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Effects of increasing co-product inclusion and reducing dietary protein on growth performance, carcass characteristics, and jowl fatty acid profile of growing–finishing pigs[1]

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ABSTRACT: Dietary inclusion of co-products (Co-P) provides opportunities for diversifying the feedstuff matrix by using local feedstuffs, reducing feed costs, and producing value-added pork. In 2 studies, we determined effects of Co-P (canola meal, distillers dried grains with solubles, and co-extruded oil seed and field pea) inclusion level and reduced dietary CP concentration on growth performance, carcass characteristics, and jowl fatty acid profiles of growing–finishing pigs. Pigs were fed isoenergetic and isolysinic diets over 4 growth phases with 8 pen observations per dietary regimen. At slaughter, carcasses were characterized for all pigs and jowl fat was collected from 2 pigs per pen. In Exp. 1, 1,056 pigs (initial BW, 35.3 ± 0.4 kg) were fed 3 levels of dietary Co-P (low, mid, and high) and 2 CP concentrations (low and normal). Overall (d 0 to 86), increasing Co-P inclusion from low to mid or high decreased ($P < 0.001$) ADFI and ADG of pigs. Low CP concentration increased ($P < 0.05$) ADFI and ADG compared with normal CP concentration. An interaction ($P = 0.026$) occurred between dietary Co-P inclusion and CP concentration for G:F; low CP reduced ($P < 0.05$) G:F compared with normal CP for pig fed low Co-P, but G:F did not differ between CP concentrations for pigs fed mid and high Co-P. Increasing dietary Co-P inclusion from low to high increased ($P < 0.001$) α-linolenic acid (ALA) in jowl fat but decreased ($P < 0.001$) carcass weight and loin depth. In Exp. 2, 1,008 pigs (initial BW, 30.3 ± 0.4 kg) were assigned to 5 dietary regimens with Co-P increasing from 2.0 to 50.0% or a sixth regimen with 10% extra supplemental AA for the 37.5% Co-P diet. Overall (d 0 to 97), increasing Co-P inclusion did not affect ADFI, ADG, and G:F. Increasing dietary Co-P inclusion linearly decreased ($P < 0.01$) carcass weight, dressing percentage, backfat thickness, and loin depth but linearly increased ($P < 0.001$) jowl ALA. Supplementing 10% extra AA to the 37.5% Co-P diet did not affect growth performance or dressing percentage but increased ($P = 0.014$) carcass leanness and decreased ($P = 0.023$) backfat thickness compared with the 37.5% Co-P diet, indicating that dietary AA supply did not limit BW gain. In conclusion, Co-P can be included by up to 50% in diets for growing–finishing pigs without affecting G:F. However, increasing dietary Co-P may reduce ADG, ADFI, and carcass weight even if diets are balanced for dietary NE and standardized ileal digestible AA content.

Key words: carcass trait, co-product, growth performance, net energy, pig

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INTRODUCTION

Canola meal, distillers dried grains with solubles (**DDGS**), and co-extruded oil seed and field pea, hereafter named co-products (**Co-P**), are alternatives to soybean meal and cereal grains. Increasing dietary Co-P may raise dietary CP because of their greater CP than cereal

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Table 1. Analyzed chemical composition and CP and indispensable AA predicted by near infrared reflectance spectroscopy of the ingredients used in experimental diets, Exp. 1 and 2[1]

Item, % as-fed	Hull-less barley	Barley	Corn DDGS	Corn:wheat DDGS[2]	LinPro[3]	ExtraPro[4]	Canola meal	Soybean meal
DM	88.1	88.0	90.5	88.0	88.0	88.0	88.0	88.0
CP	11.8	12.0	28.1	28.1	20.9	23.4	35.7	46.4
Ether extract	2.5	1.9	11.7	8.0	20.3	22.1	3.3	1.6
Crude fiber	3.6	6.0	8.7	7.1	5.4	12.8	11.7	4.9
NDF	13.9	18.7	27.6	39.8	13.5	19.8	23.3	12.4
ADF	5.1	7.0	10.1	11.1	7.8	16.0	17.8	7.4
Ash	2.1	2.3	5.2	4.9	3.7	4.8	7.3	6.2
Ca	0.04	0.04	0.07	0.11	0.16	0.24	0.65	0.26
P	0.34	0.34	0.74	0.85	0.43	0.54	1.00	0.64
Indispensable AA								
Arg	0.59	0.58	1.32	1.19	1.56	1.33	2.15	3.40
His	0.26	0.26	0.86	0.71	0.51	0.59	0.93	1.26
Ile	0.42	0.41	1.14	1.00	0.86	0.93	1.40	2.10
Leu	0.81	0.80	3.54	3.14	1.39	1.73	2.48	3.53
Lys	0.42	0.40	0.94	0.67	1.05	1.13	1.92	2.89
Met	0.20	0.19	0.59	0.52	0.31	0.36	0.70	0.64
Met + Cys	0.46	0.46	1.15	1.02	0.60	0.77	1.58	1.36
Phe	0.61	0.63	1.50	1.31	1.00	1.04	1.43	1.42
Thr	0.40	0.39	0.94	1.01	0.79	0.89	1.53	1.83
Trp	0.15	0.14	0.23	0.21	0.27	0.26	0.48	0.64
Val	0.59	0.57	1.50	1.33	1.01	1.14	1.80	2.22
Lys:CP, %	3.54	3.33	3.01	2.39	5.03	4.83	5.39	6.23

[1]DDGS = distillers dried grains with solubles.

[2]Corn:wheat DDGS was expected to contain 2.21 Mcal NE/kg and 0.41% available P (M. G. Young, unpublished data).

[3]Co-extruded full-fat flax seed and field pea (Oleet Processing Ltd., Regina, SK, Canada) was expected to contain 2.93 Mcal/kg NE and 0.20% available P (M. G. Young, unpublished data).

[4]Co-extruded full fat canola and field pea (Oleet Processing Ltd.) was expected to contain 3.35 Mcal/kg NE and 0.18% available P (M. G. Young, unpublished data).

grains (NRC, 1998). Reducing dietary CP concentration and simultaneously balancing for AA may counteract this increase (Htoo et al., 2007; Hermes et al., 2009).

Feeding Co-P originating from oilseeds may alter fatty acid profiles of pork fat. Flax seed is rich in α-linolenic acid (**ALA**) and its dietary inclusion increases pork omega-3 fatty acids (Cunnane et al., 1990; Romans et al., 1995a,b). Consumer demand for food containing omega-3 fatty acids has created opportunities for marketing such pork (Bourre, 2005); however, growth performance has not been quantified for flax seed Co-P in commercial-scale pork production.

Feed formulation using NE and standardized ileal digestible (**SID**) AA is one of the tools available to manage the risk of high inclusion of Co-P into swine diets (Zijlstra and Beltranena, 2013). Nonetheless, growth performance of pigs fed diets formulated to equal NE and SID AA with increasing inclusion of a single Co-P, expeller-pressed canola meal, was reduced (Seneviratne et al., 2010). Effects of increasing combinations of Co-P in diets on growth performance are not known.

The hypotheses were 1) increasing Co-P and reducing CP concentration by supplying extra crystalline AA in diets formulated to equal NE and SID AA will not affect growth performance and carcass characteristics of growing–finishing pigs and 2) increasing dietary flax seed co-extruded with field pea may increase omega-3 fatty acids in jowl fat and maintain growth performance and carcass characteristics. The aim of Exp. 1 was to study 2 levels of Co-P and reduced CP content. The aims of Exp. 2 were to study effects of gradually increasing dietary Co-P and extra AA supply to diets high in Co-P.

MATERIALS AND METHODS

The animal protocol was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care (CCAC, 1993).

