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Effects of coextrusion of flaxseed and field pea on the digestibility of energy, ether extract, fatty acids, protein, and amino acids in grower-finisher pigs[1]

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ABSTRACT: The objectives of this study were to determine the ileal and total tract digestibility of individual fatty acids, ether extract, energy, protein, and AA in a mix of flax and field pea (FP) and to determine whether extrusion improves the nutritive value of this mix. Five barrows (23-kg initial BW) fitted with a T-cannula at the distal ileum were fed 5 diets at 3 times the maintenance energy requirement according to a 5 × 5 Latin square design: a wheat and soybean meal control diet and 4 diets containing 30% raw or coextruded FP plus 70% control diet and chromic oxide as an indigestible marker. The 4 extrusion treatments included the following: 1) FP0, ground, nonextruded; 2) FP1, single-screw extruded; 3) FP2, twin-screw extruded with low intensity (screw speed 120 rpm; die temperature 110°C; water input 5 kg/h); and 4) FP3, twin-screw extruded with high intensity (300 rpm; 125°C; 11 kg/h). The ether extract concentration was 17.8, 19.6, 17.7, and 17.3% (as fed) in FP0, FP1, FP2, and FP4, respectively. The ADF concentration was 13.2, 11.1, 11.4, and 13.7% (as fed) in FP0, FP1, FP2, and FP4, respectively. After a 7-d acclimation, feces were collected for 2 d, and then ileal digesta was collected for 2 d. Energy digestibility in the test ingredients was calculated using the difference method. Extrusion of FP did not affect the apparent total tract digestibility (ATTD) and apparent ileal digestibility (AID) of DM, OM, and CP for grower-finisher pigs. Extrusion increased ($P < 0.05$) the ATTD of GE and ether extract and the DE content of FP, and the AID of the Arg, Ile, Leu, Lys, Phe, Thr, and Val, and total fatty acids. Extrusion tended to increase ($P < 0.10$) the AID of linolenic acid. Single-screw extrusion resulted in a greater ($P < 0.05$) ATTD of GE, OM, ether extract, and DE content of FP and AID of SFA than twin-screw extrusion. Single-screw extrusion resulted in a trend for greater ($P < 0.10$) AID of linolenic acid and total fatty acids than twin-screw extrusion. Twin-screw extrusion at high intensity resulted in less ($P < 0.05$) AID of SFA than twin-screw extrusion at low intensity, indicating that equipment and conditions should be carefully controlled for the extrusion of FP. In conclusion, coextrusion of FP increased digestibility of ether extract, fatty acids, energy, and AA.

Key words: digestibility, extrusion, fatty acid, field pea, flax, pig

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INTRODUCTION

Increased consumer awareness and demand for dietary n-3 fatty acids for human health benefits (Simopoulos, 1999; Conners, 2000) have created opportunities for the pork industry to produce n-3-enriched pork (Bourre, 2005). Flaxseed is a rich source of α-linolenic acid, and feeding pigs diets that contain flaxseed will increase the n-3 fatty acid content in carcass tissues (Cherian and Sim, 1995; Romans et al., 1995a,b; Matthews et al., 2000).

Feeding of flaxseed poses challenges for grinding and storage because of its high oil and α-linolenic acid content, respectively. Mixing flaxseed with field pea can counteract these problems (Thacker et al., 2004). A flax and field pea mix (**FP**) can be used as a source of energy, AA, and n-3 fatty acids in pig diets; however, flaxseed

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and field pea contain antinutritional factors. Flaxseed contains mucilage, phytic acid, goitrogens, allergens, and antipyridoxin (Madhusudhan et al., 1986). Field pea contains protease inhibitors, lectins, and tannins (O'Doherty and Keady, 2000). To inactivate these compounds, FP can be processed using heat, (e.g., extrusion; Melcion and Van der Poel, 1993). Positive effects of extrusion are reductions in trypsin inhibitor activity and tannin content in field pea (O'Doherty and Keady, 2000). The hypothesis of the present study was that coextrusion of FP will improve digestibility of nutrients and that the selected extrusion technology (single vs. twin screw) and conditions (high vs. low intensity) may affect nutrient digestibility (Riaz, 2001).

The objectives of this study were to determine the ileal and total tract digestibility of individual fatty acids, ether extract, energy, protein, and AA in FP and to determine whether extrusion alters the nutritive value of this mix. An additional objective was to compare nutrient and energy digestibility of diets containing 30% FP with a conventional diet.

MATERIALS AND METHODS

The animal protocol for the study was approved by the University of Alberta Faculty Animal Policy and Welfare Committee and followed established principles (CCAC, 1993).

