Tail-end dehulling of canola meal improves apparent and standardized total tract digestibility of phosphorus when fed to growing pigs

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ABSTRACT: Tail-end dehulling of canola meal (**CM**) has been shown to reduce dietary fiber and increase crude protein content in the dehulled meal. The application of this procedure also increased the total and non-phytate P content in the dehulled meal. However, it is unclear if dehulling affects P digestibility in the different fractions (i.e., the dehulled meal and the coarse fraction) and if it differs when fed to growing pigs at two different BW. Therefore, two experiments were conducted to determine the apparent (**ATTD**) and standardized (**STTD**) total tract digestibility of P in dehulled CM fed to growing pigs. Diets containing non-dehulled regular canola meal (**RCM**), and two fractions produced using sieve size of 355 µm: a low-fiber high-protein fraction (dehulled canola meal [**DCM**]) and a high-fiber low-protein fraction (coarse canola meal [**CCM**]) as the only source of P were fed to growing pigs at two different BW. A total of 48 pigs were used for the two experiments. In experiment 1, 24 barrows [(Yorkshire × Landrace) × Duroc] with initial BW of 24.5 ± 1.68 kg were individually housed in metabolism crates and fed the experimental diets for 10 d for total fecal collection. In experiment 2, 24 barrows with an average initial BW of 73.8 ± 4.93 kg were used; experimental diets and fecal collection procedures were the same as in experiment 1. Each experiment used six replicates per treatment. A P-free diet was used to determine basal endogenous losses of P (139.6 ± 10.7 and 150.89 ± 20.1 mg/kg of DMI for experiments 1 and 2, respectively). Data were analyzed as a completely randomized design. In experiment 1, the ATTD and STTD of P were greater ($P < 0.05$) for DCM (42.4% and 46.1%) than for the RCM (32.0% and 35.7%) and CCM (24.5% and 28.4%) diets. In experiment 2, the ATTD and STTD of P were greater ($P < 0.05$) for DCM (38.7% and 42.8%) than for the CCM diet (22.6% and 26.8%); whereas the values for RCM diet were intermediate (31.0% and 35.0%) and not different from the DCM and CCM. In conclusion, dehulling canola meal increased ATTD and STTD of P in growing pigs of different BW; however, there was no effect of BW.

Key words: canola meal, dehulling, digestibility, phosphorus, pig

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INTRODUCTION

Phosphorus is the third most costly nutrient in swine diets, after energy and protein. The efficiency of its utilization is affected by the fact that 60 to 75% of the total P content in seeds is in the poorly available form of phytate (myo-inositol 1,2,3,4,5,6-hexakis dihydrogen phosphate) (de Lange et al., 1993; Angel et al., 2002; NRC, 2012). Moreover, phytate P can't be digested by swine due to their negligible intestinal phytase activity (Pointillart, 1988; Jongbloed et al., 1992; Kies, 2005; Kim et al., 2017). It is estimated that solvent extracted canola meal (**CM**) from *Brassica napus* (*B. napus*) contains around 1.08% total P. Approximately 40% is non-phytate P (NRC, 2012; Slominski et al., 2012; Adhikari et al., 2015; Mejicanos et al., 2016). However, in a recent

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study, Mejicanos et al. (2017) found that through tail-end dehulling, the fraction 1 (particle size < 250 µm) increased the total P content to 1.27%, of which approximately 48% was non-phytate P. Lower fiber and higher total and non-phytate P content in dehulled fractions of CM could improve P utilization by swine. However, it is unclear if the CM fractions obtained through tail-end dehulling will have different P digestibility compared to the parent meal. Furthermore, most of the studies on P digestibility have been performed using growing pigs, and there is limited information on finishing pigs (Almeida et al., 2010; Adhikari et al., 2015; Gutierrez et al., 2015; Bournazel et al., 2018). Additionally, it is unclear if P digestibility would differ when fed to growing or finishing pigs. To effectively utilize the CM fractions obtained through the dehulling process, concerning dietary P supply, it is critical that its standardized total tract digestible P content is determined and used in diet formulation (NRC, 2012). Therefore, the objective of this study was to determine the apparent total tract digestibility (**ATTD**) and standardized total tract digestibility (**STTD**) of P in the regular canola meal (**RCM**) and the two fractions obtained by tail-end dehulling; i.e., dehulled canola meal (**DCM**), and coarse canola meal (**CCM**) fed to growing pigs of two distinct BW.

MATERIALS AND METHODS

The animal use protocol utilized in the present study was reviewed and approved by the Animal Care Committee of the University of Manitoba. Pigs were cared for in accordance with the guidelines of the Canadian Council on Animal Care (2009). The study was conducted at the T. K. Cheung Centre for Animal Science Research.

Dehulling of CM

Based on results of tail-end dehulling of CM carried by Mejicanos et al. (2017), sieve size of 355 µm was selected to produce two fractions: a low-fiber high-protein fraction (DCM) and a high-fiber low-protein fraction (CCM). The two fractions were produced at the Canadian International Grains Institute, Winnipeg, MB, Canada, using a plansifter Model MPAR-8HK (Bühler AG, Uzwil, Switzerland). All other ingredients were obtained from the local market. The analyzed chemical composition of the CM used in the current study is presented in Table 1. The CM utilized in the present study was produced using the pre-press solvent extraction method.

