Growth performance, organ weights, and blood parameters of nursery pigs fed diets containing increasing levels of cold-pressed canola cake¹

Jung Wook Lee and Tofuko A. Woyengo²

Department of Animal Science, South Dakota State University, Brookings, SD 57007

ABSTRACT: Oilseed cakes have high oil content, and thus their inclusion in swine can lead to reduced dietary inclusion of oil, and hence reduced cost of feed. An experiment was conducted to determine effects of including *Brassica napus*-derived cold-pressed canola cake (CPCC) in diets for nursery pigs on growth performance, organ weights relative to live body weight (BW), and blood parameters. A total of 160 pigs (initial BW: 7.8 ± 0.9 kg), which had been weaned at 21 d of age were housed in 40 pens (4 pigs/pen) and fed 4 diets (10 pens/diet) in a randomized complete block design for 35 d. The 4 diets were corn-soybean meal (SBM)-based basal diet and the basal diet with corn and SBM replaced by 20, 30, or 40% of CPCC. The diets were fed in 2 phases, Phase 1 from day 0 to 14 and Phase 2 from day 14 to 35; and were formulated to meet NRC (2012) nutrient recommendations for nursery pigs and to have the same net energy, standardized ileal digestible amino acid, and digestible P contents. Increasing inclusion of CPCC in diets was achieved by partial replacement of corn, SBM, limestone, and mono-calcium phosphate. Growth performance was determined by phase. On day 35, 1 pig from each pen was euthanized for determining organ weights and blood parameters. The

CPCC contained 7.63% moisture, and on a dry matter basis, it (CPCC) contained 39.6% crude protein, 2.32% Lys, 0.74% Met, 1.63% Thr, 0.50% Trp, 16.0% ether extract, 20.7% neutral detergent fiber, and 14.9 $\mu\text{mol/g}$ of glucosinolates. Increasing dietary CPCC from 0 to 40% linearly reduced ($P < 0.05$) overall (day 0 to 35) average daily gain and average daily feed intake (0.440 to 0.288 kg/d and 0.739 to 0.522 kg/d, respectively). Increasing dietary CPCC from 0 to 40% resulted in a linear increase ($P < 0.05$) in liver weight by 0.1 g/kg of BW and in thyroid gland weight by 2.2 mg/kg of BW, but in a linear reduction ($P < 0.05$) in serum tetraiodothyronine (T4) level by 0.2 ng/mL for each 1% increase in CPCC at 35 d of age. No differences were observed in heart and kidney weights relative to live BW, and in serum triiodothyronine (T3) concentration. In conclusion, increasing dietary CPCC from 0 to 40% by reducing corn and SBM levels resulted in depressed growth performance, increased metabolic activity in liver and thyroid gland, and reduced serum T4 level of pigs. Thus, the amounts of CPCC included in nursery pig diets should be based on targeted growth performance and cost of other feedstuffs in relation to that of CPCC.

Key words: blood parameters, cold-pressed canola cake, nursery pigs, organ weights, performance

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INTRODUCTION

Inclusion of oilseed cakes in pig diets can reduce feed cost because of their high oil content, which leads to reduced dietary inclusion of oil. However, canola coproducts have a high content of fiber and glucosinolates, which reduce nutrient

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²Corresponding author: tofuko.woyengo@sdstate.edu

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utilization in pigs (Woyengo et al., 2014). Aliphatic and indolic glucosinolates are predominantly present in canola (Cartea and Velasco, 2008). Aliphatic glucosinolate degradation products are bitter and adversely affect liver and kidney functions (Tripathi and Mishra, 2007). Indolic glucosinolates exhibit anticarcinogenicity by activating hepatic detoxification enzymes (Loft et al., 1992), leading to increased utilization of dietary nutrients in livers at the expense of skeletal tissue deposition. Indolic glucosinolates are more heat-labile than aliphatic glucosinolates (Jensen et al., 1995).

Oil is extracted from canola seed mainly by cold or expeller pressing, or solvent extraction (expeller pressing followed by solvent extraction) methods. Solvent extraction and expeller pressing are more efficient methods of oil extraction than cold pressing method, and the seed is exposed to less heat during cold pressing than solvent extraction or expeller pressing (Spragg and Mailer, 2007). Thus, cold-pressed canola cake (CPCC) contains more remaining oil than solvent-extracted canola meal (SECM) or expeller-pressed canola meal (EPCM). Additionally, CPCC contains more indolic glucosinolates than EPCM or SECM. Thus, the feeding value of CPCC is different from that of EPCM or SECM.