Ingredients and Extrusion Processing

A 50:50 (wt/wt) mix of FP was obtained (Oleet Processing Ltd., Regina, Saskatchewan, Canada). The mix was divided into 4 portions that were processed separately (Table 1): 1) FP0, ground through a knife mill with a 2-mm sieve, nonextruded; 2) FP1, extruded using a single-screw extruder with minimal water input; 3) FP2, extruded using a twin-screw extruder at low intensity; and 4) FP3, extruded using a twin screw at high intensity. The single-screw extruder (model 600, Insta-Pro Int., Des Moines, IA) was located at a commercial company (FP1: commercially sold as LinPRO; Oleet Processing Ltd). The twin-screw extruder (model ZSK 57-M 50/2, Werner & Pfleiderer, Stuttgart, Germany) was located at the Food Science and Technology Centre of Alberta Agriculture and Food (Brooks, Alberta, Canada).

Experimental Design and Diets

The basal and FP diets were based on wheat and soybean meal (Table 2). The 4 FP diets were formulated by replacing 30% of the basal diet with 1 of the 4 FP treatments so that all experimental diets were not limiting in AA. Canola oil, vitamins, and minerals were supplemented in the diets to supply all nutrients and energy according to NRC (1998) standards. Chromic oxide (0.3%) was included in the diets as an indigestible marker.

Experimental Protocols

The experiment was conducted at the Swine Research and Technology Centre of the University of Alberta (Edmonton, Alberta, Canada). Five crossbred barrows (Duroc × Large White-Landrace; Genex Hybrid; Hypor, Regina, Saskatchewan, Canada; initial BW = 23.1 kg) were housed individually in steel metabolism pens (height, 1.1 m; length, 2.4 m; width, 1.5 m) that allowed freedom of movement in a temperature-controlled room (20 ± 1°C). Each pen was equipped with a single-hole feeder and a low-pressure drinking nipple. Pigs were fitted with a T-cannula at the distal ileum. Pigs were fed a 20% CP pregrower diet that did not contain flaxseed or field pea during the adaptation period to the pens and the 10-d recuperation from surgery.

After recuperation from surgery, pigs were randomly assigned to 1 of 5 experimental diets according to a 5 × 5 Latin square design in 1 of 5 eleven-day experimental periods. Daily feed allowance was adjusted to 3 times the maintenance energy requirement (3 × 110 kcal of DE/kg of $BW^{0.75}$; NRC, 1998) based on the average BW at the beginning of each experimental period. The feed was fed in 2 equal meals at 0800 and 1500 h. The diets were fed as a mash. Pigs had free access to water.

Table 1. Extrusion conditions of the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded flaxseed-field pea[1]		
Extrusion conditions	FP1	FP2	FP3
Extruder type	Single screw	Twin screw	Twin screw
Screw speed, rpm	—	120	300
Screw torque, %	—	60 to 70	26
Pressure, kPa	2,750	—	—
Water input, kg/h	0	5	11
Steam input, kg/h	—	100	150
Barrel temperature at cooking zone, °C	135	100	135
Die temperature, °C	—	110	125

[1]FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix extruded as follows: FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

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The experimental periods consisted of a 7-d acclimation to experimental diets, followed by a 2-d collection of feces and then a 2-d collection of ileal digesta. Feces were collected from 0800 to 1800 h. Ileal digesta were collected from 0800 to 2000 h into plastic bags (length, 10 cm; diameter, 4 cm) that contained 8 mL of 10% (vol/vol) formic acid to minimize bacterial fermentation. Bags were removed when digesta filled approximately 50% of the bag. Collected feces and digesta were pooled by pig and period and immediately frozen at −28°C. Feces and digesta were freeze-dried before analyses.

Chemical Analysis

Feed, FP, and freeze-dried feces and digesta were ground through a 0.5-mm screen and analyzed for DM, ether extract, and ash (AOAC, 2006). Gross energy was analyzed by an adiabatic bomb calorimeter (AC-300 Automatic Calorimeter, Leco Corporation, St. Joseph, MI), and N was analyzed by combustion (method 968.06; AOAC, 2006) using an N Analyzer (FP-428, Leco Corporation).

Feed, feces, and digesta samples were analyzed for Cr_2O_3 by spectrophotometry at 440 nm after ashing at 450°C overnight (Fenton and Fenton, 1979). Feed, FP, and digesta samples were analyzed for all AA, except Met, Cys, and Trp, by HPLC (Liao et al., 2005) and for fatty acids by GLC (Sukhija and Palmquist, 1988). The 4 FP samples were analyzed for Ca, P, K, Mg, and Na (atomic emission spectrophotometry; AOAC, 2006), ADF (method 973.18; AOAC, 2006), NDF (Van Soest et al., 1991), and available Lys (method 975.44; AOAC, 2006). Analyses were carried out in duplicate.

Calculations and Statistical Analysis

Based on the results of the chemical analyses, apparent ileal digestibility (**AID**) of AA, fatty acids, ether extract, DM, OM, CP, and GE and the total tract digestibility of ether extract, DM, OM, CP, and GE were calculated using the Cr_2O_3 concentration of feed, digesta, and feces (Adeola, 2001). The digestibility coefficients of the 4 FP sources were separated from the basal diet using the difference method (Fan and Sauer, 1995). The DE content was calculated using the GE content multiplied by the digestibility coefficient for GE.