Animals and Housing

A total of 48 barrows [(Yorkshire × Landrace) × Duroc; Genesus, Oakville, MB, Canada] were obtained from Glenlea Swine Research Unit, University of Manitoba. Pigs were subjected to dietary treatments in two separate experiments. In experiment 1, 24 barrows with an initial BW of 24.53 ± 1.68 kg (mean ± SD) were used. When experiment 1 was completed, the barrows were moved to individual pens (1.7 m^2 per pig) with elevated plastic coated metal flooring in a temperature-controlled room (20–22 °C) to reach the required BW for experiment 2. A 16-h light (0600 to 2200 hours), and 8-h dark cycle was provided. Experiment 2 used 24 barrows with an initial BW of 73.83 ± 4.93 kg (mean ± SD). Pigs were randomly assigned to the experimental diets and housed individually in metabolic crates (1.8 × 0.6 m) featuring smooth transparent plexiglass sides to allow visual contact between pigs in adjacent crates. The floors consisted of plastic coated expanded metal slatted sheets. Room temperature was set at 22 °C. Water from the city of Winnipeg was provided using nipple drinkers and was available for ad libitum intake throughout the experiment. The water quality test indicated 71 ppm of calcium carbonate, and 0.63 ppm total P (Winnipeg.ca, 2017). A 16-h light (0600 to 2200 hours) and 8-h dark cycle was used.

Experimental Diets

Four mash corn starch-based diets were prepared for each experiment. Two diets contained the dehulled (DCM) and coarse fractions (CCM) obtained from the dehulling process, and one diet consisted of the RCM from *B. napus* as the only source of P. In the determination of endogenous phosphorus losses (**EPL**) a P free diet was utilized (Petersen and Stein, 2006; Adhikari et al., 2015). Limestone was added to maintain a constant Ca:total P ratio in all diets. All diets were formulated based on standardized ileal digestible AA and supplemented with vitamins, AA and minerals (except P) to meet or exceed recommended specifications for growing pigs within the 25 to 50 kg (experiment 1) and 75 to 100 kg BW range (experiment 2; NRC, 2012). Pigs were fed their respective diets at 4% of BW as recorded at the beginning of the experiment. The daily rations were offered in two equal meals at 0800 and 1600 hours. Data for the daily feed supplied was summarized, and orts were subtracted to calculate total feed intake. The composition and nutrient contents of the diets

Table 1. Analyzed chemical composition of non-dehulled (RCM), dehulled (DCM) and coarse (CCM) *B. napus* canola meals produced by sieving (as is basis)

	Canola meal[a]		
Item, %	RCM	DCM	CCM
GE, kcal/kg	4,323	4,345	4,252
DM	90.40	90.30	90.8
CP	36.20	39.50	35.40
Ether extract	3.50	3.70	2.60
Fiber fractions			
Neutral detergent fiber	26.20	17.80	30.30
Acid detergent fiber	19.40	12.10	21.10
Crude fiber	13.70	11.30	13.70
Total dietary fiber	33.00	24.57	37.25
Non-starch polysaccharides	20.54	16.97	20.99
Rhamnose	0.29	0.26	0.28
Arabinose	4.32	4.14	4.46
Xylose	1.67	1.69	1.86
Mannose	0.38	0.34	0.50
Galactose	1.53	1.38	1.66
Glucose	6.69	5.30	6.94
Uronic acids	5.66	3.86	5.29
Lignin and polyphenols	10.17	6.01	11.38
Glycoprotein (NDICP)	3.60	2.41	6.53
Ash	6.60	7.50	6.90
Total P	1.10	1.27	1.08
Phytate-bound P[b]	0.71	0.79	0.73
Non-phytate P[c]	0.39	0.48	0.35
Ca	0.67	0.60	0.67

[a]Dehulled *B. napus* (DCM, particle size < 355 µm) coarse *B. napus* (CCM, particle size > 355 µm).

[b]Phytate-bound P was calculated as 28.2% of phytate (Tran and Sauvant, 2004).

[c]Non-phytate P was calculated as the difference between total P and phytate-bound P.

used for experiment 1 are shown in Tables 2 and 3. The composition and nutrient contents of the diets used for experiment 2 are presented in Tables 4 and 5.

Experimental and Analytical Procedures

Pigs were assigned the experimental diets in a completely randomized design to give six replicates per diet. Experiment 1 had 12 d of experimental period divided into 7 d of adaptation to feeding and environment and 5 d of total fecal collection. When experiment 1 was completed, pigs were fed a corn-soybean meal (**SBM**) based commercial diet until they reached the target BW (75 kg) experiment 2. Experiment 2 had 10 d. of experimental period. The period of adaptation to feeding and environment was reduced to 5 d due to animal welfare concerns derived from the size of the animals and the limited space in the metabolic crates; the last 5 d were for total fecal collection. The total fecal collection was done as described by Ragland et al. (1998) and Woyengo et al. (2010). Briefly, on the morning of the first day of the experimental period (0800 hours), each pig received 5 g of ferric oxide (Fisher Scientific, Ontario, Canada) as an indigestible marker in 100 g of feed; the remaining portion of feed was offered after all the marked feed was consumed. The fecal collection was initiated when marker appeared in feces. On the morning of day 5 of the collection period, pigs were offered 100 g of marked feed containing ferric oxide, as indicated above, and fecal collection ended when marker appeared in feces. Fecal samples for future analyses were collected every morning from the trays underneath the metabolic crates, and crate floors into sealed sample plastic bags, weighed and then stored frozen at –20 °C.