Experimental Design and Diets

Co-extruded flax seed and field pea (50–50 mixture; **LinPro**) and co-extruded canola seed and field pea (50–50 mixture; **ExtraPro**) were obtained from a commercial source (Oleet Processing, Regina, SK, Canada). Co-

Table 2. Ingredient composition and calculated nutrient content of experimental diets (Grower 1 and 2), Exp. 1[1]

	Grower 1						Grower 2					
	Low CP			Normal CP			Low CP			Normal CP		
Item	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P
Ingredient, %												
Hull-less barley	77.34	40.15	33.02	67.11	47.60	32.96	82.14	40.02	40.38	72.05	48.89	33.97
LinPro[2]	–	20.00	20.00	–	20.00	20.00	–	20.00	20.00	–	20.00	20.00
Barley	–	16.57	16.60	–	–	–	–	19.71	9.36	–	1.61	–
Corn DDGS	–	10.00	20.00	–	10.00	30.00	–	–	–	–	–	–
Corn:wheat DDGS	–	–	–	–	–	–	–	10.00	20.00	–	10.00	30.00
ExtraPro[3]	–	–	–	–	–	2.28	–	–	–	–	–	3.34
Canola meal	8.00	8.00	7.93	8.00	8.00	12.43	8.00	8.00	8.00	8.00	8.00	10.54
Soybean meal	10.62	2.71	–	20.36	12.35	–	6.58	–	–	16.30	9.61	–
Limestone	1.14	1.17	1.24	1.11	1.14	1.34	1.10	1.16	1.27	1.06	1.19	1.40
Tallow	1.33	–	–	2.37	–	–	0.80	–	–	1.80	–	–
Salt	0.47	0.44	0.41	0.49	0.46	0.43	0.47	0.43	0.39	0.48	0.44	0.40
L-Lys HCl	0.40	0.40	0.45	0.12	0.12	0.32	0.40	0.36	0.36	0.12	0.08	0.21
Mono-dicalcium phosphate	0.31	0.19	–	0.24	0.13	0.08	0.14	–	–	–	–	–
L-Thr	0.13	0.11	0.10	0.05	–	–	0.12	0.08	0.03	–	–	–
Premix[4]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
$CuSO_4$	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
DL -Met	0.10	0.09	0.07	–	0.05	0.01	0.08	0.07	0.04	0.04	0.03	–
L-Trp	0.01	0.02	0.03	–	–	0.01	0.02	0.02	0.02	–	–	–
Phytase[5]	0.01	0.01	0.01	0.01	0.01	–	0.01	0.01	0.01	0.01	0.01	–
Calculated nutrient content, as-fed												
CP, %	16.9	18.6	19.5	19.9	21.6	22.5	15.6	17.7	19.5	18.6	20. 7	22.4
NDF, %	17.2	20.4	21.7	15.9	19.4	22.7	17.8	20.8	21.7	16.6	19.7	22.7
Ether extract, %	3.58	6.35	7.10	4.45	6.41	8.42	3.13	6.29	7.04	3.97	6.36	8.41
Ca, %	0.70	0.70	0.70	0.70	0.70	0.72	0.65	0.67	0.68	0.65	0.69	0.73
Available P, %	0.30	0.30	0.30	0.30	0.30	0.30	0.26	0.26	0.26	0.26	0.26	0.28
NE, Mcal/kg	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
SID Lys:NE, g/Mcal	4.00	4.00	4.00	4.00	4.00	4.00	3.63	3.63	3.63	3.63	3.63	3.63
SID Met:Lys	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.36
SID Thr:Lys	0.65	0.65	0.65	0.65	0.67	0.65	0.65	0.65	0.65	0.66	0.70	0.71
SID Trp:Lys	0.18	0.18	0.18	0.22	0.20	0.18	0.19	0.19	0.19	0.22	0.21	0.19

[1]Co-P = co-product; DDGS = distillers dried grains with solubles; SID = standardized ileal digestible.

[2]Co-extruded full-fat flax seed and field pea (Oleet Processing Ltd., Regina, SK, Canada).

[3]Co-extruded full fat canola and field pea (Oleet Processing Ltd.).

[4]Provided per kilogram of diet: Zn, 125 mg as ZnO; Fe, 100 mg as $FeSO_4$; Cu, 14 mg as $CuSO_4$; Mn, 25 mg as MnO; I, 0.3 mg as $Ca(IO_3)_2$; Se, 0.3 mg as Na_2SeO_3; vitamin A, 6,000 IU; vitamin D, 1,000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg; and vitamin B_{12}, 0.02 mg.

[5]Phyzyme XP 5000 (Danisco Animal Nutrition, Marlborough, UK). Provided 500 phytase units per kilogram of diet.

extruded flaxseed was selected because it has a greater digestibility of omega-3 fatty acids than ground flaxseed (Htoo et al., 2008). Corn DDGS and wheat–corn DDGS produced after co-fermentation of a 50–50 mixture of wheat and corn were obtained commercially (Husky Energy, Lloydminster, SK, Canada). The digestible nutrient profiles of LinPro and wheat/corn DDGS were reported previously (Htoo et al., 2008; Yáñez et al., 2011). Other feedstuffs were obtained via a commercial source and were of unknown origin (Table 1).

In Exp. 1, a 3 × 2 factorial arrangement of treatments was used to investigate effects of increasing dietary Co-P inclusion (low, less than 10% Co-P; mid, 35 to 45% Co-P; and high, 45 to 65% Co-P) and reducing dietary CP concentration (normal, CP content based on least-cost formulation without maximum limitation on CP content; and low, 3% reduction in CP achieved by inclusion of additional crystalline AA). Dietary CP was reduced 3% based on previous research (Zervas and Zijlstra, 2002) and was deemed to be achievable practically without reducing growth performance (Kerr et al., 1995). The resulting 6 diets were fed in 4 phases (Tables 2 and 3). The low Co-P inclusion diets did not include LinPro but up to 8% solvent-extracted canola meal, with

Table 3. Ingredient composition and calculated nutrient content of the experimental diets (Finisher 1 and 2), Exp. 1[1]

	Finisher 1						Finisher 2					
	Low CP			Normal CP			Low CP			Normal CP		
Item	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P
Ingredient, %												
Hull-less barley	87.06	37.32	34.60	76.62	41.66	35.30	85.70	25.90	18.62	80.62	42.84	35.32
Barley	–	22.71	15.46	–	7.22	–	5.97	39.36	35.25	–	8.70	3.59
LinPro[2]	–	20.00	20.00	–	20.00	20.00	–	20.00	20.00	–	20.00	20.00
Corn DDGS	–	10.00	20.00	–	15.00	30.00	–	10.00	23.00	–	15.00	30.00
Canola meal	8.00	8.00	8.00	8.00	8.00	12.35	6.19	2.82	1.17	10.00	10.00	9.14
Soybean meal	2.52	–	–	12.28	6.33	–	–	–	–	6.56	1.67	–
Limestone	1.01	1.11	1.22	1.02	1.18	1.32	1.03	1.12	1.26	0.99	1.21	1.38
Salt	0.46	0.44	0.40	0.48	0.46	0.43	0.45	0.43	0.40	0.47	0.45	0.42
L-Lys HCl	0.40	0.25	0.22	0.12	0.05	0.12	0.40	0.23	0.22	0.15	0.05	0.07
Tallow	0.25	–	–	1.35	–	0.38	–	–	–	1.11	–	–
Premix[3]	0.10	0.10	0.10	0.10	0.10	0.10	0.08	0.08	0.08	0.08	0.08	0.08
DL-Met	0.07	0.04	–	0.02	–	–	0.06	0.03	–	0.01	–	–
L-Thr	0.11	0.02	–	–	–	–	0.10	0.02	–	–	–	–
L-Trp	0.01	–	–	0.01	–	–	0.01	–	–	–	–	–
Phytase[4]	0.01	0.01	–	–	–	–	0.01	0.01	–	0.01	–	–
Calculated nutrient content, as-fed												
CP, %	14.3	17.5	19.2	17.2	20.3	22.0	12.9	16.2	18.1	15.8	19.2	21.2
NDF, %	18.4	20.9	21.8	17.1	20.6	22.9	18.7	20.6	22.0	17.9	21.5	23.0
Ether extract, %	2.66	6.34	7.13	3.59	6.77	8.37	2.38	6.14	7.10	3.45	6.83	7.97
Ca, %	0.60	0.63	0.63	0.61	0.64	0.70	0.57	0.58	0.59	0.57	0.63	0.69
Available P, %	0.24	0.24	0.24	0.24	0.24	0.28	0.21	0.21	0.22	0.21	0.22	0.26
NE, Mcal/Kg	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
SID Lys:NE, g/Mcal	3.25	3.25	3.25	3.25	3.25	3.25	2.92	2.92	2.92	2.92	2.92	2.92
SID Met:Lys	0.35	0.35	0.35	0.35	0.36	0.41	0.35	0.35	0.35	0.35	0.39	0.44
SID Thr:Lys	0.65	0.65	0.68	0.67	0.76	0.79	0.65	0.65	0.69	0.67	0.78	0.84
SID Trp:Lys	0.18	0.18	0.18	0.22	0.22	0.20	0.18	0.18	0.18	0.22	0.22	0.21

[1]Co-P = co-product; DDGS = distillers dried grains with solubles; SID = standardized ileal digestible.