To compare differences among treatments, data were subjected to ANOVA as a 5 × 5 Latin square design using the GLM procedure (SAS Inst. Inc., Cary, NC). The fixed effect of diet (n = 5) and the random effect of experimental period (n = 5) and animals (n = 5) were included in the model. The pig was used as the experimental unit, and means were reported as least squares means. Treatment means were compared using preplanned contrasts. Differences were considered significant if $P < 0.05$ and were described as tendencies if $0.05 < P < 0.10$.

Table 2. Ingredient composition (as-fed basis) of the basal and flaxseed-field pea (FP) diets

Ingredient, %	Basal diet	FP diets[1]
Wheat	71.96	49.40
50:50 flaxseed and field pea	—	30.00
Soybean meal	21.93	15.05
Canola oil	1.79	1.23
Mineral-vitamin premix[2]	4.00	4.00
Ethoxyquin[3]	0.02	0.02
Chromic oxide	0.30	0.30

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

[2]Provided the following per kilogram of diet: Na, 3.18 g as salt; Cl, 4.90 g as salt; Fe, 214 mg as ferrous sulfate; Zn, 107 mg as zinc carbonate; Mn, 48.6 mg as manganese sulfate; Cu, 124 mg as copper sulfate; I, 0.36 mg as potassium iodate; Co, 0.06 mg as cobalt sulfate; Se, 0.054 mg as sodium selenite; vitamin A, 8,928 IU; vitamin D_3, 992 IU; vitamin E, 71.2 IU; vitamin K_3, 0.62 mg; vitamin B_{12}, 0.02 mg; riboflavin, 5 mg; niacin, 22 mg; D-pantothenic acid, 15 mg; biotin, 0.09 mg; and choline, 260 mg.

[3]Provided 132 mg of ethoxyquin per kilogram of diet.

RESULTS

All pigs remained healthy and readily consumed their daily allowances throughout the experiment. Intestinal adhesions were not observed during postmortem examinations at the end of the experiment. The average BW of the pigs was 31.8, 37.7, 43.7, 50.9, and 57.3 kg at the beginning of experimental periods 1, 2, 3, 4, and 5, respectively, and 67.7 kg at the end of the experiment.

Main Constituent Composition

FP Sources. In the 4 FP samples, slight variations in the GE, AA, and ADF composition occurred (Table 3). The concentration of NDF was 3 to 5% less in the 3 extruded FP samples than the ground and not extruded FP. The total and available Lys concentrations did not differ among the 4 FP samples.

Diets. The analyzed nutrient composition of the 5 diets is reported in Table 4. Results indicate that the NRC (1998) standards for energy, CP, and AA of grower pigs were met or exceeded.

Main Constituent Digestibility

Diets. The AID of DM, OM, CP, and GE was greater ($P < 0.001$) in the basal diet than the 4 FP diets (Table 5). The AID of energy and nutrients was not different among the FP diets. The apparent total tract digestibility (**ATTD**) of DM, OM, CP, and GE was greater ($P < 0.001$) in the basal diet than the 4 FP diets. The ATTD of GE was less ($P < 0.05$) in the diet containing ground and not extruded FP and tended to be less ($P = 0.10$) for OM than the 3 diets containing extruded FP. The diet containing FP extruded using a single-screw

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Table 3. Analyzed nutrient, energy, and AA composition (as-fed basis) of the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded FP[1]			
Item	FP0	FP1	FP2	FP3
Nutrient				
DM, %	90.95	94.90	91.30	88.99
GE, Mcal/kg	4.83	5.12	5.02	4.87
OM, %	87.30	91.22	87.69	85.57
Ether extract, %	17.75	19.59	17.74	17.27
NDF, %	24.50	18.80	21.60	20.10
ADF, %	13.20	11.10	11.40	13.70
Ash, %	3.65	3.68	3.61	3.42
CP, %	22.60	22.73	22.10	21.43
Calcium, %	0.16	0.18	0.16	0.16
Phosphorus, %	0.43	0.43	0.43	0.41
Indispensable AA, %				
Arg	1.46	1.51	1.55	1.52
His	0.42	0.44	0.45	0.43
Ile	0.78	0.82	0.82	0.81
Leu	1.20	1.26	1.26	1.23
Lys	1.04	1.08	1.07	1.03
Phe	0.85	0.90	0.90	0.89
Thr	0.77	0.81	0.89	0.88
Val	0.84	0.89	0.89	0.88
Available Lys	0.94	0.97	1.00	0.95

[1]FP0, FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

extruder had a greater ($P < 0.01$) GE digestibility and a greater ($P < 0.05$) OM digestibility than the 2 diets containing FP extruded using a twin-screw extruder. The diet containing FP extruded using a twin-screw extruder at high intensity had greater ($P < 0.05$) CP digestibility than the diet containing FP extruded using a twin-screw extruder at low intensity.