In preparation for analysis, fecal samples were dried in a forced air oven at 60 °C for 5 d. Dried samples were pooled for each pig and ground using a heavy-duty blender (model CB15, Waring Commercial, Torrington, CT), then a subsample was obtained after thoroughly mixing the ground feces for chemical analysis. Diets and CM were finely ground before analysis using a Foss sample preparation Cyclotec 1093 mill (Foss Allé 1, DK-3400 Hilleroed, Denmark). Experimental diets and CM were subject to CP (N×6.25) analysis using an N analyzer, model TruSpec N (Leco Corp., St. Joseph, MI). Standard AOAC (2005) procedures were used for DM (method 930.15), ether extract (EE; method 2003.06), and ash determination (method 942.05). Phytate-P was determined using the method described by Haug and Lantzsch (1983). Dietary fiber was determined by a combination of neutral detergent fiber (NDF) and detergent-soluble non-starch polysaccharide (NSP) measurements and was calculated as the sum of NDF and detergent soluble NSP (Slominski et al., 1994). The NDF was determined using an Ankom fiber analyzer (Ankom Technology, Macedon, NY) and according to AOAC (2005) method 2002.04. Total NSP were determined by gas-liquid chromatography (component neutral sugars) using an SP-2340 column and Varian CP3380 gas chromatograph (Varian Inc., Palo Alto, CA) and colorimetry (uronic acids) using a Biochrom Ultrospec 50 (Biochrom Ltd., Cambridge, UK) and the procedure described by Englyst and Cummings (Englyst and Cummings, 1984; Englyst and Cummings, 1988) with some modifications (Slominski and Campbell, 1990).

Table 2. Composition of experimental diets fed to growing pigs in experiment 1 (as-fed-basis)

	Diets			
Ingredients, %	RCM	DCM	CCM	P-Free
Non-dehulled canola meal	32.00	-	-	-
Dehulled canola meal	-	28.00	-	-
Coarse canola meal	-	-	32.00	-
Corn starch	23.26	26.48	23.00	47.28
Dextrose	10.00	10.00	10.00	-
Sucrose	20.00	20.00	20.00	20.00
Vegetable oil	4.00	4.00	4.00	4.00
Limestone	0.28	0.38	0.26	0.52
Solka floc	-	-	-	4.00
Vit-min premix[a]	1.00	1.00	1.00	1.00
Potassium carbonate	-	-	-	0.40
Magnesium oxide	0.01	0.02	0.01	0.10
Iodized salt	0.50	0.50	0.50	0.50
Pork gelatin	8.00	8.80	8.50	20.00
Lysine-HCl	0.24	0.23	0.22	0.25
$_{DL}$-Methionine	0.09	0.09	0.09	0.35
$_{L}$-Threonine	0.12	0.11	0.11	0.31
$_{L}$-Tryptophan	0.07	0.08	0.06	0.16
$_{L}$-Histidine	-	-	-	0.19
$_{L}$-Isoleucine	0.06	0.10	0.06	0.26
$_{L}$-Valine	0.16	0.06	0.03	0.21
$_{L}$-Leucine	0.21	0.15	0.16	0.47

[a]Supplied per kg of diet, Vitamins: vitamin A, 1560 IU; vitamin D3, 180 IU; vitamin E, 13.2 IU; vitamin K, 0.6 mg; thiamin (B1): 1.2 mg; riboflavin, 3.0 mg; pantothenate, 6.6 mg; choline, 360 mg; niacin, 12 mg; vitamin B6, 1.2 mg; vitamin B12, 12 µg; biotin, 200 µg; folic acid, 0.36 mg. Minerals: Cu, 10 mg; Zn, 110 mg; Fe, 120 mg; Mn, 10 mg; I, 0.4 mg; Se, 0.3 mg.

The content of NSP was measured in both the meals and the NDF residues. Neutral detergent soluble NSP was calculated as total sample NSP minus NSP present in the NDF residue, and total dietary fiber was determined by the summation of NDF and NDF-soluble NSP. The contents of CP (N × 6.25) and ash in NDF residue were also measured. The value for lignin and associated polyphenols was calculated by difference [NDF − (NSP + protein + ash)] (Slominski et al., 1994). Diets, fecal samples and CM for Ca and P analysis were ash at 600°C for 12 h, digested according to the AOAC (2005) method 985.01 and determined using a Varian Inductive Coupled Plasma Mass Spectrometer (Varian Inc., Palo Alto, CA). The GE of the diets was measured using an adiabatic bomb calorimeter (Model 6400, Parr Instruments, Moline, IL) calibrated using benzoic acid as a standard. The concentration of phytate-bound P in the CM was calculated as 28.2% of analyzed phytate (Tran and Sauvant, 2004). Non-phytate P was calculated by subtracting phytate-bound P from total P.

Calculations and Statistical Analysis

The ATTD (%) of P in each of the 3 P-containing diets was calculated using the following equation:

$$\text{ATTD} = \left[\left(\text{Pi} - \text{Pf}\right) / \text{Pi}\right] \times 100$$

Where ATTD is apparent total tract digestibility; Pi is the total P intake (g) during the 5 d of fecal collection of each experimental period; Pf is the total fecal output of P originating from the feed intake during the collection period (g; Petersen and Stein, 2006). The ATTD of Ca was also calculated using the same equation.