Effects of including EPCM or SECM in pig diets on performance, thyroid gland, liver, and kidney functions have been reported (Parr et al., 2015; Velayudhan et al., 2017). However, information is lacking on the effects of including CPCC in diets for pigs on the fore-mentioned response criteria. Objective of this study was to determine effects of including CPCC in diets for nursery pigs on growth performance, visceral organ weights, and blood parameters.

MATERIALS AND METHODS

The experimental animal procedures were reviewed and approved by the Institutional Animal Care and Use Committee at South Dakota State University (#16-101A).

Animals and Housing

A total of 160 pigs [initial BW of 7.8 ± 0.9 kg; Large White-Landrace female (line 42) $\times$ Duroc male (line 280); Pig Improvement Company] weaned at 21 d of age were obtained from Swine Education and Research Facility, South Dakota State University (Brookings, SD). The pigs were fed common commercial starter diet during the first 7 d

post-weaning. Pigs were then individually weighed and housed in 40 pens (4 pigs/pen). Pens (1.8×2.4 m) had fully slated-concrete floors, metal spindle walls (1.0 m high), and solid polyvinyl chloride gates. Each pen was equipped with a cup drinker, a double-spaced dry feeder, and a heat lamp. Room temperature was maintained at 28 ± 1 °C during the first 1 wk. Thereafter, the room temperature was maintained at 27 ± 2 °C throughout the experiment.

Experimental Diets

Four experimental diets included a corn-soybean meal (SBM)-based basal diet containing 0, 20, 30, or 40% of CPCC (Table 1). The CPCC fed in the current study was derived from *Brassica napus* seed, and was sourced from OKC Farm (Raymond, Alberta, Canada) in one lot, and had been produced by heating the canola seed at 23 °C for 15 min, followed by pressing of the heated canola seed at less than 70 °C (barrel temperature) for 2 min using a screw press expeller (Model KEK-P0500, Remscheid, Germany). The CPCC was delivered to South Dakota State University within 4 d after its production. The experimental diets were formulated to similar net energy (NE), crude protein (CP), Ca, standardized total tract digestible P, and standardized ileal digestible Lys, Met, Thr, and Trp contents. The experimental diets were fed in 2 phases; Phase 1 for 14 d, and Phase 2 for 21 d. The diets were fed as mash, and were formulated to meet or exceed NRC (2012) nutrient recommendations for nursery pigs. Phase 1 diets contained 2,485 kcal/kg NE; 1.35, 0.39, 0.79, and 0.24% standardized ileal digestible content of Lys, Met, Thr, Trp, respectively, and 0.40% standardized total tract digestible P content. Phase 2 diets contained 2,473 kcal/kg NE, 1.23, 0.36, 0.73, and 0.22% standardized ileal digestible content of Lys, Met, Thr, Trp, respectively, and 0.33% standardized total tract digestible P content.

Experimental Design and Procedure

The 4 diets were allotted to the 40 pens with 4 pigs per pen in a randomized complete block design. Diets and fresh water were offered to pigs ad libitum during the entire period. Pig BW and feed intake were determined by phase to calculate average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F). At the end of the trial, 1 pig (per pen) with BW that was close to the pen average BW was selected, and then euthanized by captive bolt penetration. The liver,

Table 1. Ingredient composition and analyzed nutrient content of experimental diets (as-fed basis)¹

Item	Phase 1				Phase 2			
	Cold-pressed canola cake, %				Cold-pressed canola cake, %			
	0	20	30	40	0	20	30	40
Ingredient, %								
Corn	55.96	48.60	44.29	41.58	67.76	54.68	49.84	46.91
Soybean meal	24.70	12.50	7.00	-	26.50	19.80	14.81	8.00
Cold-pressed canola cake	-	20.00	30.00	40.00	-	20.00	30.00	40.00
Fish meal	4.00	4.00	4.00	4.00	2.50	2.50	2.50	2.50
Soy protein ² , 56% CP	1.50	1.50	1.50	1.50	-	-	-	-
Whey permeate	10.00	10.00	10.00	10.00	-	-	-	-
Soybean oil	0.73	0.39	0.30	-	-	0.30	0.25	-
Limestone	0.95	0.77	0.66	0.57	1.03	0.81	0.70	0.62
Monocalcium phosphate	0.55	0.40	0.34	0.27	0.62	0.40	0.35	0.27
Lysine HCl	0.39	0.53	0.58	0.68	0.39	0.36	0.40	0.49
DL-Met	0.07	0.06	0.04	0.04	0.07	0.02	0.01	-
L-Thr	0.10	0.14	0.15	0.19	0.11	0.08	0.08	0.11
Salt	0.65	0.68	0.70	0.71	0.62	0.65	0.65	0.68
Vitamin premix ³	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mineral premix ⁴	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed composition, %								
Dry matter	89.29	90.17	90.38	90.64	88.24	88.81	88.86	89.79
Crude protein	20.18	22.21	21.89	23.14	19.07	22.17	21.18	21.63
Ash	6.45	6.85	6.40	6.73	6.01	5.66	5.39	5.85
Ether extract	4.47	4.56	5.04	8.01	4.44	5.72	6.83	7.28
Neutral detergent fiber	8.37	11.87	11.76	12.93	10.37	15.37	12.21	14.58
Acid detergent fiber	2.66	4.99	6.01	6.85	4.39	6.14	6.36	7.12