[2]Co-extruded full-fat flax seed and field pea (Oleet Processing Ltd., Regina, SK, Canada).

[3]Provided per kilogram of Finisher 1 diet: Zn, 125 mg as ZnO; Fe, 100 mg as $FeSO_4$; Cu, 14 mg as $CuSO_4$; Mn, 25 mg as MnO; I, 0.3 mg as $Ca(IO_3)_2$; Se, 0.3 mg as Na_2SeO_3; vitamin A, 6,000 IU; vitamin D, 1,000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg; and vitamin B_{12}, 0.02 mg. For the Finisher 2 diets, the amounts are 80% of the Finisher 1 diet.

[4]Phyzyme XP 5000 (Danisco Animal Nutrition, Marlborough, UK). Provided 500 phytase units per kilogram of diet.

the balance of supplemental dietary protein originating from soybean meal. The mid Co-P diets contained 20% LinPro to meet the required threshold of ALA in jowl fat to market omega-3 fatty acid pork (Juárez et al., 2010); the high Co-P inclusion diets contained 20% LinPro and did not contain soybean meal. Hull-less barley was replaced with Co-P and barley.

In Exp. 2, the effects of increasing dietary inclusion of Co-P (2.0, 12.5, 25.0, 37.5, and 50.0%) and 37.5% Co-P added with 10% extra of Lys, Thr, Met, and Trp (37.5% Co-P + 10%, AA) were tested by feeding 6 experimental diet regimens in a completely randomized design (Tables 4 and 5). Based on data from Exp. 1, which indicated reduced growth performance at mid (35 to 45%) dietary Co-P inclusion, 10% extra of the first 4 limiting AA were added to ensure that our feed quality evaluation and feed formulation methods did not inadvertently cause a deficiency for those indispensable AA. Five of the 6 diets were formulated to linearly increase dietary Co-P with a fixed ratio of LinPro, canola meal, and DDGS (1.5:1.0:2.5) by replacing wheat and soybean meal.

Both pig performance studies were conducted as 4 growth phases. Diets were formulated to be isoenergetic (NE) and equal in SID Lys within growth phase. For feed formulation, the NE values for feedstuffs were obtained from Sauvant et al. (2004) and the SID AA val-

Table 4. Ingredient composition and calculated nutrient content of Grower 1 and Grower 2 diets, Exp. 2[1]

	Grower 1 diet						Grower 2 diet					
	Co-P level, %						Co-P level, %					
Item	2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA	2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA
Ingredient, %												
Hull-less barley	45.47	47.24	40.01	41.40	47.33	41.99	49.99	49.99	44.55	26.17	12.76	24.51
Barley	–	–	–	–	–	–	7.21	18.25	26.54	33.86	34.92	35.32
Wheat	36.18	27.94	26.29	15.87	–	15.03	30.41	11.54	–	–	–	–
Soybean meal	12.18	8.78	5.65	2.51	–	2.52	7.58	4.94	1.20	–	–	–
Canola meal	2.00	2.50	5.00	7.50	10.00	7.50	2.00	2.50	5.00	7.50	10.00	7.50
LinPro[2]	–	5.00	10.00	15.00	20.00	15.00	–	5.00	10.00	15.00	20.00	15.00
Corn DDGS	–	5.00	10.00	15.00	20.00	15.00	–	5.00	10.00	15.00	20.00	15.00
Limestone	1.33	1.34	1.33	1.31	1.32	1.33	1.26	1.25	1.25	1.30	1.34	1.30
Tallow	1.16	0.57	0.21	–	–	–	–	–	–	–	–	–
Salt	0.49	0.47	0.46	0.44	0.42	0.44	0.48	0.45	0.43	0.42	0.42	0.42
L-Lys HCl	0.46	0.48	0.50	0.50	0.48	0.60	0.46	0.48	0.50	0.45	0.37	0.55
Mono-dicalcium phosphate	0.29	0.26	0.17	0.13	0.15	0.13	0.19	0.19	0.15	–	–	–
L-Thr	0.16	0.16	0.14	0.12	0.10	0.18	0.15	0.14	0.13	0.08	0.02	0.14
DL-Met	0.11	0.09	0.07	0.05	0.03	0.09	0.11	0.10	0.08	0.06	0.02	0.08
Premix[3]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
$CuSO_4$	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
L-Trp	0.02	0.02	0.02	0.02	0.02	0.04	0.01	0.02	0.02	0.01	–	0.03
Phytase[4]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Calculated nutrient content, as-fed												
CP, %	16.3	16.8	17.9	18.8	19.9	19.0	14.8	15.3	16.0	17.7	19.8	17.8
NDF, %	14.3	15.5	16.4	17.8	19.4	17.8	15.9	17.5	18.7	19.2	19.5	19.1
Ca, %	0.70	0.70	0.70	0.70	0.72	0.71	0.65	0.65	0.66	0.68	0.70	0.68
P, %	0.54	0.55	0.57	0.59	0.62	0.59	0.51	0.53	0.55	0.57	0.58	0.56
Available P, %	0.30	0.30	0.30	0.30	0.31	0.30	0.27	0.27	0.27	0.27	0.27	0.27
NE, Mcal/kg	2.40	2.40	2.40	2.40	2.40	2.40	2.35	2.35	2.35	2.35	2.35	2.35
SID[1] Lys:NE, g/Mcal	3.96	3.96	3.96	3.96	3.96	4.29	3.62	3.62	3.62	3.62	3.62	3.96
SID Met:Lys	0.34	0.34	0.34	0.34	0.34	0.35	0.36	0.36	0.36	0.36	0.36	0.36
SID Thr:Lys	0.66	0.66	0.66	0.66	0.66	0.66	0.65	0.65	0.65	0.65	0.65	0.65
SID Trp:Lys	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.20	0.19

[1]Co-P = co-product; DDGS = distillers dried grains with solubles; SID = standardized ileal digestible.

[2]Co-extruded full-fat flax seed and field pea (Oleet Processing Ltd., Regina, SK, Canada).

[3]Provided per kilogram of diet: Zn, 125 mg as ZnO; Fe, 100 mg as $FeSO_4$; Cu, 14 mg as $CuSO_4$; Mn, 25 mg as MnO; I, 0.3 mg as $Ca(IO_3)_2$; Se, 0.3 mg as Na_2SeO_3; vitamin A, 6,000 IU; vitamin D, 1,000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg; and vitamin B_{12}, 0.02 mg.

[4]Phyzyme XP 5000 (Danisco Animal Nutrition, Marlborough, UK). Provided 500 phytase units per kilogram of diet.

ues from NRC (1998). The NE values for corn:wheat DDGS, LinPro, and ExtraPro were predicted by an equation (Eq. [4]; Noblet et al., 1994) and the available P for corn:wheat DDGS was assumed similar to corn DDGS and for LinPro and ExtraPro was provided by the manufacturer (Table 1). The CP and indispensable AA content of ingredients was predicted by near infrared reflectance spectroscopy (Evonik Industries AG, Hanau, Germany), and resulting values were used in the actual diet formulations (Table 1). In Exp. 1, all diets were formulated to contain 2.40 Mcal NE/kg. In Exp. 2, the NE content of diets decreased gradually from 2.40 Mcal NE/kg in Grower 1 to 2.30 Mcal NE/kg in Finisher 1 and 2 to provide additional challenge for pigs to maintain their energy intake on diets containing high levels of Co-P. Beyond Lys, other indispensable AA were formulated in an ideal ratio to SID Lys (NRC, 1998). The main cereal grains were wheat, barley, and hull-less barley. Diets

Table 5. Ingredient composition and calculated nutrient content of Finisher 1 and Finisher 2 diets, Exp. 2[1]