The EPL was expressed relative to the DMI of the animals and calculated from pigs fed the P-free diet using the following equation (Petersen and Stein, 2006):

$$\text{Basal EPL}\left(\text{mg / kg of DM}\right) = \left[\left(\text{Pf / Fi}\right) \times 1{,}000 \times 1{,}000\right],$$

where Fi is the total feed (g of DM) intake during the 5-d collection period. The endogenous losses for each of the P-containing diets were calculated by multiplying the calculated EPL per kilogram of DMI by the DMI of each pig for the 5-d collection period. The endogenous losses were then subtracted from the total fecal output of P, and the total amount of fecal P was partitioned into P originating from endogenous losses and P originating from undigested dietary P.

The STTD of P for each ingredient was calculated by correcting ATTD values for the EPL, as described by Petersen and Stein (2006) using the following equation:

$$\text{STTD}\left(\%\right) = \left\{\left[\text{Pi} - \left(\text{Pf} - \text{EPL}\right)\right]\right) / \text{Pi}\right\}$$

Data were analyzed using the Mixed procedure of SAS (SAS software 9.4, SAS Institute, 2013) as a completely randomized design. Each pig was considered as an experimental unit. Means were separated using Tukey's honestly significant difference test. The PROC UNIVARIATE of SAS was used to confirm that variances were homogeneous and to analyze for outliers. Outliers were removed. All statements of significance are based on $P < 0.05$ and trends were observed at $0.05 < P \leq 0.10$.

RESULTS

Chemical Composition of DCM

The analyzed chemical compositions of the CM and fractions used in the formulation of the

Table 3. Calculated and analyzed nutrient content of experimental diets fed to growing in experiment 1 (%, as-fed-basis)

	Diets			
	RCM	DCM	CCM	P-Free
Calculated composition				
CP[a]	20.00	20.00	20.00	20.00
NE, kcal/kg	2,271	2,295	2,259	2,293
Ca	0.36	0.36	0.36	0.30
Total P	0.36	0.36	0.34	0.00
Potassium	0.50	0.50	0.50	0.40
Magnesium	0.10	0.10	0.10	0.10
Arginine	1.56	1.24	1.31	1.56
Histidine	0.34	0.34	0.36	0.34
Isoleucine	0.51	0.51	0.51	0.51
Leucine	0.99	0.99	0.99	0.99
Lysine	0.98	0.98	0.98	0.98
Methionine	0.35	0.35	0.36	0.53
Met + Cys	0.55	0.55	0.55	0.55
Threonine	0.59	0.59	0.59	0.59
Tryptophan	0.17	0.17	0.17	0.17
Phenylalanine + Tyr	1.63	1.28	1.30	1.63
Valine	0.64	0.64	0.64	0.64
Analyzed composition				
DM	92.00	91.90	92.18	92.18
GE, kcal/kg	4,084	4,156	4,156	4,108
CP	23.24	24.35	23.24	26.33
Ether extract	2.81	4.63	3.68	3.53
Ash	2.75	2.79	2.77	1.41
NDF	11.73	7.93	11.70	4.73
Ca	0.29	0.23	0.22	0.19
Total P	0.35	0.36	0.32	0.00

[a]All diets were formulated to contain the following quantities of the ileal digestible indispensable AA (%): Arg, 0.45; His, 0.34; Ile, 0.51; Leu, 0.99; Lys, 0.98; Met, 0.28; Met + Cys, 0.55; Phe, 0.59; Phe + Tyr, 0.92; Thr, 0.59; Trp, 0.17; Val, 0.64.

experimental diets are presented in Table 1. The total P was 1.1%, 1.27% and 1.08%; the non-phytate P was 0.39%, 0.48% and 0.35%; the phytate-bound P was 0.71%, 0.79% and 0.73%; for RCM, DCM and CCM, respectively. Whereas CP was 36.2%, 39.5% and 35.4%; total dietary fiber was 33.0%, 24.6% and 37.3%, for RCM, DCM and CCM, respectively.

Experiment 1

All pigs remained healthy and readily consumed their assigned diet throughout the experiment. The analyzed values for DM, GE, CP, Ash, and P were similar for all diets. However, NDF was lower for diets containing DCM compared to diets containing RCM and CCM (7.93% vs. 11.73% and 11.70%, respectively). Ether extract content was higher for diets containing DCM compared to diets with CCM and RCM (4.63% vs. 3.68% and 2.81%, respectively). Analyzed values for Ca were higher for diets containing RCM compared to diets containing DCM and CCM (0.29% vs. 0.23% and 0.22%, respectively). The determined basal EPL value was 139.6 ± 11 mg/kg of DMI (Table 6).

There were no differences ($P > 0.10$) among treatments for total feed and P intake (Table 7). However, Ca intake was greater ($P < 0.001$) for diets containing RCM than for diets containing DCM and CCM. Feeding DCM reduced ($P < 0.001$) total fecal output, reduced ($P < 0.05$) Ca output; and tended to reduce ($P < 0.10$) P output, compared to feeding RCM and CCM. Dehulled CM had greater ATTD of P ($P < 0.001$) compared to RCM and CCM (42.4% vs. 32.0% and 24.5%, respectively). Likewise, STTD of P was greater ($P < 0.001$) for DCM compared to RCM and CCM (46.1% vs. 35.7% and 28.4%, respectively). The ATTD of Ca was less ($P < 0.001$) for CCM compared to RCM and DCM (36.9% vs. 51.1% and 54.8%, respectively; Table 7). However, as limestone was added to the diets, digestibility of Ca corresponds to a mix of CM and other sources.