FP Sources. The ileal DE content tended to be greater ($P < 0.10$) in the 3 extruded FP sources than the ground and not extruded FP (Table 6). Differences in AID of energy and nutrients were not observed. The ATTD of GE ($P < 0.05$) and the DE content ($P < 0.01$) of ground and not extruded FP were less than of the 3 extruded FP sources. The DE content and ATTD of GE and OM were greater ($P < 0.05$) in FP extruded using a single-screw extruder than the 2 FP extruded using a twin-screw extruder. The FP extruded using a twin-screw extruder at high intensity tended to have a greater ($P < 0.10$) CP digestibility than the FP extruded using a twin-screw extruder at low intensity.

AA Digestibility

Diets. The AID was greater ($P < 0.05$) for Arg, His, Ile, Leu, Phe, Thr, and Val in the basal diet than in the 4 FP diets (Table 7). Among the AA, the AID of the basal diet was 89.6% for Lys and 81.3% for Thr. The AID of the diet containing ground and not extruded FP was less ($P < 0.05$) for Arg, Ile, Leu, Lys, Phe, Thr, and Val and tended to be less ($P < 0.10$) for His than of the 3 diets containing extruded FP. The AID of AA was not different for the diet containing FP extruded using a single-screw extruder compared with the 2 diets containing FP extruded using a twin-screw extruder. The AID of the diet containing FP extruded using a twin-screw extruder at high intensity was greater ($P < 0.05$) for His than the diet containing FP extruded using a twin-screw extruder at low intensity.

FP Sources. The AID of Arg, Ile, Leu, Lys, Phe, Thr, and Val was greater ($P < 0.05$) and tended to be

Table 4. Analyzed nutrient, energy, and AA composition (as-fed basis) of the experimental diets

	Diet[1]				
Item	Basal	FP0	FP1	FP2	FP3
Nutrient					
DM, %	88.91	89.21	90.24	89.04	89.11
GE, Mcal/kg	3.88	4.13	4.14	4.27	4.15
OM, %	82.63	82.66	83.52	84.54	82.50
Ether extract, %	2.68	7.43	8.54	8.69	7.15
Ash, %	6.28	6.56	6.73	6.50	6.61
CP, %	22.44	22.05	19.74	18.48	21.10
Indispensable AA, %					
Arg	0.89	1.02	1.04	0.95	1.02
His	0.45	0.40	0.40	0.35	0.42
Ile	0.67	0.68	0.70	0.64	0.68
Leu	1.15	1.13	1.15	1.07	1.13
Lys	0.96	0.99	0.99	0.98	0.98
Phe	0.78	0.77	0.80	0.75	0.78
Thr	0.65	0.68	0.65	0.64	0.68
Val	0.69	0.71	0.74	0.68	0.71

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

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Table 5. The apparent ileal and total tract digestibility of DM, OM, CP, and GE of the experimental diets

	Diet[1]						*P*-value			
Item	Basal	FP0	FP1	FP2	FP3	SEM	Basal vs. FP	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Ileal digestibility, %										
DM	79.2	75.2	75.5	76.9	75.7	0.6	<0.001	0.259	0.293	0.200
OM	81.2	77.1	77.7	78.8	77.6	0.6	<0.001	0.177	0.477	0.143
CP	86.9	83.0	83.7	83.2	84.5	0.6	<0.001	0.269	0.819	0.183
GE	82.1	76.8	78.0	78.3	78.2	0.7	<0.001	0.129	0.737	0.889
Total tract digestibility, %										
DM	86.6	83.1	84.7	83.8	83.5	0.6	<0.001	0.205	0.169	0.675
OM	88.9	85.2	87.1	85.8	85.8	0.5	<0.001	0.100	0.048	0.996
CP	86.7	84.4	83.5	82.9	85.3	0.6	<0.001	0.418	0.385	0.012
GE	86.8	80.8	84.5	82.3	81.9	0.6	<0.001	0.013	0.009	0.668

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea mix (FP) processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

Table 6. The apparent ileal and total tract digestibility of DM, OM, CP, and GE of the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded FP[1]					*P*-value		
Item	FP0	FP1	FP2	FP3	SEM	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Ileal digestibility, %								
DM	66.2	67.6	71.9	67.7	2.4	0.338	0.465	0.256
OM	68.1	70.4	73.5	69.4	2.2	0.266	0.692	0.219
CP	74.0	77.6	76.7	79.0	2.2	0.192	0.933	0.487
GE	67.0	71.0	71.5	71.0	2.3	0.156	0.921	0.901
DE, Mcal/kg of DM	3.56	3.83	3.93	3.89	0.1	0.053	0.624	0.842
Total tract digestibility, %								
DM	75.0	80.5	77.5	76.0	1.9	0.202	0.141	0.602
OM	77.3	83.4	78.9	78.9	1.6	0.128	0.049	0.996
CP	79.2	77.3	76.1	81.9	1.9	0.722	0.484	0.064
GE	69.6	80.6	73.9	72.8	1.9	0.021	0.013	0.688
DE, Mcal/kg of DM	3.70	4.35	4.06	3.99	0.10	0.006	0.031	0.621