	Finisher 1 diet						Finisher 2 diet					
	Co-P level, %						Co-P level, %					
Item	2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA	2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA
Ingredient, %												
Barley	52.40	55.12	52.62	41.10	29.90	41.81	61.43	64.37	53.21	41.95	30.86	42.34
Wheat	37.06	26.38	20.00	19.19	17.99	18.29	31.73	20.91	19.75	18.63	17.28	18.12
Soybean meal	6.08	3.61	–	–	–	–	2.57	–	–	–	–	–
Canola meal	2.00	2.50	5.00	7.50	10.00	7.50	2.00	2.50	5.00	7.50	10.00	7.50
LinPro[2]	–	3.75	7.50	11.25	15.00	11.25	–	3.75	7.50	11.25	15.00	11.25
Corn DDGS	–	6.25	12.50	18.75	25.00	18.75	–	6.25	12.50	18.75	25.00	18.75
Limestone	1.21	1.21	1.24	1.30	1.35	1.30	1.12	1.12	1.15	1.20	1.26	1.20
Salt	0.53	0.49	0.46	0.43	0.41	0.43	0.52	0.48	0.46	0.43	0.41	0.43
L-Lys HCl	0.39	0.40	0.42	0.33	0.24	0.43	0.37	0.39	0.30	0.21	0.12	0.30
L-Thr	0.14	0.12	0.11	0.04	–	0.10	0.12	0.11	0.04	–	–	0.03
Premix[3]	0.10	0.10	0.10	0.10	0.10	0.10	0.07	0.07	0.07	0.07	0.07	0.07
DL-Met	0.08	0.06	0.04	–	–	0.03	0.06	0.04	0.01	–	–	–
Phytase[4]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	–	0.01
Calculated nutrient content, as-fed												
CP, %	14.3	15.1	16.0	18.1	20.3	18.3	13.0	13.7	15.9	18.0	20.2	18.1
NDF, %	15.6	18.0	20.4	22.2	24.0	22.2	5.8	18.7	20.5	22.3	24.1	22.3
Ca, %	0.60	0.60	0.61	0.64	0.67	0.64	0.55	0.55	0.57	0.59	0.62	0.59
Available P, %	0.24	0.24	0.24	0.24	0.24	0.24	0.22	0.22	0.22	0.22	0.22	0.22
NE, Mcal/kg	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
SID Lys:NE, g/Mcal	3.22	3.22	3.22	3.22	3.22	3.57	2.83	2.83	2.83	2.83	2.83	3.13
SID Met:Lys	0.35	0.35	0.35	0.35	0.40	0.35	0.35	0.35	0.36	0.40	0.46	0.36
SID Thr:Lys	0.70	0.70	0.70	0.70	0.73	0.70	0.70	0.70	0.70	0.74	0.84	0.70
SID Trp:Lys	0.19	0.19	0.19	0.22	0.24	0.19	0.19	0.19	0.22	0.25	0.27	0.22

[1]Co-P = co-product; DDGS = distillers dried grains with solubles; SID = standardized ileal digestible.

[2]Co-extruded full-fat flax seed and field pea (Oleet Processing Ltd., Regina, SK, Canada).

[3]Provided per kilogram of Finisher 1 diet: Zn, 125 mg as ZnO; Fe, 100 mg as $FeSO_4$; Cu, 14 mg as $CuSO_4$; Mn, 25 mg as MnO; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as Na_2SeO_3; vitamin A, 6,000 IU; vitamin D, 1,000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg; and vitamin B_{12}, 0.02 mg. For the Finisher 2 diets, the amounts are 70% of the Finisher 1 diet.

[4]Phyzyme XP 5000 (Danisco Animal Nutrition, Marlborough, UK). Provided 500 phytase units per kilogram of diet.

were fortified with premixes to meet the mineral and vitamin requirements of growing–finishing pigs (NRC, 1998).

Experimental Procedures

The 2 experiments were conducted sequentially (Drumloche Test Barn Farm, Lougheed, AB; Alberta Pig Company, Sherwood Park, AB, Canada). Pigs used were the progeny of Duroc sires (Designed Genetics Inc., Lockport, MB, Canada) × Large White/Landrace dams (Line 277; Fast Pigs, Saskatoon, SK, Canada). The facility, management, and vaccination program were described previously (Seneviratne et al., 2010).

In Exp. 1, 1,056 pigs (528 barrows and 528 gilts) with an initial age of 74 d and BW of 35.3 ± 0.4 kg were used. Pigs were randomly allotted within sex to 24 pens with 22 pigs per pen for a total of 48 pens, and pens were blocked by initial BW.

In Exp. 2, 1,008 cross bred pigs (504 barrows and 504 gilts) with an initial age of 65 d and average BW of 30.3 ± 0.4 kg were used. Pigs were randomly allotted within sex to 24 pens with 21 pigs per pen for a total of 48 pens, and pens were blocked by initial BW.

In both studies, the 6 experimental diet regimens were randomly allocated to pen within sex and block with a total of 8 pens per dietary regimen. After arrival, pigs were fed a pregrower diet during a 5-d acclamation period and were then switched to experimental diets. The test diets were fed as 4 phases with phase 1, 2, 3, and 4 ending on d 13, 38, 59, and 86 for Exp. 1 and d 19, 38, 60, and 97 for Exp. 2, respectively.

In Exp. 1, pigs were weighed as pen groups at the start of feeding the test diets (d 0) and on d 14, 28, 42, 56, 62, 75, 82, and 97. Pig BW was estimated for d 13, 38, 59, and 86 (by extrapolating ADG from actual weigh days) to associate growth performance of pigs with the 4 feeding phases. In Exp. 2, pigs were weighed at the start of feeding the test diets (d 0) and on d 8, 20, 34, 50, 62, 75, and 89. Pig BW was estimated for d 19, 38, 60, and 97 (by extrapolating ADG from actual weigh days) to associate growth performance of pigs with the 4 feeding phases.

Using a robotic feed delivery system (Feed Logic Co., Willmar, MN), feed dropped in each pen feeder was electronically weighed and tracked. Feed remaining in the pen feeder was determined at the end of each growth phase by measuring leveled feed remaining in the hopper multiplied by diet bulk density, which resulted in a maximum feed weight error of 0.1% (Seneviratne et al., 2010). If a pig died or had to be removed from a study, this pig and the remaining pigs in the pen were weighed, so that feed consumed could be matched with number of pigs and BW changes within a growth phase. Collected data were used to calculate ADG, ADFI, and G:F for each growth phase and the overall trial.

In both studies, pigs were fed the phase 4 diets until reaching the predetermined market weight (118 kg). The fastest growing pigs reached market weight on d 86 for Exp. 1 and d 97 for Exp. 2. Pigs were slaughtered at a commercial slaughter facility (Britco Pork Inc., Langley, BC, Canada). The warm pig carcasses were graded for backfat and loin depth using a light-reflectance probe (Destron PG-100; Destron Technologies, Markham, ON, Canada) between the third and fourth last ribs, 7 cm off the midline. The lean percentage of the carcass was calculated using the equation developed for the Canadian Pork Council (CPC, 1994):

$$\text{Lean (\%)} = 68.1863 - 0.7833 \times \text{Fat (mm)} + 0.0689 \times \text{Lean (mm)} + 0.0008 \times \text{Fat} \times \text{Fat} - 0.0002 \times \text{Lean} \times \text{Lean} + 0.0006 \times \text{Fat} \times \text{Lean}.$$

Chemical Analyses

Ingredients were analyzed at a commercial laboratory for DM (method 930.15), ether extract (method 920.39A), crude fiber (method 978.10), ADF (method 973.18), ash (method 942.05), Ca (method 968.08), and P (method 946.06), using AOAC International (AOAC, 2006) methods, and NDF (Holst, 1973).

Jowl tissue was collected at slaughter from 2 randomly selected pigs per pen, 1 pig each from the first 2 wk of pigs being shipped for slaughter. The tissue was dissected free of skin and meat before grinding and homogenization. Then equal weights of the 2 samples per pen were pooled for a total of 8 pen samples per dietary regimen. Jowl fat was analyzed for fatty acid content using gas chromatography (method 996.06; AOAC, 2006). The profile of fatty acids was calculated as follows (Benz et al., 2010):

Total SFA = C8:0 + C10:0 + C12:0 + C14:0 + C16:0 + C17:0 + C18:0 + C20:0 + C22:0 + C24:0.

Total MUFA = C14:1 + C16:1 + C18:1 cis-9 + C18:1n-7 + C20:1 + C24:1.