Experiment 2

The composition, calculated and analyzed nutrient contents of the experimental diets used in experiment 2 are presented in Tables 4 and 5. The analyzed values for DM, GE, CP, Ash, and P were similar for all the diets. However, NDF was lower for diets containing DCM compared to diets containing RCM and CCM (5.36% vs. 9.85% and 8.78%, respectively). Analyzed values for ether extract were higher for diets containing DCM compared to diets containing RCM and CCM (5.26% vs. 4.78% and 4.94%, respectively). Whereas, values for Ca were higher for diets containing RCM compared to diets containing DCM and CCM (0.29% vs. 0.25% and 0.25%, respectively). The determined basal EPL value was 150.89 ± 20 mg/kg of DMI (Table 6).

There were no differences ($P > 0.10$) among treatments for total feed intake, Ca and P output (Table 8). However, P intake was greater ($P < 0.01$) for diets containing DCM compared to diets containing RCM and CCM. Whereas Ca intake was greater ($P < 0.01$) for diets containing RCM and CCM compared to diets containing DCM. Feeding DCM resulted in less ($P < 0.001$) total fecal output than feeding RCM and CCM. However, feeding DCM resulted in higher ($P < 0.001$) concentration of Ca and P in feces compared to feeding RCM and

Table 4. Composition of experimental diets fed to growing pigs in experiment 2 (as-fed-basis)

Ingredients, %	Diet 1 RCM	Diet 2 DCM	Diet 3 CCM	P-free diet
Non-dehulled canola meal	32.00	-	-	-
Dehulled canola meal	-	28.00	-	-
Coarse canola meal	-	-	32.00	-
Corn starch	24.10	28.05	24.20	48.51
Dextrose	10.00	10.00	10.00	0.00
Sucrose	20.00	20.00	20.00	20.00
Vegetable oil	4.00	4.00	4.00	4.00
Limestone	0.27	0.39	0.27	0.52
Solka floc	-	-	-	4.00
Vit-Min premix[a]	1.00	1.00	1.00	1.00
Potassium carbonate	-	-	-	0.40
Magnesium oxide	0.01	0.02	0.01	0.10
Iodized salt	0.50	0.50	0.50	0.50
Pork gelatin	8.00	8.00	8.00	20.00
Lysine-HCl	0.07	-	-	-
$_{DL}$-Methionine	-	-	-	0.22
$_{L}$-Threonine	0.03	-	-	0.18
$_{L}$-Tryptophan	0.02	0.04	0.02	0.12
$_{L}$ Histidine	-	-	-	0.09
$_{L}$-Isoleucine	-	-	-	0.14
$_{L}$-Leucine	-	-	-	0.22
Total	100.00	100.00	100.00	100.00

[a]Supplied per kg of diet, Vitamins: vitamin A, 2000 IU; vitamin D3, 200 IU; vitamin E, 40 IU; vitamin K, 2 mg; thiamin (B1), 1.5 mg; riboflavin, 7.0 mg; pantothenate, 14 mg; choline, 350 mg; niacin, 21 mg; vitamin B6 2.5 mg; vitamin B12: 25 µg; biotin, 70 µg; folic acid, 1 mg. Minerals: Cu, 10 mg; Zn, 110 mg; Fe, 120 mg; Mn, 10 mg; I, 0.4 mg; Se, 0.3 mg.

CCM diets. No differences ($P > 0.10$) were observed for P and Ca output among diets.

The ATTD of Ca and P and the STTD of P are shown in Table 8. The ATTD and STTD of P were greater ($P < 0.05$) in DCM than in CCM. However, values for RCM were intermediate and not different from those of either DCM and CCM ($P > 0.05$). The ATTD of Ca in diets containing DCM was less ($P < 0.05$) than in diets containing RCM and CCM; but values of ATTD of Ca in RCM and CCM were not different ($P > 0.10$). However, like in experiment 1, limestone was added to the diets, therefore, digestibility of Ca corresponds to a mix of CM and other sources.

DISCUSSION

Efficient use of P in swine diets is necessary to minimize feed cost and to decrease the potential environmental impact associated with P accumulation in soils and surface water bodies due to land application of swine manure (Baxter et al., 2003; Adhikari, 2013; Environment and Climate Change Canada, 2017). Several strategies have been developed to maximize the use of P in swine diets, and moreover, minimize P excretion, including phase feeding (Han et al., 2000), the use of microbial phytase (Jongbloed et al., 1992; Kies, 2005; Adhikari et al., 2016), replacing conventional ingredients with high available P varieties (Baxter et al., 2003), and the use of STTD P in formulating swine diets (Petersen and Stein, 2006; NRC, 2012). Therefore, it is crucial to determine STTD of P in different feed ingredients.

Dehulling of canola has been investigated to reduce fiber content, increase protein content, and enhance the nutritive value of the meal (Thakor et al., 1995; Hansen et al., 2017; Mejicanos et al., 2017). Front-end dehulling (i.e., removal of hulls before oil extraction) and tail-end dehulling (i.e., removal of hulls from the meal after oil extraction), improve the quality of the CM, however, factors are preventing the crushing industry from implementing the suggested technologies. Among them: losses of oil during the front-end dehulling process, the excessive fineness of the dehulled meal and the consequent difficulties with percolation of the miscella (Khajali and Slominski, 2012). Kracht et al. (2004) improved the nutritive value of CM using front-end dehulling, with a notable reduction in CF, NDF and ADF contents (38%, 28% and 25%, respectively); moreover, increasing CP and sugar by 7% and 14%, respectively. McCurdy and March (1992) defined a tail-end dehulling process for solvent extracted CM, in which the meal was ground using a disc mill and sieved using a U.S. standard mesh 70, producing a low-fiber fraction. More recently, in Norway it has been developed a tail-end dehulling process which combines ball milling with sieving technology, achieving high separation of hulls and endosperm (Hansen et al., 2017). Air classification has been utilized effectively to achieve tail-end dehulling of CM, this method is based on the difference in particle size and density between hulls and embryo (Beltranena and Zijlstra, 2011). Other factors affecting implementation of dehulling in CM include the high cost associated with air classification, and the variations in the methods currently suggested for tail-end dehulling (McCurdy and March, 1992; Kracht et al., 2004; Beltranena and Zijlstra, 2012; Hansen et al., 2017; Mejicanos et al., 2017). Therefore, dehulled CM is not available at a commercial level, moreover, there is no information available regarding ATTD and STTD of P in dehulled CM. The information available considers mainly regular CM from *B. napus* and *B. juncea* (Adhikari et al., 2015; Maison et al.,