¹The experimental diets were fed in 2 phases; Phase 1 from day 1 to 14 and Phase 2 from day 14 to 35.

²Soy protein was a hydrolyzed soy protein product (HP 300) from Hamlet Protein (Horsens, Denmark).

³Provided the following per kilogram of diet: 2226 IU vitamin A, 340 IU vitamin D₃, 11.3 IU vitamin E, 0.01 mg vitamin B₁₂, 0.91 mg menadione, 2.04 mg riboflavin, 12.5 mg pantothenic acid, 11.3 mg niacin, 0.23 mg folic acid, 0.68 mg pyridoxine, 0.68 mg thiamine, and 0.04 mg biotin.

⁴Provided the following per kilogram of diet: 75 mg Zn as ZnSO₄, 75 mg Fe as FeSO₄, 7 mg Cu as CuSO₄, and 20 mg Mn as MnSO₄.

kidneys, thyroid gland, and heart were isolated and collected from the euthanized pigs, blot dried and weighed. Prior to euthanasia, 10 mL of blood was collected from each pig that had been ear-marked for euthanasia via jugular vein puncture into 2 sets of vacutainer tubes; EDTA coated and serum tubes (BD Vacutainer, Plymouth, UK; 5 mL/tube) and immediately stored on ice. Blood samples collected in serum vacutainer tubes were immediately (~30 min after their collection) centrifuged at $2,000 \times g$ for 10 min at 4 °C to recover serum, which was stored frozen at -20 °C for latter determination of serum triiodothyronine (T₃) and tetraiodothyronine (T₄) concentrations. Blood samples collected in EDTA-coated vacutainer tubes were analyzed for complete blood count (CBC).

Sample Preparation and Analyses

The CPCC and experimental diets were ground to pass through a 1.00-mm screen using a Wiley

mill (Thomas-Wiley Laboratory Mill Model 4, Thomas Scientific, NJ). The ground CPCC and diet samples were analyzed for dry matter (DM), CP, ether extract (EE), ash, acid detergent fiber (ADF), and neutral detergent fiber (NDF). The samples were analyzed for DM by oven drying at 135 °C for 2 h (method 930.15), CP by a combustion procedure (method 990.03), EE (method 2003.06), dry ash (method 942.05) as per AOAC (2007); and for ADF and NDF (Van Soest et al., 1991) on a Ankom 200 Fiber Analyzer (Ankom Technology, Fairport, NY). Samples were analyzed for AA [method 982.30 E (a, b, and c); AOAC, 2006] at the University of Missouri Experiment Station laboratories (Columbia, MO). Glucosinolate content was quantified by gas chromatography (POS Pilot Plant Corp., Saskatoon, SK, Canada) according to the method of Daun and McGregor (1981). The CBC profile was determined using a hematology analyzer (Abbott CD 3500, Abbott Diagnostics Division, Mountain View, CA). Blood serum concentration of

T3 was determined using an immunoassay analyzer (Immulite 1000, DPC, Los Angeles, CA), whereas blood serum concentration of T4 was determined using Clinical Chemistry Auto-Analyzer System (Vet Axcel Chemistry Analyzer, Alfa Wassermann Diagnostic Technologies, West Caldwell, NJ).

Statistical Analysis

Data were analyzed using the MIXED procedure of SAS (ver. 9.3, SAS Institute Inc., Cary, NC) in a randomized complete block design with pen as the experimental unit. The model included treatment as the fixed effect and block as the random effect. Linear and quadratic contrasts for unequally spaced levels were performed to determine the effects of increasing inclusion of CPCC in nursery diets. To test the hypotheses, $P < 0.05$ was considered significant. If pertinent, trends ($0.05 \leq P < 0.10$) are also reported.