Total PUFA = C18:2n-6 + C18:3n-3 + C18:3n-6 + C20:2 + C20:4n-6.

Unsaturated fatty acid (**UFA**):SFA ratio = (total MUFA + total PUFA)/total SFA.

PUFA:SFA ratio = total PUFA/total SFA.

The iodine value of jowl fat was calculated using this equation (AOCS, 1998):

C16:1 (0.95) + C18:1 (0.86) + C18:2 (1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1 (0.723).

Statistical Analyses

Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC) with pen as the experimental unit. Block was the random effect in the model, and period was the repeated term for analyses of growth performance variables. Initial pen BW of pig was used as a covariate for analyses of growth performance data. Warm carcass weight was used as a covariate for analyses of carcass characteristics. Differences were considered significant if $P < 0.05$.

In Exp. 1, the model included the main effects of increasing dietary Co-P inclusion, reducing CP concentration, sex, and interactions. Preplanned contrasts compared low vs. mid and low vs. high Co-P. When an interaction between Co-P and CP was significant, means were separated using the Tukey means test. In Exp. 2, the model included the main effect of increasing dietary Co-P inclusion and sex. Linear and quadratic effects of dietary Co-P inclusion were tested using the 5 diets with regular dietary AA content. In Exp. 2, a preplanned contrast compared effects of feeding diets with 37.5% Co-P inclusion with and without 10% extra AA.

RESULTS

In Exp. 1, 3.9% of pigs and 2.8% of pigs in Exp.2 did not complete the study and were excluded from analyses. For both studies, the number of removals and deaths did not differ among dietary regimens. The Lys:CP of the selected feedstuffs was at least 3.0 except for corn:wheat

Table 6. Effect of dietary co-product inclusion and CP concentration on growth performance of pigs by feeding phase and the entire trial (d 0 to 86), Exp. 1[1,2]

	Low CP			Normal CP				*P*-value			
									Co-P		
Item	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	SEM	CP	Low vs. Mid	Low vs. High	CP × Co-P
BW, kg											
d 0	35.3	35.4	35.4	35.4	35.4	35.4	0.4	0.804	0.823	0.931	0.984
d 13	49.5	48.5	48.4	49.3	48.4	47.6	0.5	0.022	<0.001	<0.001	0.223
d 38	74.9	71.8	71.8	74.5	71.5	69.8	0.8	0.004	<0.001	<0.001	0.069
d 59	95.0^{a}	90.3^{b}	90.1^{b}	94.2^{a}	90.1^{b}	87.2^{c}	0.8	0.001	<0.001	<0.001	0.022
d 86	119.4	114.0	114.2	119.1	113.7	111.5	1.1	0.037	<0.001	<0.001	0.115
ADG, kg											
d 0 to 13	1.09	1.01	1.00	1.08	1.00	0.94	0.02	0.022	<0.001	<0.001	0.185
d 14 to 38	1.06	0.97	0.98	1.05	0.96	0.93	0.02	0.010	<0.001	<0.001	0.113
d 39 to 59	1.00	0.92	0.91	0.98	0.93	0.87	0.02	0.105	<0.001	<0.001	0.172
d 60 to 86	0.90	0.88	0.90	0.92	0.88	0.90	0.02	0.652	0.029	0.307	0.796
d 0 to 86	1.01	0.94	0.94	1.00	0.94	0.91	0.01	0.025	<0.001	<0.001	0.095
ADFI, kg											
d 0 to 13	2.38^{a}	2.05^{bc}	2.04^{bc}	2.15^{b}	2.02^{bc}	1.96^{c}	0.04	<0.001	<0.001	<0.001	0.001
d 14 to 38	2.80	2.59	2.53	2.72	2.50	2.39	0.06	<0.001	<0.001	<0.001	0.562
d 39 to 59	3.19	2.96	2.90	3.01	2.89	2.85	0.08	<0.001	<0.001	<0.001	0.052
d 60 to 86	3.16	3.02	3.05	3.10	3.07	2.97	0.07	0.201	0.004	<0.001	0.075
d 0 to 86	2.93	2.72	2.70	2.81	2.69	2.61	0.06	<0.001	<0.001	<0.001	0.092
G:F											
d 0 to 13	0.459^{b}	0.494^{a}	0.491^{a}	0.500^{a}	0.500^{a}	0.481^{ab}	0.008	0.042	0.021	0.288	<0.001
d 14 to 38	0.379	0.375	0.385	0.385	0.387	0.387	0.004	0.016	0.657	0.208	0.326
d 39 to 59	0.316^{ab}	0.313^{ab}	0.316^{ab}	0.329^{a}	0.322^{ab}	0.306^{b}	0.007	0.210	0.278	0.010	0.025
d 60 to 86	0.286	0.292	0.294	0.299	0.286	0.303	0.007	0.193	0.405	0.205	0.147
d 0 to 86	0.343^{b}	0.345^{b}	0.348^{ab}	0.356^{a}	0.348^{ab}	0.347^{ab}	0.005	0.028	0.196	0.446	0.026

[a–d]Within a row, means without a common superscript differ ($P < 0.05$).

[1]Co-P = co-product.

[2]Grower 1: d 0 to 13; Grower 2: d 14 to 38; Finisher 1: d 39 to 59; Finisher 2: d 60 to 86. Least-squares means based on 8 pen observations (22 pigs) per diet.

DDGS (Table 1). For Exp. 1, only the main dietary factors and their interaction are presented. For both studies, interactions between dietary treatments and sex were not significant for growth performance, carcass characteristics, and jowl fatty acid profiles; therefore, combined data for gilts and barrows are presented.

Experiment 1

Growth Performance. Increasing dietary Co-P inclusion from low to mid and high reduced ($P < 0.001$; Table 6) pig BW on d 13, 38, and 86. Reducing CP concentration increased ($P < 0.001$) pig BW on d 13, 38, and 86. An interaction ($P < 0.05$) occurred between increasing Co-P inclusion and reducing CP concentration on d 59 in that low, compared with normal CP concentration, reduced BW for high Co-P inclusion but not for low and mid Co-P inclusion.

Increasing dietary Co-P inclusion from low to mid and high reduced ($P < 0.001$; Table 6) ADG for d 0 to 13, 14 to 38, and 39 to 59 and for the entire study (d 0 to 86). Reducing CP concentration increased ($P < 0.05$) ADG for d 0 to 13 and 14 to 38 and for the entire study.

Increasing dietary Co-P inclusion from low to mid and high reduced ($P < 0.01$; Table 6) ADFI for d 14 to 38, 39 to 59, and 60 to 86 and for the entire study. Reducing dietary CP concentration increased ($P < 0.001$) ADFI for d 14 to 38 and 39 to 59 and for the entire study. An interaction ($P < 0.05$) occurred between increasing dietary Co-P inclusion and reducing CP concentration for d 0 to 13 because low compared with normal CP concentration increased ADFI for low Co-P inclusion but not for mid and high Co-P inclusion.

For G:F, an interaction ($P < 0.05$; Table 6) occurred between increasing dietary Co-P inclusion and reducing CP concentration for d 0 to 13 and 39 to 59 and for the entire study. For the entire study, low CP resulted in a reduced ($P < 0.05$) G:F compared with normal CP for low Co-P, but G:F did not differ between CP concentrations for mid and high Co-P. Increasing Co-P inclusion from low to high increased ($P < 0.05$) G:F for d 39 to 59.

Table 7. Effect of dietary co-product inclusion level and CP concentration on carcass characteristics and days after d 86 required for pigs to reach slaughter weight, Exp. 1[1,2]

	Low CP			Normal CP				*P*-value			
									Co-P		
Item	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	SEM	CP	Low vs. Mid	Low vs. High	CP × Co-P
Days to slaughter[3]	30.9[c]	35.5[b]	36.0[b]	31.7[c]	36.8[b]	38.6[a]	0.6	<0.001	<0.001	<0.001	0.029
Carcass weight, kg	94.8[a]	92.9[b]	92.5[b]	95.0[a]	92.6[b]	91.6[c]	0.3	0.019	<0.001	<0.001	0.005
Dressing,[4] %	78.3	77.2	77.0	78.3	76.9	76.5	0.1	<0.001	<0.001	<0.001	0.125
Backfat,[4] mm	20.2[a]	19.8[a]	19.6[a]	18.7[b]	19.5[a]	19.9[a]	0.2	<0.001	0.203	0.207	<0.001
Loin depth,[4] mm	63.6[b]	62.7[bc]	62.0[cd]	64.6[a]	62.2[cd]	61.5[d]	0.4	0.795	<0.001	<0.001	<0.001
Estimated lean,[4] %	60.1[b]	60.2[b]	60.3[b]	60.8[a]	60.3[b]	60.1[b]	0.1	0.002	0.027	0.017	<0.001

[a–d]Within a row, means without a common superscript differ ($P < 0.05$).