Table 5. Calculated and analyzed nutrient content of experimental diets fed to growing pigs in experiment 2 (as-fed-basis)

	Diet 1	Diet 2	Diet 3	
Item, %	RCM	DCM	CCM	P-free diet
Calculated Composition				
CP[a]	19.16	18.57	18.82	19.42
NE, kcal/kg	2,293	2,300	2,262	2,279
Ca	0.36	0.36	0.36	0.298
Total P	0.36	0.36	0.34	0.00
Potassium	0.50	0.50	0.50	0.40
Magnesium	1.00	1.00	1.00	1.00
Arginine	1.24	1.25	1.24	1.56
Histidine	0.36	0.35	0.36	0.25
Isoleucine	0.45	0.40	0.45	0.39
Leucine	0.82	0.82	0.82	0.74
Lysine	0.85	0.77	0.75	0.78
Methionine	0.26	0.26	0.26	0.4
Met + Cys	0.46	0.46	0.46	0.42
Threonine	0.51	0.47	0.48	0.46
Tryptophan	0.13	0.13	0.13	0.13
Phenylalanine + Tyr	1.28	1.23	1.26	1.63
Valine	0.60	0.56	0.60	0.44
Analyzed composition				
DM	91.83	91.94	92.13	92.08
GE, kcal/kg	4,108	4,108	4,132	4,251
CP	19.06	20.33	20.47	21.33
Ether extract	4.78	5.26	4.94	4.24
Ash	2.46	2.49	2.36	1.46
NDF	9.85	5.36	8.78	2.25
Ca	0.29	0.25	0.25	0.12
Total P	0.36	0.37	0.35	0.011

[a]All diets were formulated to contain the following quantities of the ileal digestible indispensable AA (g/kg): Arg, 0.33; His, 0.25; Ile, 0.39; Leu, 0.74; Lys, 0.73; Met, 0.21; Met + Cys, 0.42; Phe, 0.44; Phe + Tyr, 0.69; Thr, 0.46; Trp, 0.13; Val, 0.48.

2015), and more recently, ATTD and STTD of P in high-protein CM (She et al., 2017).

In the present study, it was determined that compared to RCM, DCM had 32% less NDF, 38% less ADF, 17% less NSP, 41% less lignin and polyphenols and 26% less total dietary fiber. However, DCM had 9% more CP, 16% more total P, 23% more non-phytate P, 11% more phytate-bound P. Phytate-bound P levels in DCM are comparable to those found in high-protein CM (Parr et al., 2015). Levels of total and phytate-bound P in RCM and DCM determined in the present experiment are consistent with values reported by Kracht et al. (2004). However, when compared to high-protein CM and RCM, DCM had higher levels of non-phytate P (0.26% and 0.39% vs. 0.48%, respectively). Furthermore, high-protein CM has almost twice the levels of glucosinolates (**GSL**) than regular CM (14.2 to 15.5 vs. 8.7 µmol/g, respectively; Parr et al., 2015). Higher GSL content in dehulled CM compared to its parent meal (9.6 vs. 9.2) has been observed (Mejicanos et al., 2017). The DCM obtained by sieving in the present study had lower CP content than the high-protein CM evaluated by Parr et al. (2015). However, they have similar values of GE, EE, NDF, and ADF. When compared to RCM, CCM had a reduction in CP of 2%, total P of 2%, non-phytate P of 10%. However, NDF increased by 15%, ADF by 9%, NSP by 2.2%, and lignin and polyphenols by 12%.

Table 6. Basal endogenous phosphorus losses (EPL) in pigs fed P free diets

	Experiment 1		Experiment 2	
Item	Mean	SE	Mean	SE
ATFI[a], g DM	5,202	196	10,835	736
P output[b], g	0.72	0.036	1.58	0.17
Average EPL, mg/kg DM	139.60	10.7	150.89	20.1

[a]Average total feed intake during the 5-d collection period (n = 6).

[b]Total fecal output of P during the 5-d collection period (n = 6).