[1]FP0, FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

Table 7. The apparent ileal AA digestibility of the experimental diets

	Diet[1]						*P*-value			
Item	Basal	FP0	FP1	FP2	FP3	SEM	Basal vs. FP	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Indispensable AA, %										
Arg	91.3	85.5	90.2	90.8	89.4	0.6	0.005	0.001	0.940	0.121
His	95.9	93.3	93.8	93.4	94.5	0.3	0.001	0.070	0.674	0.018
Ile	87.8	81.2	86.0	86.3	85.3	0.7	0.002	0.001	0.811	0.355
Leu	84.4	76.3	82.8	83.0	81.7	1.0	0.007	0.001	0.723	0.358
Lys	89.6	82.8	87.6	88.4	87.9	1.4	0.107	0.005	0.755	0.780
Phe	88.0	80.9	86.2	87.4	86.1	0.6	0.002	0.001	0.493	0.174
Thr	81.3	75.6	78.0	78.7	79.8	1.0	0.014	0.017	0.356	0.456
Val	78.1	67.0	75.8	76.2	76.2	1.1	0.011	0.001	0.803	0.969

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea mix (FP) processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

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Table 8. The apparent ileal AA digestibility of the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded FP[1]					*P*-value		
Item	FP0	FP1	FP2	FP3	SEM	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Indispensable AA, %								
Arg	77.9	88.8	90.4	87.1	1.6	0.001	0.998	0.189
His	87.6	89.5	89.5	91.4	1.0	0.066	0.469	0.231
Ile	68.7	82.8	83.9	80.9	2.3	0.001	0.901	0.378
Leu	58.9	79.3	80.4	76.0	3.3	0.001	0.781	0.380
Lys	69.2	84.9	87.2	85.5	4.7	0.015	0.802	0.800
Phe	66.6	82.6	86.4	82.4	2.1	0.001	0.511	0.212
Thr	64.4	72.7	74.5	77.1	2.8	0.013	0.395	0.538
Val	52.4	71.8	73.3	72.8	3.1	0.001	0.756	0.912

[1]FP0, FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

greater ($P < 0.10$) for His in the 3 extruded FP sources than ground and not extruded FP (Table 8). The AID of AA was not different for FP extruded using a single-screw extruder compared with the 2 FP extruded using a twin-screw extruder.

Fatty Acid Composition

FP Sources. The concentration of fatty acids was slightly greater in ground and not extruded FP than the 3 extruded FP sources (Table 9). As expected, the concentration of linolenic acid (C18:3) ranged from 49.6 to 51.1% as a percentage of total fatty acids, and linolenic acid had the greatest concentration of the fatty acids in each of the 4 FP sources. The fatty acid profiles, expressed as percentages of total fatty acids, were similar among the 4 FP sources.

Diets. The total fatty acid concentration in the 4 FP diets ranged from 6.5 to 7.9% (as fed) and compared with 2.7% in the basal diet (Table 10). In the 4 FP diets, linolenic acid was the fatty acid with the greatest concentration.

Fatty Acid Digestibility

Diets. The AID of the fatty acids, palmitic, arachidic, oleic, vaccenic, linoleic, and linolenic and saturated, unsaturated, and total fatty acids was greater ($P < 0.05$; Table 11) in the basal diet than the FP diets and tended to be greater ($P < 0.10$) for stearic and ether extract. The AID of the diet containing ground and not extruded FP was less ($P < 0.05$) for palmitic, stearic, arachidic, oleic, vaccenic, and linolenic acids and SFA, PUFA, and total fatty acids and tended to be less ($P <$

Table 9. Analyzed fatty acid composition of the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded FP[1]			
Item	FP0	FP1	FP2	FP3
Fatty acid, % of total fatty acids				
C16:0 (palmitic)	6.04	6.10	6.20	5.87
C18:0 (stearic)	3.56	3.23	3.19	3.28
C20:0 (arachidic)	0.15	0.11	0.13	0.11
C18:1n-9 (oleic)	19.36	18.38	18.27	18.49
C18:1n-7 (vaccenic)	0.72	0.71	0.76	0.69
C18:2 (linoleic)	20.55	20.61	20.54	20.51
C18:3 (linolenic)	49.62	50.85	50.92	51.05
Fatty acid, % as-fed basis				
C16:0 (palmitic)	0.90	0.81	0.76	0.77
C18:0 (stearic)	0.53	0.43	0.39	0.43
C20:0 (arachidic)	0.02	0.01	0.02	0.01
C18:1n-9 (oleic)	2.89	2.45	2.24	2.43
C18:1n-7 (vaccenic)	0.11	0.10	0.09	0.09
C18:2 (linoleic)	3.07	2.75	2.52	2.69
C18:3 (linolenic)	7.41	6.79	6.24	6.70
SFA	1.46	1.26	1.17	1.22
PUFA	13.48	12.09	11.09	11.91
Total fatty acids	14.96	13.38	12.29	13.15