RESULTS

The analyzed CP content in the diets was similar to the calculated CP content in the diets (Table 1). Progoitrin was the most abundant aliphatic glucosinolate, whereas 4-hydroxyglucobrassicin was the most abundant indolic glucosinolate present in CPCC fed in the current study (Table 2). Data on effect of dietary inclusion of CPCC on growth performance are presented in Table 3. An increase in the dietary level of CPCC resulted in a linear reduction ($P < 0.05$) in BW of pigs for day 14 and 35 (Table 3). Increasing dietary inclusion of CPCC from 0 to 40% linearly decreased ($P < 0.05$) ADG and ADFI of pigs for day 0 to 14 and day 14 to 35, and for the entire experiment (day 0 to 35). For day 0 to 14 and for the entire experiment, G:F was linearly reduced ($P < 0.05$) with the increasing levels of dietary CPCC. However, no significant differences were observed in G:F for day 14 to 35.

Data on effect of dietary inclusion of CPCC on organ weights and blood parameters of pigs are presented in Table 4. There were no effects of dietary level of CPCC on heart, and kidneys relative to live BW. However, an increase in the dietary level of CPCC resulted in a linear ($P < 0.05$) increase in liver and thyroid gland weights relative to live BW. Also, an increase in the dietary level of CPCC resulted in a quadratic increase ($P < 0.05$) in thyroid gland weight relative to live BW such that thyroid gland weight increased ($P < 0.05$) when dietary CPCC was increased from 0 to 30%, and then decreased ($P < 0.05$) when dietary CPCC was

Table 2. Analyzed nutrient and glucosinolate content of cold-pressed canola cake (% dry matter basis)¹

Item	Cold-pressed canola cake
Nutrient composition, %	
Moisture	7.63
Crude protein	39.56
Ash	6.49
Ether extract	16.01
Neutral detergent fiber	20.67
Acid detergent fiber	14.32
Indispensable amino acids	
Arg	2.35
His	1.04
Ile	1.67
Leu	2.77
Lys	2.32
Met	0.74
Phe	1.66
Thr	1.63
Trp	0.50
Val	2.07
Dispensable amino acids	
Ala	1.76
Asp	2.71
Cys	1.01
Glu	6.46
Gly	1.97
Pro	2.37
Ser	1.43
Tyr	1.08
Glucosinolates ² , µmol/g	
Gluconapin (3-Butenyl)	1.98
Glucobrassicinapin (4-Pentenyl)	0.42
Progoitrin (2-OH-3-butenyl)	4.63
Gluconapoleiferin (2-OH-4-pentenyl)	0.10
Total aliphatics	7.13
Glucoerucin (CH ₃ -thiobutenyl)	<0.02
Gluconasturtiin (Phenylethyl)	0.32
Glucoberteroiin (CH ₃ -thiopentenyl)	0.63
Glucobrassicin (3-CH ₃ -indolyl)	1.00
4-Hydroxyglucobrassicin (4-OH-3-CH ₃ -indolyl)	5.57
Total glucosinolates	14.9

¹The analysis was done in duplicate and, hence the presented data are means of 2 values.

²Glucosinolate values were analyzed by gas chromatography (Daun and McGregor, 1981) at POS Pilot Plant Corp. (Saskatoon, SK, Canada).

further increased to 40%. Dietary CPCC linearly increased ($P < 0.05$) mean corpuscular volume and mean corpuscular hemoglobin. Red blood cell distribution width was quadratically increased ($P < 0.05$) by the increasing dietary inclusion of CPCC such that red blood cell distribution width increased with an increase in the dietary level of

Table 3. Growth performance of nursery pigs fed increasing levels of cold-pressed canola cake¹

Item ²	Cold-pressed canola cake, %				SEM	P-value		
	0	20	30	40		Diet	Linear	Quadratic
BW, kg								
Day 0	7.8	7.8	7.9	7.9	0.082	0.501	0.237	0.510
Day 14	11.5	10.5	10.3	9.9	0.213	<0.001	<0.001	0.573
Day 35	23.3	20.0	19.4	18.2	0.548	<0.001	<0.001	0.390
ADG, kg								
Day 0–14	0.267	0.199	0.174	0.142	0.013	<0.001	<0.001	0.809
Day 14–35	0.551	0.446	0.428	0.387	0.020	<0.001	<0.001	0.471
Day 0–35	0.440	0.350	0.328	0.288	0.015	<0.001	<0.001	0.595
ADFI, kg								
Day 0–14	0.389	0.322	0.289	0.259	0.015	<0.001	<0.001	0.862
Day 14–35	0.961	0.813	0.800	0.683	0.026	<0.001	<0.001	0.705
Day 0–35	0.739	0.621	0.598	0.522	0.020	<0.001	<0.001	0.969
G:F								
Day 0–14	0.680	0.617	0.602	0.547	0.022	0.002	<0.001	0.678
Day 14–35	0.571	0.548	0.538	0.567	0.017	0.466	0.610	0.171
Day 0–35	0.593	0.563	0.551	0.551	0.015	0.201	0.042	0.542

¹Data are means of 10 pens of pigs with 4 pigs per pen.

²BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; and G:F = gain to feed ratio. The pig BW and feed intake were determined by phase to calculate ADG, ADFI, and G:F by phase and for the entire experiment.

Table 4. Organ weights, complete blood counts and serum thyroid hormones of nursery pigs fed increasing levels of cold-pressed canola cake¹

Item	Cold-pressed canola cake, %				SEM	P-value		
	0	20	30	40		Diet	Linear	Quadratic
Organ weights								
Heart, g/kg of BW	6.6	6.8	6.9	6.5	0.300	0.574	0.712	0.252
Kidneys, g/kg of BW	6.1	6.5	6.5	6.1	0.327	0.399	0.996	0.119
Liver, g/kg of BW	32.9	36.1	37.6	38.1	1.555	0.103	0.016	0.698
Thyroid gland, mg/kg of BW	132.8	181.9	266.0	191.7	18.268	<0.001	<0.001	0.011
Complete blood counts ²								
HGB, g/dL	12.2	12.1	11.7	11.7	0.304	0.434	0.128	0.925
LYM, 10 ³ μL	8.74	7.25	9.01	6.66	1.228	0.358	0.371	0.785
MCV, fL	55.7	52.8	52.8	50.5	1.371	0.051	0.010	0.899
MCH, pg	18.0	16.9	16.9	16.2	0.471	0.053	0.009	0.914
MCHC, g/dL	32.3	32.0	32.0	32.1	0.351	0.913	0.565	0.615
MONO, %	2.80	3.00	2.83	2.13	0.472	0.407	0.361	0.215
RBC, M/μL	6.80	7.13	6.96	7.25	0.180	0.241	0.108	0.935
RDW, %	26.0	30.4	35.7	27.7	2.435	0.032	0.188	0.027
WBC, K/μL	17.1	15.4	17.2	14.4	2.218	0.681	0.487	0.811
Serum ³								
T3, ng/mL	0.791	0.758	0.779	0.559	0.084	0.157	0.104	0.200
T4, ng/mL	38.7	38.5	38.1	31.2	1.846	0.009	0.015	0.031

¹Pigs were housed in 40 pens (4 pigs/pen) and 1 pig per pen with BW that was close to the pen average BW was selected at the end of the trial, and then euthanized to collect liver, kidneys, thyroid gland and heart. Prior to euthanasia, 10 mL of blood was collected from each pig to determine complete blood counts, serum triiodothyronine (T3), and tetraiodothyronine (T4) concentrations.

²HGB = hemoglobin; LYM = lymphocyte; MCV = mean corpuscular volume; MCH = mean corpuscular hemoglobin; MCHC = mean corpuscular hemoglobin concentration; MONO = monocyte; RBC = red blood cell; RDW = red blood cell distribution width; and WBC = white blood cell.

³T3 = triiodothyronine; T4 = tetraiodothyronine.

CPCC from 0 to 30% ($P < 0.05$), and then decreased ($P < 0.05$) with an increase in dietary level of CPCC from 30 to 40%. The other CBC features including

hemoglobin, lymphocyte, mean corpuscular hemoglobin concentration, monocyte, red blood cell, and white blood cell were not affected by dietary

inclusion of CPCC. Dietary CPCC quadratically reduced ($P < 0.05$) the serum T4 concentration such that an increase in the dietary level of CPCC from 0 to 30% did not affect serum T4 level, but a further increase in the dietary level of CPCC to 40% resulted in a decrease ($P < 0.05$) in the serum T4 concentration.