The two main concerns regarding tail-end dehulling are the yield of dehulled meal and marketability of the coarse fraction containing the hulls. In that respect, the tail-end dehulling procedure used in the present study was effective in producing a high nutrient density meal. Moreover, the yield obtained utilizing sieving technology (particle size < 355 µm) in CM from eight Canadian processing facilities, was an average 25.9% (Mejicanos et al., 2017). The combination of ball milling and sieving (sieve size 150 µm) can yield 42% dehulled meal (Hansen et al., 2017). However, as the yield of the dehulled meal increases, the fiber content of the fraction comprising the hulls also increases. In a study investigating CM fractionation, it was observed that total dietary fiber rose to 35.5% in the particle size of 355–600 µm, compared to 30.1% and 21.4% in the parent meal and the dehulled fraction Fine 1, respectively (Mejicanos et al., 2017). Regarding marketability of the meals, regulations established by the Canadian Oilseed Processors Association, COPA (2016) indicated that the combined values for protein and fat in CM could not be below 37% and stipulate a maximum of 12% for crude fiber. In the present study, the combined values for CP and fat were: 39.70%, 37.98%, and 43.24% for RCM, CCM, and DCM, respectively. Moreover, despite crude fiber values in the parent meal being above the requirements for overseas export (13.7%), dehulling reduced crude fiber content in the DCM to 11.3%, which is within limits established by COPA.

Table 7. ATTD of P and Ca and STTD of P by growing pigs fed diets containing non-dehulled (RCM), dehulled (DCM) and coarse (CCM) canola meal from *B. napus* in experiment 1

	Canola meal				
Item	RCM	DCM	CCM	SEM	*P*-value
Average BW (kg)	25.33	26.88	27.18		
Feed intake, g/d (as is)					
Feed intake	1,120	1,143	1,139	56.23	0.954
Ca intake	3.28[a]	2.61[b]	2.46[b]	0.126	0.001
P intake	3.88	4.00	3.76	0.187	0.607
Fecal output (DM basis)					
Total feces, g/d	92[a]	59[b]	103[a]	3.3	< 0.001
Ca in feces, %	1.71[b]	2.00[a]	1.50[b]	0.065	< 0.001
P in feces, %	2.84[b]	3.92[a]	2.71[b]	0.099	< 0.001
Ca output, g/d	1.60[a]	1.18[b]	1.55[a]	0.090	0.012
P output, g/d	2.7	2.3	2.7	0.15	0.090
Digestibility, %					
ATTD of Ca	51.1[a]	54.8[a]	36.9[b]	1.77	< 0.001
ATTD of P	32.0[b]	42.4[a]	24.5[c]	1.29	< 0.001
STTD[d] of P	35.7[b]	46.1[a]	28.4[c]	1.29	< 0.001

[a,b,c] Data within a row without a common letter are different ($P < 0.05$).

[d]Values for the STTD of P were calculated by correcting the ATTD values for the basal endogenous loss of P. The basal endogenous loss of P was estimated in pigs fed the P-free diet at 139.6 ± 11 mg/kg of DMI.

Calcium intake was different between RCM, DCM, and CCM diets for both experiments. As Ca intake increased, ATTD of Ca increased, which is consistent with observations by González-Vega et al. (2013) indicating that the ATTD of Ca increased with increasing Ca level in the diets. The RCM, DCM, and CCM were the sole source of P in the experimental diets. Calcium carbonate was supplemented in all diets to achieve a Ca:P ratio of 1:1. However, the average analyzed total Ca and P in the diets were 0.25 and 0.34%, for experiment 1; and 0.26 and 0.36 % for experiment 2, respectively. Resulting in Ca:P ratios of 0.83:1, 0.64:1, and 0.69:1 for RCM, DCM and CCM, respectively, for experiment 1. Whereas, the Ca:P ratios were 0.81:1, 0.68:1 and 0.71:1, respectively, for experiment 2. Deviating from the target ratio, and differences in Ca:P ratio between diets represent a potential confounding factor on the ATTD and STTD of P between meals, as differences in Ca:P ratios could be a factor in the differences in digestibility between diets, rather than the meals. However, Vipperman et al. (1974) found that the optimal Ca:P ratio is valid only when the dietary levels of these two elements are supplied in the correct amount, indicating higher plasma P concentrations in pigs fed diets containing 0.25% Ca and 0.50% P (0.5:1 Ca:P ratio) compared to pigs fed diets containing 0.50% Ca and 0.50% P (1:1 Ca:P ratio), as the animal can draw from bones during periods of dietary shortage (Harrison and Fraser, 1960; Campbell and Douglas, 1965). Furthermore, it has been indicated that the Ca:P ratio is less critical if the diets contain excess P (Prince et al., 1984) and that a narrower Ca:P ratio could result in more efficient P utilization (Hancock et al., 1986; Jongbloed, 1987). In a study regarding ATTD and STTD of P in 36 samples of CM-rapeseed from North America and Europe, was observed that the supplementation of 0.7% of calcium carbonate to all diets (40% CM-rapeseed) resulted in dietary Ca content in the range of 0.47 to 0.76%. The dietary P content of the diets ranged from 0.41 to 0.52%, resulting in Ca:P ratios between 1:1 to 1.7:1. The ATTD and STTD of P for CM were 44.99 and 48.82 %, respectively (Maison et al., 2015), which is higher than the values found in the present study for RCM for growing pigs.

When compared total fecal output on the pigs fed diets containing DCM and RCM, a reduction of 36 and 38%, for experiment 1 and experiment 2, respectively, was observed. The decrease in fecal output can be attributed to higher nutrient density and lower fiber content in DCM compared to RCM. Using ingredients with low-fiber content in place of high-fiber ingredients has been shown to reduce manure volume considerable (Granhi, 2001).