[1]FP0, FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

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Table 10. Fatty acids composition of the experimental diets

	Diet[1]				
Item	Basal	FP0	FP1	FP2	FP3
Fatty acid, % of total fatty acids					
C16:0 (palmitic)	13.53	8.19	7.68	7.50	8.06
C18:0 (stearic)	1.84	3.12	2.90	2.79	3.05
C20:0 (arachidic)	0.33	0.20	0.23	0.27	0.19
C18:1n-9 (oleic)	29.27	22.50	26.05	27.74	23.03
C18:1n-7 (vaccenic)	2.09	1.13	1.42	1.54	1.20
C18:2 (linoleic)	43.51	27.08	26.21	26.09	26.61
C18:3 (linolenic)	9.43	37.78	35.51	34.07	37.88
Fatty acid, % as-fed basis					
C16:0 (palmitic)	0.36	0.53	0.57	0.59	0.53
C18:0 (stearic)	0.05	0.20	0.21	0.22	0.20
C20:0 (arachidic)	0.01	0.01	0.02	0.02	0.01
C18:1n-9 (oleic)	0.79	1.46	1.93	2.20	1.51
C18:1n-7 (vaccenic)	0.06	0.07	0.11	0.12	0.08
C18:2 (linoleic)	1.17	1.76	1.94	2.07	1.74
C18:3 (linolenic)	0.25	2.45	2.63	2.70	2.48
SFA	0.42	0.75	0.80	0.84	0.74
PUFA	2.27	5.74	6.61	7.09	5.81
Total fatty acids	2.69	6.49	7.42	7.94	6.56

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea mix (FP) processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

0.10) for linoleic acid and ether extract than of the 3 diets containing extruded FP. The ATTD of ether extract was less ($P < 0.001$) in the diet containing ground and not extruded FP than of the 3 diets containing extruded FP. The diet containing FP extruded using a single-screw extruder had a greater ($P < 0.05$) AID of palmitic, stearic, arachidic, oleic, vaccenic, and linolenic acids and of saturated, unsaturated, and total fatty acids than the 2 diets containing FP extruded using a twin-screw extruder and a greater ATTD of ether extract ($P < 0.01$). The diet containing FP extruded using a twin-screw extruder at low intensity had a greater ($P < 0.05$) AID of stearic, arachidic, oleic, vaccenic, and SFA and tended to have a greater AID of palmitic acid ($P < 0.10$) than the diet containing FP extruded using a twin-screw extruder at high intensity.

FP Sources. The AID and ATTD of the fatty acids in the 4 FP sources (Table 12) mimicked the differences observed in the FP diets. In ground and not extruded FP, the AID of SFA and ATTD of ether extract were less ($P < 0.01$) and the AID of unsaturated fatty acid tended to be less ($P < 0.10$) than of the 3 extruded FP

Table 11. The apparent ileal digestibility of fatty acids and apparent ileal and total tract digestibility of ether extract in the experimental diets

	Diet[1]						*P*-value			
Item	Basal	FP0	FP1	FP2	FP3	SEM	Basal vs. FP	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Ileal digestibility, %										
C16:0 (palmitic)	84.1	72.5	82.4	77.8	74.2	1.3	<0.001	0.002	0.001	0.067
C18:0 (stearic)	76.4	63.9	80.7	73.1	65.8	2.3	0.055	0.005	0.002	0.048
C20:0 (arachidic)	74.7	51.5	66.7	67.6	47.5	3.0	<0.001	0.021	0.028	<0.001
C18:1n-9 (oleic)	90.0	74.1	87.1	82.4	75.6	1.5	<0.001	<0.001	<0.001	0.007
C18:1n-7 (vaccenic)	89.3	77.1	86.0	83.8	79.1	1.5	<0.001	0.004	0.024	0.041
C18:2 (linoleic)	91.1	80.9	88.4	86.0	82.6	2.3	0.024	0.095	0.166	0.313
C18:3 (linolenic)	92.3	75.4	90.5	83.8	78.6	3.2	0.015	0.034	0.036	0.278
SFA	83.0	69.8	81.6	76.3	71.5	1.5	<0.001	0.002	0.001	0.041
Unsaturated fatty acids	90.8	76.8	88.8	84.0	79.0	2.4	0.007	0.023	0.028	0.165
Total fatty acids	88.7	75.5	87.6	82.7	77.7	2.2	0.008	0.016	0.019	0.135
Ether extract	92.2	85.2	91.2	88.6	87.5	1.9	0.071	0.099	0.192	0.685
Total tract digestibility, %										
Ether extract	87.0	79.3	91.0	86.5	84.3	1.2	0.218	<0.001	0.003	0.210

[1]Diet FP0, FP1, FP2, and FP3 each contained 30% of a 50:50 flaxseed-field pea (FP) mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