[1]Co-P = co-product.

[2]Least-squares means based on 8 pen observations (22 pigs) per diet.

[3]Pen average number of days from d 86 until slaughter.

[4]Warm carcass weight used as a covariate.

Carcass Characteristics. An interaction ($P < 0.05$; Table 7) occurred between increasing dietary Co-P inclusion and reducing CP concentration for days to slaughter, carcass weight, backfat thickness, loin depth, and estimated lean percentage. Reducing CP concentration reduced ($P < 0.05$) days to slaughter and increased ($P < 0.05$) carcass weight for high Co-P but not for low and mid Co-P inclusion. Reducing CP concentration increased ($P < 0.05$) backfat thickness and reduced ($P < 0.05$) loin depth and lean percentage for low Co-P but not for mid and high Co-P inclusion. Increasing dietary Co-P inclusion from low to mid and from low to high reduced ($P < 0.001$) dressing percentage. Low CP concentration ($P < 0.001$) increased dressing percentage.

Fatty Acid Profile. An interaction ($P < 0.05$; Table 8) occurred between increasing dietary Co-P and reducing dietary CP for most jowl fatty acids, totals fatty acids, ratios, and iodine value. For example, increasing Co-P inclusion from low to high increased ($P < 0.05$) ALA, total PUFA, omega-3 fatty acids, and iodine value for both CP concentrations, but increasing Co-P inclusion from low to mid increased ($P < 0.05$) ALA, total PUFA, and iodine value only for low CP concentration.

Experiment 2

Growth Performance. Increasing dietary Co-P inclusion linearly reduced ($P < 0.05$; Table 9) pig BW at d 19, 38, and 60. Increasing Co-P inclusion linearly reduced ($P < 0.05$) ADG for d 0 to 19 and 20 to 38. Increasing Co-P inclusion linearly reduced ($P < 0.01$) ADFI from d 0 to 19 and 20 to 38. Adding 10% AA to the 37.5% Co-P diet did not affect pig BW, ADG, or ADFI at any time point. Increasing Co-P inclusion did not affect G:F. Adding 10% AA to the 37.5% Co-P diet did not change G:F for d 0 to 97.

Carcass Characteristics. Increasing dietary Co-P inclusion quadratically ($P < 0.05$; Table 10) increased days to reach slaughter weight and linearly decreased ($P < 0.05$) carcass weight, dressing percentage, backfat thickness, and loin depth but did not affect estimated lean percentage. Adding 10% AA to the 37.5% Co-P diet decreased ($P < 0.05$) backfat and increased ($P < 0.05$) lean percentage.

Fatty Acid Profile. Increasing dietary Co-P inclusion quadratically reduced ($P < 0.05$; Table 11) 18:0 stearic acid and UFA:SFA ratio and linearly increased ($P < 0.05$) jowl ALA, total PUFA, and iodine value and linearly decreased ($P < 0.05$) total SFA. Specifically, increasing dietary Co-P inclusion from 2 to 50% increased ($P < 0.001$) jowl ALA linearly from 3.61 to 7.82%. Adding 10% AA to the 37.5% Co-P diet did not affect fatty acid profile or iodine value.

DISCUSSION

Two experiments were conducted to study the effects of increasing dietary Co-P inclusion and differing CP concentration, a gradual increase of dietary Co-P inclusion with additional AA supplied at a high dietary Co-P inclusion, on growth performance, carcass characteristics, and jowl fatty acid profile of pigs. The results indicated that pigs can be fed diets with considerable quantities of Co-P (up to 50%) at the expense of a slight reduction in ADFI and ADG. Increasing dietary Co-P inclusion consistently reduced carcass weight. Quality of the Co-P may influence pig responses. In the present study, the minimal Lys:CP of 3.0 for cereal grains and their Co-P indicated that protein or Lys quality of these feedstuffs was high, except for the corn:wheat DDGS that was used for 1 phase in Exp. 1 (Fontaine et al., 2007).

Table 8. Effect of dietary co-product inclusion level and CP concentration on jowl fatty acid profile and calculated iodine value, Exp. 1[1,2]

	Low CP			Normal CP				*P*-value			
									Co-P		
Item	Low Co-P	Mid Co-P	High Co-P	Low Co-P	Mid Co-P	High Co-P	SEM	CP	Low vs. Mid	Low vs. High	CP × Co-P
Fatty acid, %											
10:0 Capric	0.100^{bc}	0.093^{cd}	0.085^{d}	0.106^{ab}	0.114^{a}	0.092^{cd}	0.005	<0.001	0.925	<0.001	0.007
12:0 Lauric	0.083^{a}	0.078^{b}	0.076^{b}	0.085^{a}	0.084^{a}	0.076^{b}	0.002	0.006	0.008	<0.001	0.014
14:0 Myristic	1.34^{a}	1.26^{b}	1.26^{b}	1.36^{a}	1.32^{a}	1.21^{b}	0.03	0.080	0.025	<0.001	0.005
16:0 Palmitic	21.41^{a}	19.48^{c}	19.80^{bc}	21.16^{a}	20.79^{ab}	18.86^{c}	0.49	0.876	<0.001	<0.001	<0.001
16:1 Palmitoleic	2.34	2.06	2.09	2.45	2.30	2.06	0.08	0.033	<0.001	<0.001	0.080
18:0 Stearic	9.71^{a}	8.77^{b}	8.77^{b}	9.03^{b}	9.16^{b}	8.15^{c}	0.23	<0.001	<0.001	<0.001	<0.001
18:1 Oleic	2.88^{a}	2.50^{c}	2.61^{bc}	3.02^{a}	2.81^{ab}	2.58^{bc}	0.12	0.011	<0.001	<0.001	0.033
18:2 Linoleic	11.67^{d}	14.07^{bc}	14.60^{ab}	12.30^{d}	12.90^{cd}	15.88^{a}	0.59	0.380	<0.001	<0.001	0.001
18:3 α-Linolenic	4.47^{c}	9.27^{a}	8.41^{ab}	5.22^{c}	6.64^{bc}	9.26^{a}	1.04	0.461	<0.001	<0.001	0.002
20:0 Arachidic	0.154^{ab}	0.145^{bc}	0.140^{c}	0.148^{bc}	0.160^{a}	0.140^{c}	0.003	0.240	0.533	<0.001	0.002
20:1 Gadoleic	0.82^{a}	0.72^{cd}	0.69^{d}	0.78^{ab}	0.75^{bc}	0.67^{d}	0.02	0.366	<0.001	<0.001	0.022
20:2 Dihono-γ-linolenic	0.52^{c}	0.59^{ab}	0.56^{ab}	0.51^{c}	0.54^{bc}	0.61^{a}	0.02	0.569	<0.001	<0.001	0.004
20:3 Podocarpic	0.076^{a}	0.071^{c}	0.073^{bc}	0.071^{c}	0.075^{ab}	0.070^{ab}	0.001	0.804	0.575	0.394	<0.001
20:3 Eicosatrienoic	0.076^{a}	0.071^{b}	0.073^{ab}	0.071^{b}	0.075^{ab}	0.073^{ab}	0.001	0.397	0.575	0.394	<0.001
Total SFA	32.79^{a}	29.82^{c}	30.13^{bc}	31.89^{a}	31.65^{ab}	28.53^{c}	0.72	0.504	<0.001	<0.001	<0.001
Total MUFA	44.85^{a}	40.48^{cd}	40.44^{cd}	44.16^{ab}	42.32^{bc}	39.81^{d}	0.91	0.677	<0.001	<0.001	0.018
Total PUFA	17.47^{c}	25.19^{a}	24.74^{ab}	18.87^{c}	21.12^{bc}	26.97^{a}	1.78	0.852	<0.001	<0.001	0.002
UFA:SFA	1.93^{c}	2.23^{ab}	2.21^{b}	2.00^{c}	2.03^{c}	2.39^{a}	0.08	0.607	<0.001	<0.001	<0.001
PUFA:SFA	0.56^{b}	0.87^{a}	0.86^{a}	0.62^{b}	0.69^{b}	0.99^{a}	0.08	0.993	<0.001	<0.001	<0.001
Omega-3	5.29^{c}	9.34^{a}	8.48^{ab}	5.29^{c}	6.71^{bc}	9.33^{a}	1.04	0.458	<0.001	<0.001	0.002
Omega-6	12.93^{d}	15.85^{bc}	16.26^{ab}	13.58^{d}	14.41^{cd}	17.64^{a}	0.71	0.553	<0.001	<0.001	0.002
Omega-6:omega-3	4.86^{a}	2.63^{c}	2.96^{bc}	3.97^{ab}	3.70^{b}	2.29^{c}	0.37	0.442	<0.001	<0.001	<0.001
Iodine value	73.4^{c}	86.0^{a}	84.8^{ab}	76.0^{c}	79.0^{bc}	88.7^{a}	2.8	0.890	<0.001	<0.001	<0.001

$^{a–d}$Within a row, means without a common superscript differ ($P < 0.05$).