The ATTD of P in experiment 1 and experiment 2 were, for diets containing RCM, 32% and 31%, respectively; these values are in accordance with those indicated by NRC (2012) and Adhikari et al. (2015; 28% ± 4% and 30%, respectively), nevertheless higher than the values (24% ± 3%) found by Rodehutscord et al. (1997). However, dehulling increased the ATTD of P in DCM compared to RCM from 32% to 42%, and from 31% to 39% for experiment 1 and experiment 2, respectively. Nevertheless, when comparing CCM to RCM, a reduction on ATTD of P from 32% to 25%, and from 31% to 23 % for experiment 1 and experiment 2, respectively, was observed. The increase in ATTD of P in DCM could be due to its higher non-phytate P content, which is known to be highly digestible (Jongbloed, 1987; Ravindran et al., 2000). Higher fiber content on CCM could be associated with lower ATTD of P. However, a P digestibility study in CM from *B. napus* and *B. juncea* found no differences in ATTD between the 2 meals despite distinct NDF content (24.2 vs. 16%, respectively). Still, the two meals had comparable phytate and non-phytate P contents (Adhikari et al., 2015). Furthermore, no effect of fiber on ATTD was observed in a study on the effects of rapeseed meal fiber content on

Table 8. ATTD of P and Ca and STTD of P by growing pigs fed diets containing non-dehulled (RCM), dehulled (DCM) and coarse (CCM) from *B. napus* in experiment 2

	Canola meal				
Item	RCM	DCM	CCM	SEM	*P*-value
Average BW (kg)	73.02	74.03	73.53		
Feed intake, g/d (as is)					
Feed intake	3,032	3,115	3,034	44.94	0.361
Ca intake	8.64[a]	6.15[b]	8.94[a]	0.112	< 0.001
P intake	10.35[b]	11.02[a]	10.11[b]	0.156	0.004
Fecal output (DM basis)					
Total feces, g/d	256[a]	158[b]	277[a]	11.551	<0.001
Ca in feces, %	1.89[b]	2.79[a]	1.82[b]	0.076	<0.001
P in feces, %	2.80[b]	4.27[a]	2.82[b]	0.067	<0.001
Ca output, g/d	4.87	4.45	5.04	0.357	0.511
P output, g/d	7.16	6.76	7.82	0.405	0.222
Digestibility, %					
ATTD of Ca	43.8[a]	27.6[b]	43.6[a]	4.89	0.049
ATTD of P	31.0[ab]	38.7[a]	22.6[b]	3.35	0.016
STTD[c] of P	35.0[ab]	42.8[a]	26.8[b]	3.35	0.018

[a,b]Data within a row without a common letter are different ($P < 0.05$).

[c]Values for the STTD of P were calculated by correcting the ATTD values for the basal endogenous loss of P. The basal endogenous loss of P was estimated in pigs fed the P-free diet at 150.89 ± 20 mg/kg of DMI.

P digestibility in growing pigs (Bournazel et al., 2018). Diets in the present experiment were formulated according to total P content of the meal. However, non-phytate P content was higher for DCM compared to RCM and CCM (0.48% vs. 0.39%, and 0.35%, respectively), which could be the main reason for differences in P digestibility, rather than fiber content of the meals.

The basal EPL found in the present study using the P-free diet were 139.6 ± 11 mg/kg DMI and 150.9 ± 20 mg/kg DMI for experiment 1 and experiment 2, respectively. The basal EPL was in accordance with values described by Petersen and Stein (2006); Almeida and Stein (2010); NRC (2012); Sulabo and Stein (2013); and Adhikari et al. (2015). However, EPL found in the present experiment was lower than the 499 mg/kg DMI value observed in gestating sows with initial BW of 201 kg (Bikker et al., 2016), which indicates comparable EPL in growing and finishing pigs, however, larger EPL would be observed in bigger pigs such as sows.

The STTD of P in experiment 1 and experiment 2 were: for diets containing RCM, 35.7% and 35.0%, respectively. The observed values are consistent with those reported by NRC (2012; 32% ± 6 SD). However, the STTD of P of RCM was lower than the values reported by Maison et al. (2015) and She et al. (2017; 48.2% and 45.2%, respectively). It has been indicated that dietary CP level should be considered in P digestibility studies (Xue et al., 2017), as the ileal digestion of P could be limited by a deficiency in AA intake. However, the diets fed in the present study were balanced following ileal digestible AA. Therefore, the observed ATTD and STTD of P were not affected by AA deficiencies.

The STTD of P for diets containing DCM were 46.1% and 42.8% for experiment 1 and experiment 2, respectively. These results are in accordance with a digestibility study feeding high-protein CM to growing pigs by She et al. (2017) indicating STTD of P of 48.78%. Higher STDD of P observed in DCM compared to RCM and CCM could be attributed to the chemical composition of the DCM which contain greater amounts of non-phytate P rather than lower fiber content (Adhikari et al., 2015; Bournazel et al., 2018). A reduction on STTD of P in CCM compared to DCM for experiment 1 and experiment 2, respectively, was observed. The reduction in P digestibility can be attributed to higher non-phytate P in DCM compared to CCM (0.48% vs. 0.35%, respectively). This is consistent with observations by Bournazel et al. (2018) who studying the effects of fiber content in rapeseed meal on P and Ca digestibility, found that when using front-end dehulled rapeseed meal instead of whole rapeseed meal, or adding hulls, fiber content had no effect on ATTD of P. However, Partrige (1978) observed a reduction in the apparent absorption of P when cellulose was included at high levels (90 g/kg), which suggests that the type of fiber can affect P digestibility.

In conclusion, tail-end dehulling of CM improves the ATTD and STTD of P in CM fed to growing pigs of two distinctive BW. The results from this study also indicate that feeding high nutrient density DCM to growing and finishing pigs would reduce manure volume and P discharge into the environment, improving P utilization in swine diets.

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