with an average initial BW of 42 kg) and four replicates/treatment.
[b] Dashes indicate p>0.15.

treatments were numerically similar (table 13). However, pellet moisture decreased as cone pressure was increased 0 to 35.2 kg/cm^2. The amount of moisture loss for the diets expanded at 42.2 kg/cm^2 was 3.0 and 3.8% for the SBM and raw soybean (RB) diets, respectively. Starch gelatinization for the SBM diets were 19% greater than the RB diets. In general, starch gelatinization increased as cone pressure was increased. Also, urease activity decreased from 1.66 to 0.21 pH rise in the RB as cone pressure was increased from 0 to 42.2 kg/cm^2.

Overall production rates for all treatments varied (quadratic effect, $p<0.06$) from 891 to 954 kg/h (tables 14). Diet formulation had no significant effect ($p<0.10$) on the amount of fines produced. However, the RB diets tended to generate the fewest amount of fines at 0, 14.1 and 42.2 kg/cm^2 cone pressure. Formulation influenced the amount of energy required ($p<0.007$) for the expander and pellet mill with the RB diets having lower gross total energy usage. Standard pellet durability was also influenced ($p<0.05$) by diet formulation with the RB diets having a higher PDI.

An increase in cone pressure from 0 to 42.2 kg/cm^2 increased the amount of whole pellets produced (quadratic effect, $p<0.001$), with the greatest improvement being realized as cone pressure was increased from 0 to 14.1 kg/cm^2. Again, expander energy consumption increased (quadratic effect, $p<0.001$) as cone pressure was increased from 0 to 42.2 kg/cm^2. Pelleting energy consumption decreased as cone pressure was increased (quadratic effect, $p<0.001$) from 0 to 14.1

Table 13. Effects of cone pressure on diet characteristics in soybean meal and raw soybean diets

Item Cone pressure, kg/cm[3]	Soybean meal				Raw soybean			
	0	14.1	28.1	42.2	0	14.1	28.1	42.2
Conditioned mash moisture, %	15.6	15.7	15.7	15.8	15.6	15.4	15.5	15.5
Pellet moisture, %	15.3	15.1	14.6	12.8	15.4	14.9	13.9	11.7
Moisture loss, %	0.3	0.6	1.1	3.0	0.2	0.5	1.6	3.8
Starch gelatinization, %	26.0	33.7	46.3	66.0	20.7	41.3	37.4	39.5
Urease activity, pH rise	0.00	0.01	0.00	0.00	1.66	0.42	0.16	0.21

Table 14. Effects of cone pressure on processing characteristics in soybean meal and raw soybean diets[a]

Item	Soybean meal				Raw soybean				SE
	Cone pressure, kg/cm[3]								
	0	14.1	28.1	42.2	0	14.1	28.1	42.2	
Production rate, kg/h									
Overall	894	895	954	891	896	912	908	900	15
Fines	211	46	43	48	133	55	40	29	18
Screened pellets	683	849	911	843	763	857	868	871	24
Screened pellets electrical energy consumption, kWh/t									
Pellet mill									
Idle	11.2	9.0	8.7	9.2	9.9	9.0	8.8	8.9	0.2
Specific	7.4	3.5	2.7	4.2	5.8	2.3	2.5	2.6	0.5
Gross	18.6	12.5	11.4	13.4	15.7	11.3	11.3	11.5	0.5
Expander									
Idle	37.0	29.8	29.7	29.9	33.8	29.4	29.8	29.4	0.9
Specific	0.5	10.1	20.8	63.9	1.1	10.3	16.2	22.5	2.5
Gross	37.5	39.9	50.5	93.8	34.9	39.7	46.0	51.9	2.6
Total gross	56.1	52.4	61.9	107.2	50.6	51.0	57.3	63.4	2.8
Overall production electrical energy consumption, kWh/t									
Pellet mill									
Idle	8.5	8.5	8.4	8.7	8.3	8.5	8.5	8.6	0.1
Specific	5.6	3.3	2.6	4.0	5.0	2.2	2.4	2.5	0.4
Gross	14.1	11.8	11.0	12.7	13.3	10.7	10.9	11.1	0.4
Expander									
Idle	28.2	28.2	28.4	28.3	28.5	28.1	28.5	28.4	0.4
Specific	0.4	9.5	19.9	60.4	0.9	9.7	15.5	21.8	2.5
Gross	28.6	37.7	48.3	88.7	29.4	37.8	44.0	0.2	2.5
Total gross	42.7	49.5	59.3	101.4	42.7	48.5	54.9	61.3	2.6
Pellet durability index, %									
Standard	47.4	81.9	93.1	91.5	79.3	86.1	84.3	84.3	3.3
Modified	24.5	71.1	91.2	89.7	69.9	71.5	76.7	78.3	4.4

[a] Three replicates/treatment.

kg/cm^2, with smaller differences as cone pressure was further increased to 42.2 kg/cm^2. Pellet durability increased as cone was increased form 0 to 14.1 kg/cm^2, with only slight numerical improvements as cone pressure was further increased to 42.2 kg/cm^2.

Several interactions occurred as cone pressure was increased. Most noteworthy was that the gross and specific energy consumption for the expander increased at a slower rate for the RB diets compared to the SBM diets as cone pressure was increased from 14.1 to 42.2 kg/cm^2 (formulation × quadratic cone pressure interaction, $p<0.001$). Also, pellet durability exhibited a similar trend as cone pressure was increased, except that smaller improvements were made in the RB diets compared to the dramatic improvement in pellet quality as cone pressure was increased from 0 to 11.7 kg/cm^2 for the SBM diets (formulation × quadratic cone pressure interaction, $p<0.008$).