[1]Co-P = co-product; UFA = unsaturated fatty acid.

[2]Least-squares means based on 8 pen observations (22 pigs) per diet.

Voluntary intake of feed and, therefore, dietary energy intake are important determinants of growth performance (Bikker et al., 1995). In the present study, increasing Co-P inclusion reduced ADFI throughout Exp. 1 and at the start of Exp. 2. Increasing dietary Co-P inclusion was accomplished by changing diet ingredient composition and maintaining NE content; however, macronutrient composition differed greatly among diets. Increasing dietary Co-P inclusion increased dietary fiber, protein, and ether extract content. Importantly, formulating diets containing Co-P to equal NE did not result in equal ADFI and, therefore, dietary energy intake (Seneviratne et al., 2010).

Increasing dietary Co-P inclusion may have reduced ADFI for several reasons. First, pigs had to adapt to the reduced density (Avelar et al., 2010) and therefore, increased bulk volume of feed intake required to maintain energy intake and pigs may have reached a physical limitation because of gut size (Nyachoti et al., 2004). Second, some alternative ingredients may have contained antinutritional factors that contribute to reduced feed intake (Kennelly and Aherne, 1980; van Heugten, 2001). Third, the high level of added fat required to compensate for the low energy content of Co-P may have decreased feed intake (Fowler, 1985). The unfavorable response to high dietary fat addition may be associated with an inadequate supply of readily available energy for optimum protein use (Henry, 1985). Therefore, dietary macronutrient content might have played a role in the present study in reducing ADFI for diets high in Co-P.

Finally, the energy content of diets in subsequent phases might also be important for adaption to diets high in Co-P inclusion. In Exp. 1, dietary NE content was kept constant at 2.4 Mcal/kg during the trial whereas diet NE content was gradually reduced from 2.4 to 2.3 in Exp. 2 over the 4 feeding phases. In Exp. 1, pigs did not seem to adapt to high dietary Co-P inclusion whereas pigs in Exp. 2 adapted before the midpoint of the trial. Pigs are likely more sensitive to dietary NE during the energy-dependent phase of growth than in the fattening

Table 9. Effect of increasing dietary co-product inclusion level on growth performance of pigs, by feeding phase, Exp. 2[1,2]

Item	Co-P level, % 2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA	SEM	*P*-value[3] Linear	Quadratic	Cont
BW, kg										
d 0	30.3	30.3	30.3	30.3	30.3	30.3	0.4	0.805	0.956	0.097
d 19	49.8	49.7	49.6	48.9	48.7	49.1	0.4	<0.001	0.185	0.285
d 38	71.1	71.1	70.9	69.8	69.2	70.0	0.5	<0.001	0.147	0.659
d 60	93.9	95.4	94.5	93.2	92.7	93.6	0.8	0.030	0.094	0.616
d 97	126.1	128.0	125.2	124.5	125.2	125.4	1.3	0.097	0.933	0.506
ADG, kg										
d 0 to 19	1.07	1.06	1.06	1.02	1.01	1.04	0.01	<0.001	0.232	0.239
d 20 to 38	1.12	1.14	1.12	1.11	1.08	1.10	0.02	0.030	0.209	0.928
d 39 to 60	1.08	1.15	1.12	1.11	1.11	1.12	0.02	0.772	0.171	0.694
d 61 to 97	0.97	0.97	0.95	0.97	0.97	0.99	0.03	0.903	0.575	0.445
d 0 to 97	1.06	1.07	1.05	1.05	1.04	1.06	0.02	0.182	0.517	0.386
ADFI, kg										
d 0 to 19	2.16	2.11	2.07	2.06	2.01	2.06	0.03	<0.001	0.862	0.962
d 20 to 38	2.87	2.86	2.86	2.79	2.73	2.87	0.05	0.004	0.178	0.109
d 39 to 60	3.38	3.47	3.48	3.44	3.40	3.46	0.07	0.953	0.125	0.767
d 61 to 97	3.74	3.75	3.68	3.68	3.78	3.83	0.07	0.955	0.183	0.068
d 0 to 97	3.14	3.16	3.13	3.11	3.12	3.18	0.04	0.337	0.990	0.113
G:F										
d 0 to 19	0.493	0.500	0.507	0.492	0.500	0.499	0.005	0.557	0.126	0.212
d 20 to 38	0.395	0.401	0.396	0.399	0.401	0.386	0.004	0.307	0.956	0.018
d 39 to 60	0.321	0.333	0.322	0.323	0.329	0.324	0.004	0.377	0.853	0.882
d 61 to 97	0.265	0.264	0.265	0.269	0.263	0.264	0.009	0.945	0.793	0.674
d 0 to 97	0.337	0.341	0.338	0.338	0.335	0.334	0.005	0.569	0.398	0.427

[1]Co-P = co-product.

[2]Grower 1: d 0 to 19; Grower 2: d 20 to 38; Finisher 1: d 39 to 60; and Finisher 2: d 61 to 97. Least-squares means based on 8 pen observations (21 pigs) per diet.

[3]Linear and quadratic effects of increasing dietary Co-P inclusion level, and Cont = contrast between diets containing 37.5% Co-P with and without added AA.

phase (Campbell et al., 1985). Pigs may, therefore, require time to adapt to diets high in Co-P inclusion by increasing their gut capacity.

In general, energy content is the primary dietary factor affecting voluntary feed intake (Henry, 1985). However, feed intake may also be modulated by other factors, including dietary protein content and AA profile (Nyachoti et al., 2004). Feed intake can be depressed not only by a deficiency in dietary indispensable AA but also by excessive supply of some indispensable AA. For example, the ideal ratio of dietary Leu to Lys is 100 to 110% in swine feeds (Wang and Fuller, 1989; Chung and Baker, 1992). In Exp. 1, increasing dietary Co-P inclusion increased the content of branched-chain AA, especially Leu that reached from 79 to 134% above the requirement for the high Co-P inclusion diet with nor-

Table 10. Effect of increasing dietary co-product inclusion level on carcass characteristics of pigs, Exp. 2[1,2]

Item	Co-P level, % 2.0	12.5	25.0	37.5	50.0	37.5 + 10% AA	SEM	*P*-value[3] Linear	Quadratic	Cont
Days to slaughter[4]	34.0	33.5	34.4	36.6	38.1	34.9	1.1	<0.001	0.046	0.089
Carcass weight, kg	99.8	100.1	100.0	98.8	99.0	98.8	0.4	0.012	0.587	0.907
Dressing, %	78.6	78.5	78.0	77.7	77.0	77.0	0.2	<0.001	0.240	0.060
Backfat,[5] mm	20.9	21.3	20.7	20.5	20.4	19.8	0.2	0.048	0.563	0.023
Loin depth,[5] mm	65.3	64.5	64.9	63.9	63.4	64.0	0.5	0.003	0.566	0.842
Estimated lean,[5] %	59.9	59.7	59.9	59.9	59.9	60.2	0.2	0.266	0.720	0.014

[1]Co-P = co-product.

[2]Least-squares means based on 8 pen observations (21 pigs) per diet.

[3]Linear and quadratic effects of increasing dietary Co-P inclusion level, and Cont = Contrast between diets containing 37.5% Co-P with and without added AA.