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Table 12. The apparent ileal digestibility of fatty acids and apparent ileal and total tract digestibility of ether extract in the coextruded 50:50 flaxseed-field pea (FP)

	Coextruded FP[1]					*P*-value		
Item	FP0	FP1	FP2	FP3	SEM	FP0 vs. FP1, FP2, and FP3	FP1 vs. FP2 and FP3	FP2 vs. FP3
Ileal digestibility, %								
C16:0 (palmitic)	61.8	81.0	73.1	65.0	2.6	0.006	0.005	0.059
C18:0 (stearic)	61.3	81.6	72.5	63.6	2.6	0.006	0.003	0.043
C20:0 (arachidic)	36.4	62.3	64.7	49.2	7.9	0.098	0.611	0.412
C18:1n-9 (oleic)	64.5	85.9	79.8	67.3	2.6	0.001	0.460	0.669
C18:1n-7 (vaccenic)	62.9	84.1	81.2	68.8	3.2	0.003	0.047	0.024
C18:2 (linoleic)	72.0	86.5	82.6	75.1	5.0	0.138	0.246	0.311
C18:3 (linolenic)	74.1	90.3	83.2	77.5	4.1	0.074	0.079	0.353
SFA	61.1	80.8	72.6	63.9	2.6	0.006	0.005	0.046
Unsaturated fatty acids	71.4	88.2	82.0	74.6	3.8	0.051	0.069	0.208
Total fatty acids	70.1	87.2	80.9	73.2	3.6	0.039	0.052	0.177
Ether extract	82.4	90.7	86.2	85.7	2.9	0.162	0.212	0.891
Total tract digestibility, %								
Ether extract	76.3	92.9	86.2	83.2	1.6	<0.001	0.003	0.221

[1]FP0, FP1, FP2, and FP3 were a 50:50 flaxseed-field pea mix processed as follows: FP0, ground and not extruded; FP1, extruded using a single-screw extruder; FP2, extruded using a twin-screw extruder at low intensity; and FP3, extruded using a twin-screw extruder at high intensity.

sources. The AID of SFA and ATTD of ether extract in FP extruded using a single-screw extruder was greater ($P < 0.01$) than in the 2 FP extruded using a twin-screw extruder. The AID of SFA was greater ($P < 0.05$) in FP extruded using a twin-screw extruder at low intensity than FP extruded using a twin-screw extruder at high intensity.

DISCUSSION

Little information exists on the composition of flax products and their digestibility of nutrients (including n-3 fatty acids) and energy of flax products in swine. The present study was, therefore, conducted to determine the digestibility of fatty acids, ether extract, energy, protein, and AA in a FP mix fed to grower-finisher pigs. To enhance nutrient digestibility, FP were coextruded, similar to coextrusion of full-fat canola seed and field pea (Kiarie and Nyachoti, 2006). Flax is an oilseed containing 35% ether extract, and field pea is a legume seed containing around 22% CP and 41% starch (CVB, 1994). Coextrusion of FP, therefore, allows the blending of macronutrients, and single extrusion of flax might produce a product with undesirable handling characteristics due to the released oil. Extrusion might improve nutrient digestibility because of cell wall disruption and the potential inactivation of heat-labile antinutritional factors in FP (Harper, 1978).

The effects of extrusion on DM and CP digestibility are not consistent among studies with swine. The extrusion of FP did not affect the AID or ATTD of DM, OM, and CP for pigs in the present study. In a previous study, extrusion did not affect ATTD of CP and increased ATTD of OM of a field pea diet fed to grower-finisher pigs (O'Doherty and Keady, 2001). Similarly, extrusion of corn did not affect the ATTD and AID of CP and indispensable AA for 20-kg pigs (Herkelman et al., 1990). In a recent study, extrusion did not affect the AID of total AA of corn in grower pigs (Muley et al., 2007). In contrast, extrusion increased the AID of CP of field pea with an elevated trypsin inhibitor activity (Mariscal-Landín et al., 2002). Extrusion of a cereal and soybean meal-based diet improved the ATTD of DM and CP in early weaned pigs compared with pelleting (Sauer et al., 1990). Extrusion should inactivate heat-labile antinutritional factors in feedstuffs and improve CP digestibility and increase starch gelatinization and improve OM digestibility (O'Doherty and Keady, 2001; Mariscal-Landín et al., 2002). However, proteins in feedstuffs are temperature-sensitive. Under the influence of heat, proteins may denature, coagulate, or form Maillard reaction products. Protein denaturation generally has a neutral effect on CP digestibility for balanced diets for nonruminant animals (Peisker, 1992).

Extrusion improved the AID of AA in the FP in the present study. A substantial amount of Lys may be lost due to condensation between ε-NH_2 of Lys and C = O of reducing sugars when legume or cereal legume blends are extruded under high temperature or shear force conditions at a low-moisture content (Björck and Asp, 1983). The AID analysis of AA has limitations for heat-processed feedstuffs, especially for Lys with extensive heat (Van Barneveld et al., 1995). However, the content of available and, thus, intact Lys and the AID of Lys were identical among the 4 FP samples, indicating that extrusion did not damage the Lys in the FP in the present study.