DISCUSSION

The EE content of CPCC (16.0%) was greater than the values for EPCM (9.9%) and SECM (3.2%) reported by [NRC \(2012\)](#), which was due to the fact that cold pressing is a less efficient method of oil extraction than expeller pressing or solvent extraction method. The NDF value of CPCC (20.7%) was less than the value for EPCM (23.8%) reported by [NRC \(2012\)](#). The EE value for CPCC (16.0%) fed in the current study was lower than EE value for CPCC (31.3%) reported by [Woyengo et al. \(2016\)](#). However, the CP and AA values for CPCC fed in the current study were greater than values that were reported for CPCC by [Woyengo et al. \(2016\)](#). The NDF value of CPCC (20.7%) fed in the current study was greater than the NDF value (18.2%) that was reported by [Woyengo et al. \(2016\)](#) for CPCC. The greater CP, AA, and NDF values for CPCC fed in the current study could have been attributable to the lower EE content in CPCC fed in the current study than that for CPCC fed in the study of [Woyengo et al. \(2016\)](#). The total glucosinolate content of CPCC (14.9 $\mu\text{mol/g}$) fed in the current study was greater than the values that were reported by [Landro et al. \(2011; 3.8 \$\mu\text{mol/g}\$ \)](#) and [Parr et al. \(2015; 8.7 \$\mu\text{mol/g}\$ \)](#) for SECM, and by [Woyengo et al. \(2011; 8.0 \$\mu\text{mol/g}\$ \)](#) and [Velayudhan et al. \(2017; 9.3 \$\mu\text{mol/g}\$ \)](#) for EPCM. The total glucosinolate content of CPCC was greater than the average Canadian values that were reported by [Canola Council of Canada \(2015; 4.2 \$\mu\text{mol/g}\$ \)](#) for SECM. The greater total glucosinolate content in CPCC fed in the current study than in EPCM or SECM fed in the previous studies could be attributable to the fact that the CPCC was exposed to less heat than EPCM or SECM during oil extraction. Glucosinolates are heat-labile and hence degradable by heat ([Newkirk and Classen, 2002](#)). The total aliphatic glucosinolate value (7.8 $\mu\text{mol/g}$) for CPCC was comparable to the values that were reported by [Parr et al. \(2015; 5.9 \$\mu\text{mol/g}\$ \)](#) for SECM and by [Velayudhan et al. \(2017; 7.5 \$\mu\text{mol/g}\$ \)](#) for EPCM. However, the total indolic glucosinolate value (6.6 $\mu\text{mol/g}$) for CPCC fed in the current study was greater than the values that were reported by [Parr et al. \(2015; 2.8 \$\mu\text{mol/g}\$ \)](#), and [Newkirk et al. \(2003; 4.8 \$\mu\text{mol/g}\$ \)](#) for SECM,

and by [Velayudhan et al. \(2017; 1.4 \$\mu\text{mol/g}\$ \)](#), and [Woyengo et al. \(2011; 2.8 \$\mu\text{mol/g}\$ \)](#) for EPCM. [Jensen et al. \(1995\)](#) reported a greater reduction in the indolic glucosinolate content than in the aliphatic glucosinolate content in rapeseed meal due to toasting. [Newkirk and Classen \(2002\)](#) also reported a substantial reduction of glucobrassicin (an indolic glucosinolate) content but not of aliphatic glucosinolates content of SECM due to toasting of the SECM, implying that the indolic glucosinolates are more susceptible to heat treatment than the aliphatic glucosinolates. Thus, the similarities between CPCC fed in the current study and SECM or EPCM fed in the studies of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#) with regard to the aliphatic glucosinolate content, and the greater indolic glucosinolate content in CPCC than in SECM or EPCM fed in the previous studies could be attributed to the fact that the CPCC was exposed to less heat than EPCM or SECM during oil extraction.

An increase in the dietary level of CPCC from 0 to 40% linearly reduced ADG of pigs despite the fact that the diets were formulated to be similar in NE and digestible nutrient content. This reduction in ADG of pigs due to increasing dietary inclusion of CPCC was a result of the reduction in ADFI, the increase in liver weights relative to live BW, and the decrease in the serum level of T4 with an increase in dietary level of CPCC. Growth of pigs is positively related to nutrient intake. Thus, reduction in nutrient intake as evidenced by the reduction in ADFI due to dietary CPCC can result in reduced ADG of pigs. An increase in visceral organ mass of pigs, which is mainly due to increased metabolic activity in visceral organs, result in increased energy expenditure by visceral organs at the expense of skeletal tissue deposition ([Nyachoti et al., 2000](#)). Therefore, an increase in metabolic activities in the liver due to an increase in dietary level of CPCC in the current study as evidenced by the increase in liver weights relative to live BW resulted in increased energy expenditure at the expense of growth and development, leading to the reduced ADG of pigs. Thyroid hormones affect energy metabolism and promotes growth and development partly through stimulation of growth hormone synthesis ([Fisher et al., 1982; Hulbert, 2000](#)). Therefore, the reduction in serum level of T4 due to dietary CPCC could have resulted in reduced ADG of pigs.