[4]Pen average number of days from d 97 until slaughter.

[5]Warm carcass weight used as a covariate.

Table 11. Effect of increasing dietary co-product inclusion level on jowl fatty acid profile and calculated iodine value of pigs, Exp. 2[1,2]

Item	Co-P level, %					37.5 + 10% AA	SEM[2]	*P*-value[3]		
	2.0	12.5	25.0	37.5	50.0			Linear	Quadratic	Cont
Fatty acid, %										
10:0 Capric	0.17	0.17	0.19	0.17	0.14	0.18	0.02	0.364	0.112	0.609
12:0 Lauric	0.08	0.09	0.08	0.08	0.08	0.08	0.01	0.092	0.586	0.799
14:0 Myristic	1.48	1.54	1.45	1.40	1.33	1.37	0.05	0.013	0.261	0.709
16:0 Palmitic	23.2	24.1	22.8	21.7	21.3	20.3	0.6	<0.001	0.090	0.656
16:1 Palmitoleic	3.11	2.97	2.69	2.47	2.34	2.39	0.14	<0.001	0.893	0.665
18:0 Stearic	9.14	9.79	9.36	8.87	8.20	9.02	0.32	0.008	0.029	0.731
18:1 Oleic	41.01	39.45	39.71	38.35	37.88	38.16	1.26	0.087	0.905	0.912
18:2 Linoleic	10.31	9.55	11.30	12.82	14.02	13.22	0.77	<0.001	0.226	0.708
18:3 α-Linolenic	3.61	2.44	4.78	6.63	7.82	6.69	0.85	<0.001	0.214	0.966
20:0 Arachidic	0.15	0.15	0.15	0.15	0.15	0.16	0.01	0.690	0.810	0.449
20:1 Gadoleic	0.68	0.71	0.68	0.64	0.65	0.60	0.03	0.169	0.636	0.244
20:2 Dihono-γ-linolenic	0.44	0.41	0.47	0.51	0.56	0.53	0.02	<0.001	0.145	0.527
20:3 Podocarpic	0.06	0.07	0.06	0.06	0.07	0.07	0.01	0.275	0.249	0.131
20:4 Arachidonic	0.15	0.15	0.13	0.14	0.14	0.14	0.01	0.168	0.242	0.909
20:3 Eicosatrienoic	0.41	0.30	0.57	0.73	0.86	0.75	0.09	<0.001	0.273	0.871
Total SFA	34.23	35.84	34.00	32.34	30.24	32.15	0.93	<0.001	0.054	0.856
Total MUFA	44.81	43.12	43.07	41.46	40.87	41.14	1.35	0.038	0.906	0.861
Total PUFA	14.97	12.91	17.30	20.89	23.48	21.39	1.70	<0.001	0.213	0.837
UFA:SFA	1.78	1.56	1.78	1.94	2.17	1.95	0.09	<0.001	0.023	0.914
PUFA:SFA	0.46	0.37	0.51	0.66	0.81	0.81	0.07	<0.001	0.092	0.910
Omega 3	4.01	2.73	5.34	7.37	8.68	7.44	0.94	<0.001	0.219	0.959
Omega-6	10.96	10.18	11.96	13.52	14.80	13.95	0.79	<0.001	0.217	0.696
Omega-6:omega-3	5.75	5.49	3.09	1.96	1.87	1.99	0.85	<0.001	0.651	0.983
Iodine value	69.63	65.70	72.65	78.41	83.11	79.00	2.79	<0.001	0.153	0.885

[1]Co-P = co-product; UFA = unsaturated fatty acid.

[2]Least-squares means based on 8 pen observations (21 pigs) per diet.

[3]Linear and quadratic effects for increasing dietary Co-P inclusion, and Cont = contrast between diets containing 37.5% Co-P with and without added AA.

mal CP concentration. Reduced ADFI and corresponding reduced ADG of pigs fed mid and high Co-P inclusion diets in Exp. 1 could have been partly due to excess dietary Leu. In Exp. 2, Leu content reached only 35 to 94% above requirements for the 50% Co-P diet but did not reduce ADFI. Furthermore, the 10% added AA did not reduce ADFI, perhaps because the increase in dietary Lys content actually reduced the Leu to Lys ratio. Therefore, dietary AA profile may play a role in achieved feed intake but was not likely the sole contributing factor to the reduced ADFI in Exp. 1.

Carcass characteristics and pork quality are the ultimate determinants of a successful swine feeding program. In both studies, carcass weight was reduced at a similar slaughter BW (data not shown), indicating that increasing dietary Co-P inclusion and, consequently, dietary fiber reduced dressing percentage (Seneviratne et al., 2010). Pigs adapt to diets with increased fiber content by increasing gut volume and weight (Jørgensen et al., 1996). Increasing dietary Co-P inclusion increased viscera weight, which in turn increased the energy and AA requirements of these organs in pigs (Yen, 1997; Nyachoti et al., 2000). Therefore, increased viscera size and weight at equal NE and SID intake may reduce protein deposition in the carcass and thereby reduce loin depth. Finally, increased backfat in pigs fed diets with a low CP concentration may have been due to more dietary energy being available for fat synthesis, because less energy was required for catabolism of excess dietary CP. Formulating swine diets using the NE and SID AA systems may reduce the risk of compromising growth performance when feeding up to 50% dietary Co-P in swine diets or fluctuating dietary macronutrient profile (Zijlstra and Beltranena, 2013) although some insist that energetic losses as heat increment should not be considered in feed evaluation and formulation (Flachowsky, 2008). However, restrictions for maximum dietary Co-P inclusion might be required in feed formulation to guarantee equal carcass weight and loin depth.

Pork fatty acid composition mostly reflects dietary fatty acid profile (Raes et al., 2004), especially in pigs with high ADFI such as in the present study. The potential for using dietary Co-P inclusion to enrich fatty acid profile in pork fat was, therefore, evaluated. We obtained a fat sample from the jowl because it has limited economic value and responds to changes in dietary fat similar to backfat (Benz et al., 2011) although jowl fat was less responsive to increased DDGS than backfat and belly fat (Benz et al., 2010). In the present study, pigs were fed co-extruded flax seed and field pea, in addition to DDGS and canola meal as Co-P in diets. The co-extruded flax seed and field pea provided energy and AA but was also a source of omega-3 fatty acids, as 35% of ether extract is ALA (Thacker et al., 2004; Htoo et al., 2008). Co-extrusion of flax seed not only enhanced ALA concentration in pork but also facilitated feed processing and delivery that may limit incorporating of singular flax seed in swine diets (Thacker et al., 2004). The combined results of these experiments concur with previous studies that have demonstrated that the incorporation of flax seed into swine diets increased pork fat ALA concentration (Romans et al., 1995a; Matthews et al., 2000; Thacker et al., 2004; Juárez et al., 2010).

The enrichment in pork ALA may provide health benefits for consumers (Simopoulos, 1998), thereby expanding market opportunities for omega-3 pork. However, in the present study, achieved pork ALA enrichment was less than in previous research. The difference can be attributed to different research protocols. Previous research was conducted in facilities with fewer weaned or growing–finishing pigs that were fed diets with omega-3 fatty acids for a longer time or with a greater content of omega-3 fatty acids. The present study was conducted at commercial scale with pigs fed diets that provided less omega-3 fatty acids. Most of the previous studies were conducted with flax seed that is high in ALA (51% of total lipid; Olomu and Baracos, 1991) whereas the present study used co-extruded flax seed and field pea that had a diluted ALA content (35% of total lipid; Thacker et al., 2004) but still increased jowl omega-3 fatty acids content. The fatty acid profiles of jowl fat in the present study met previously defined targets to increase the PUFA to SFA ratio above 0.4 (Wood et al., 2004).

In conclusion, up to 50% Co-P can be incorporated into swine diets depending on the type of Co-P fed. Increasing dietary Co-P may enhance carcass omega-3 fatty acid profile but may also reduce ADG, ADFI, and carcass weight of pigs even though diets were balanced for NE and SID AA. The reduced ADG was mainly due to the reduced ADFI, to which high dietary content of fiber and fat or potential dietary AA imbalance may have contributed. Supplementing extra dietary AA above requirements to pigs fed high Co-P increased carcass leanness but did not improve ADG, indicating that other factors may have reduced carcass weight.

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