2) Nutrient digestibility

Digestibility of nutrients were affected ($p<0.007$) by diet formulation (tables 16 and 17). The RB diets had lower DM, N and GE digestibilities as compared to the SBM diets. The DE of the RB diets were lower ($p<0.02$) than the SBM diets.

DM ($p<0.06$), N ($p<0.02$), and GE ($p<0.001$) digestibilities of the dietary treatments increased as cone pressure was increased 0 to 42.2 kg/cm^2. Also, the DE of the diet increased ($p<0.001$) as the dietary treatments were subjected to greater cone pressures.

Although these effects were significant, they were not independent of several noteworthy interactions. For

Table 15. Processing characteristics probability table, p<

Item	Diet (1)	Cone pressure			Interactions		
		Linear (2)	Quadratic (3)	Cubic (4)	1×2	1×3	1×4
Production rate, kg/h							
Overall	-[a]	-	0.06	0.10	-	-	0.06
Fines	0.10	0.001	0.001	0.09	-	0.06	-
Screened pellets		0.001	0.001	-	-	0.06	-
Screened pellets electrical energy consumption, kWh/t							
Pellet mill							
Idle	0.04	0.001	0.001	-	0.05	0.02	-
Specific	0.005	0.001	0.001	0.14	-	-	-
Gross	0.001	0.001	0.001	0.07	-	0.03	-
Expander							
Idle	0.11	0.001	0.001	-	-	-	-
Specific	0.001	0.001	0.001	0.05	0.001	0.001	0.11
Gross	0.001	0.001	0.001	-	0.001	0.001	0.13
Total gress	0.001	0.001	0.001	-	0.001	0.001	0.13
Overall production electrical energy consumption, kWh/t							
Pellet mill							
Idle	-	-	-	-	-	-	-
Specific	0.007	0.001	0.001	-	-	-	0.14
Gross	0.003	0.001	0.001	-	-	-	0.09
Expander							
Idle	-	-	-	-	-	-	-
Specific	0.001	0.001	0.001	0.06	0.001	0.001	0.13
Gross	0.001	0.001	0.001	0.07	0.001	0.001	0.12
Total gross	0.001	0.001	0.001	0.10	0.001	0.001	0.08
Pellet durability index, %							
Standard	0.05	0.001	0.001	-	0.001	0.008	-
Modified	0.13	0.001	0.002	-	0.001	0.002	-

[a] Dashes indicate p>0.15.

Table 16. Effects of cone pressure on nutrient digestibility in soybean meal and raw soybean diets[a]

Item	Soybean meal				Raw soybean				SE
	Cone pressure, kg/cm^{3}								
	0	14.1	28.1	42.2	0	14.1	28.1	42.2	
ADFI, g	3,367	3,354	3,358	3,422	3,076	2,872	2,985	2,809	97
DM digestibility, %	81.2	83.1	82.6	81.7	78.3	78.7	80.4	82.0	1.0
N digestibility, %	75.8	77.4	77.1	77.8	58.1	68.8	71.1	73.8	3.0
GE digestibility, %	81.1	84.0	84.0	83.3	75.1	77.7	80.4	82.8	1.2
DE of diet, kcal/kg	3,296	3,405	3,428	3,403	2,979	3,134	3,327	3,471	47

[a] A total of 64 pigs (eight pigs/pen with an average initial BW of 86 kg) and three replicates/treatment

Table 17. Nutrient digestibility probability table, p<

Item	Diet (1)	Cone pressure			Interactions		
		Linear (2)	Quadratic (3)	Cubic (4)	1×2	1×3	1×4
ADFI	0.001	-[a]	-	-	-	-	-
DM digestibility	0.007	0.06	-	-	0.10	-	-
N digestibility	0.001	0.02	-	-	0.04	-	-
GE digestibility	0.001	0.001	-	-	0.02	-	-
DE of diet	0.001	0.001	-	-	0.001	-	-

[a] Dashes indicate p>0.15.

example, the pigs fed the RB diets had greater improvements in N and GE digestibility as cone pressure was increased compared to the pigs fed the SBM diets (formulation × cone pressure interaction, $p<0.04$). Also, DE of the diet increased at a greater rate for the RB diets as cone pressure was increased above 28.1 kg/cm^2 cone pressure (formulation × cone pressure interaction, $p<0.002$). These effects in the RB diets were in part due to the destruction of the antinutritional factors (i.e., trypsin and urease) associated with feeding raw soybeans.

In conclusion, expander processing increased the total energy requirements of a feed manufacturing facility. As cone pressure was increased, pellet quality and starch gelatinization increased and antinutritional factors decreased. Expander processing conditions did influence the digestibility of nutrients in corn, sorghum, midds, and raw soybeans diets. However, expander processing conditions did not affect the nutrient digestibility in wheat-based diets. Thus, an acceptable compromise must be reached between the increased operating and capital costs compared to any improvements in nutrient digestibility or growth performance.

IMPLICATIONS

The benefits of hydrothermal processing are encouraging from a feed manufactures and animal nutritionists view point. The reduction in the energy required by the pelleting press could increase the overall throughput of a feed mill provided that the expander is of adequate size. Along with the added improvements in pellet quality and feed hygiene, which have been demonstrated to improve animal performance and health status, the expander will allow animal nutritionists an increased flexibility to utilize a wider spectrum of ingredients in diet formulation. However, any potential improvement in growth performance or nutrient digestibility must offset the higher operating and capital costs associated with expander technology.

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