In the current study, ADG of pigs fed diets containing $\geq 20\%$ CPCC was lower than that of pigs fed diet containing 0% CPCC, which is in contrast to the results reported by [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#) who did not observe

a reduction in ADG due to an increase in dietary level of conventional SECM or EPCM from 0 to 20%. In the current study and those of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#), the levels of canola coproducts in diets were increased by the partial replacement of corn and SBM in the diets. The CPCC fed in the current study had lower fiber content than the conventional SECM or EPCM fed in the studies of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#), implying that the differences in the effects of dietary canola coproduct on ADG between the current study and the previous 2 studies could not have been due to differences in the fiber content of canola coproducts. However, as previously mentioned, the CPCC had similar aliphatic glucosinolate content, but greater indolic glucosinolate content than the values that were earlier reported for the conventional SECM and EPCM. The indolic glucosinolates are degraded into anticarcinogenic products that increase metabolic activity of various visceral organs such as liver by activating various enzymes that are involved in inactivation of carcinogens ([Cartea and Velasco, 2008](#)), leading to the increased energy expenditure in the visceral organs at the expense of growth. Therefore, the reduction in ADG of pigs in the current study due to inclusion of CPCC at 20%, and lack of effect of including the conventional SECM or EPCM at 20% on ADG of pigs in the studies of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#) could have been attributable to greater content of indolic glucosinolates in CPCC fed in the current study than in SECM and EPCM fed in the studies of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#). Indolic glucosinolates have been considered to be beneficial because of their anticarcinogenic activity in humans; however, it appears that they have negative effect on growth performance of pigs.

The increasing inclusion of CPCC in diets from 0 to 40% resulted in a linear reduction in ADFI. As previously mentioned, canola coproducts have high content of fiber and glucosinolates, which result in reduced voluntary feed intake in pigs ([Mejicanos et al., 2016](#)). Voluntary feed intake of pigs fed diets containing fiber is reduced mainly due to the bulkiness and prolonged postprandial satiety effect of fiber ([de Leeuw et al., 2008](#)). [Zhou et al. \(2013\)](#) reported no differences in ADFI of pigs fed air-classified fractions of SECM that contained similar glucosinolate levels, but differed in fiber content, indicating that low voluntary feed intake of canola coproducts is mainly due to glucosinolates. The reduction in ADFI due to dietary CPCC is in agreement with the results from the study of [Parr](#)

[et al. \(2015\)](#), who reported that ADFI of diets for nursery pigs was linearly reduced with an increase in dietary level of SECM from 0 to 40%. Similarly, [Velayudhan et al. \(2017\)](#) reported a linear reduction in ADFI of growing pigs due to an increase in dietary level of EPCM from 0 to 30%.

The increased liver weights relative to live BW due to an increase in dietary level of CPCC from 0 to 40% may be explained by increased metabolic activity in the liver due to increased absorption (from the gastrointestinal tract) of myrosinase-catalyzed toxic degradation products of glucosinolates that are detoxified in the liver. Hepatic detoxification enzymes in rats were activated due to intake of allyl isothiocyanate, which are toxic glucosinolates found in canola coproducts ([Munday and Munday, 2002](#)). Also, consumption of toxic allyl nitriles (toxic glucosinolates found in canola coproducts) resulted in increased activity of detoxification enzymes in hepatic tissues of mouse and rats ([Nho and Jeffery, 2001](#); [Tanii et al., 2005](#)). Results of the current study are in agreement with those from the study of [Parr et al. \(2015\)](#), who observed an increased liver weight of nursery pigs due to an increase in dietary level of high-protein SECM from 0 to 40%. However, results of the current study are not in agreement with those from the study of [Velayudhan et al. \(2017\)](#), who did not observe an increase in liver weight of growing pigs due to an increase in dietary level of EPCM from 0 to 30%. Also, [Parr et al. \(2015\)](#) did not observe an increase in liver weight of nursery pigs due to an increase in dietary level of conventional SECM from 0 to 40%. As previously mentioned, the CPCC fed in the current study had similar aliphatic glucosinolate content, but greater indolic glucosinolate content than the conventional SECM and EPCM fed in the studies of [Parr et al. \(2015\)](#) and [Velayudhan et al. \(2017\)](#). Thus, the differences among studies with regard to the effects of dietary canola coproducts on the size of liver in pigs could have been due to differences in composition of glucosinolates in the canola coproducts.