Extrusion of FP improved the ATTD but not the AID of ether extract in the present study, similar to previous work that indicated that the extrusion of corn improved the ATTD but not the AID of ether extract in 20-kg pigs (Herkelman et al., 1990). In the present study, the variability among the treatment means was

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greater for the AID than the ATTD coefficients, contributing to less chance of treatment separation of AID coefficients. The greater AID, observed for unsaturated fatty acids compared with SFA, is consistent with previous research (Overland et al., 1993). Similar to ether extract, extrusion improved the AID of fatty acids in FP. Improved ether extract digestibility caused by extrusion is mainly due to the disruption of fat globules because of the shearing effect of the screw on the lipid structures, thereby providing easier access for lipase enzymes in the digestive tract (Hancock and Behnke, 2001). Single-screw extrusion of FP resulted in a greater AID for fatty acids than twin-screw extrusion, indicating that knowledge of the optimum extrusion equipment and conditions to achieve maximum digestibility of fatty acids is important (Serrano, 1997). Maximum shear stress to disrupt the lipid structures in the FP likely occurred with the single-screw extruder in the present study (Riaz, 2001), thereby explaining the greatest AID or ATTD for fatty acids and ether extract. Shear in the twin-screw extruder was further decreased in FP extruded using a twin-screw extruder at high intensity compared with FP extruded using a twin-screw extruder at low intensity. The difference was, perhaps, a reflection of the decreased screw torque because of extra water addition to FP extruded using a twin-screw extruder at high intensity, thereby decreasing the uplift in its fatty acid digestibility. Extent of both shear and processing temperature might, thus, be important to maximize digestibility of ether extract and fatty acids in FP. Based on our results, ground and single-screw-extruded FP can provide 54.9 and 61.3 g of digestible n-3 fatty acid/kg of FP for grower-finisher pigs, respectively.

In swine feed formulation, energy content is the greatest cost factor (Zijlstra et al., 2001). In the present study, extrusion increased energy digestibility, especially for single-screw extrusion. Single-screw extrusion increased the ATTD of GE by 11% and the DE content from 3.70 to 4.35 Mcal/kg (DM basis). Extrusion decreased the content of NDF in FP mixes in the present study, indicating that extrusion modifies the physicochemical properties of fiber via partial solubilization or degradation (Björck et al., 1984), an important finding because of the inverse relationship between fiber content and energy digestibility (Zijlstra et al., 1999). Extrusion improved the energy digestibility of cereal grains for grower pigs (Noland et al., 1976; Herkelman et al., 1990; O'Doherty and Keady, 2001) and FP mix for broiler chicken (Thacker et al., 2005). Extrusion processing improved the digestibility of the important energy-yielding nutrient, starch, in corn fed to piglets (Van der Poel et al., 1989). The effect of extrusion on digestibility of the energy-yielding nutrient with the greatest energy content (i.e., fat) was discussed previously. As a result of extrusion, the nutrient and fiber fractions might become more accessible to digestion or fermentation in the gastrointestinal tract, resulting in increased energy digestibility (Marty et al., 1994; O'Doherty and Keady, 2000). Twin-screw extrusion of FP compared with single-screw extrusion did not increase in the ATTD of GE, ether extract, and some fatty acids. Contributing factors to temperature and shear of the product during extrusion, such as water and steam input, temperature, screw speed, and pressure, should be carefully managed (Serrano, 1997) to ensure that excess processing is avoided.

The inclusion of a regular grower pig diet as a basal diet in the experiment allowed for comparisons between diets containing FP and a typical swine diet. The AID and ATTD of DM, OM, CP, and GE and the AID of the majority of AA and fatty acids and ether extract were greater in the basal diet that contained wheat and soybean meal than in the FP-containing diets. The decreased nutrient digestibility of diets containing FP is thus clearly an ingredient effect that might be due to antinutritional factors such as the greater fiber content in the raw FP mix (Madhusudhan et al., 1986; O'Doherty and Keady, 2000) that may increase digesta viscosity and lead to decreased nutrient digestibility (Bell and Keith, 1993). The negative effects, in particular for the digestibility of ether extract and fatty acids, and some AA, may be moderated by extruding the FP mix. Ground flax can be included up to 15% in pig diets without detrimental effects on growth performance (Romans et al., 1995a,b); however, data from the present study indicate that extrusion enhances nutrient digestibility of flax. Therefore, coextruded flax will be used in future experiments at our laboratories to study the effect of extruded flax on the n-3 fatty acid profile in pork.

In conclusion, extrusion of FP mix improved the digestibility of ether extract, energy, AA, and some fatty acids and thereby increased the content of DE and n-3 fatty acids. Extrusion technologies should be considered to optimize feeding programs for n-3-enriched pork. The extruded FP mix can be used as a source of energy and AA at the inclusion rate used in the present study.

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