Feeding the increasing dietary level of CPCC did not affect heart and kidney weights relative to live BW, which could have been mainly due to the inadequate ingestion of glucosinolates to result in an enlargement in the heart and kidneys of pigs. [Roland et al. \(1996\)](#) reported that feeding 12% rapeseed meal induced hepatic hypertrophy in gnotobiotic rats without any significant effects on the kidney weight. Similarly, [Schöne et al. \(1990\)](#) also reported that feeding 15% rapeseed cake resulted in the enlarged liver of pigs, whereas the kidneys

were not affected by dietary rapeseed cake rich in glucosinolates. Woyengo et al. (2011) reported a linear increase in the liver weight relative live BW, but not in heart and kidney weights relative to live BW, due to increasing inclusion of EPCM in diets for broilers from 0 to 40%, indicating that the heart and kidneys of monogastric animals may be less susceptible to glucosinolate degradation products than the liver.

The increased thyroid gland weights and reduced serum T4 level due to dietary CPCC could be explained by the increased metabolic activity of thyroid gland and reduced synthesis of T4 in the thyroid gland due to impairment of iodine uptake by thyroid gland by dietary glucosinolates. Glucosinolate degradation products impair the uptake of iodine by thyroid gland and reduce synthesis of T4, leading to enlarged thyroid gland and reduced serum level of T4 (Schöne et al., 1997; Tripathi and Mishra, 2007). The increased thyroid gland weights of pigs observed in the current study is in agreement with the results from the study of Velayudhan et al. (2017), who reported increased thyroid gland weights and reduced serum level of T4 in growing pigs due to an increase in the dietary level of EPCM. Parr et al. (2015) also reported that an increase in dietary level of high-protein SECM from 0 to 40% resulted in the enlargement of thyroid gland and a reduction in serum T4 level in nursery pigs.

Increasing dietary level of CPCC did not adversely affect hemoglobin content and red blood cell count of pigs. Dietary inclusion of rapeseed meal resulted in reduced red blood cell count and blood hemoglobin content of pigs due to glucosinolate-induced iodine deficiency (Schöne et al., 1990). However, in the current study, dietary CPCC did not affect red blood cell count and blood hemoglobin content of pigs. Also, in the previous studies, red blood cell count and blood hemoglobin content of pigs were not affected by dietary EPCM (Velayudhan et al., 2017) or SECM (Parr et al., 2015). The calculated total glucosinolate content in diets fed in the current study and in the studies of Velayudhan et al. (2017) and Parr et al. (2015) was less than 7 $\mu\text{mol/g}$, whereas the calculated total glucosinolate content in diets fed in the study of Schöne et al. (1990) was 10.4 $\mu\text{mol/g}$. Woyengo et al. (2011) observed a reduction in ADG and an increase liver weight of broilers, but nonsignificant change in blood hemoglobin content due to an increase in concentration of glucosinolates in diets from 0 to 3.2 $\mu\text{mol/g}$ through dietary inclusion of EPCM, implying that the amounts of dietary glucosinolates

that are required to affect blood parameters are greater than those required to affect growth performance and liver weight. Thus, the lack of effect of dietary CPCC in the current study and of dietary EPCM and SECM in the studies of Velayudhan et al. (2017) and Parr et al. (2015) on red blood cell count and blood hemoglobin content of pigs could have been due to relatively lower content of glucosinolates in canola coproducts than in rapeseed meal, leading to lower dietary glucosinolate content in canola coproduct-based diets. In the current study, mean corpuscular volume and mean corpuscular hemoglobin were linearly reduced by an increase in dietary level of CPCC. The reduced concentrations of mean corpuscular volume and mean corpuscular hemoglobin of pigs by the dietary CPCC indicates that the size of red blood cells and hemoglobin content in them were reduced by dietary CPCC. However, Parr et al. (2015) did not observe a reduction in mean corpuscular volume and mean corpuscular hemoglobin of nursery pigs due to an increase in dietary level of conventional or high-protein SECM from 0 to 40%. The differences between the current study and that of Parr et al. (2015) with regard to the effects of dietary canola coproducts on mean corpuscular volume and mean corpuscular hemoglobin of pigs could have been due to the differences in the content and composition of glucosinolates among the canola coproducts.

In conclusion, increasing the dietary inclusion level of CPCC from 0 to 40% resulted in depressed growth performance, increased metabolic activity in the liver and thyroid gland, and reduced serum T4 level of nursery pigs. The indolic glucosinolates and hence total glucosinolates values for the CPCC were greater than the values that were previously reported for EPCM or SECM. It appears that the indolic glucosinolates that were present in CPCC had negative effects on growth performance, liver and thyroid gland functions of nursery pigs. Therefore, dietary CPCC should be included in nursery diets based on targeted growth performance and price of CPCC.

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