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Non Ruminant Nutrition

Chemical composition and digestible and metabolizable energy contents in cold-pressed canola expellers fed to growing pigs

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Abstract

Cold-pressed canola expellers (**CPCE**) are a byproduct of canola oil production obtained using the pressing method without thermal and chemical treatment. While CPCE is a valuable source of dietary energy and protein in swine nutrition, the discrepancy in processing conditions leads to variability in the nutritional quality of CPCE from different sources. This study aimed to determine the chemical composition, and digestible energy (**DE**) and metabolizable energy (**ME**) values of CPCE when fed to growing pigs. Samples of CPCE were collected from five processing facilities across Western Canada. The physical appearance of the CPCE samples hinted at a potential quality variation. Samples were subjected to a complete chemical characterization. Variations ($P < 0.05$) were observed in the chemical composition, with the exception of non-phytate phosphorus, xylose, mannose, and galactose. On a g/kg dry matter **(DM)** basis, CPCE samples ranged as follows: ether extract from 85 to 177; crude protein (**CP**) from 351 to 419; neutral detergent fiber 231 to 300; total dietary fiber from 326 to 373; glycoproteins from 30 to 76; non-starch polysaccharides from 188 to 204, non-phytate phosphorus from 5.5 to 6.4, and gross energy (**GE**) in kcal/kg 5,027 to 5,635. The total glucosinolates **(GLS)** ranged from 5.0 to 9.7 µmol/g DM. Thirty-six (36) growing barrows, with an average initial body weight of 19.2 ± 1.0 kg, were individually housed in metabolism crates and assigned to one of the six experimental diets in a completely randomized design, with six pigs per diet. The diets included a corn–soybean meal (SBM)-based basal diet (100%) and five (5) experimental diets in which 18% of the basal diet was substituted with CPCE from different producers. Pigs were fed the experimental diets for 10 d, with 5-d adaptation period, followed by a 5-d period for the total, but separate, collection of feces and urine. Significant differences ($P < 0.05$) among processing plants were observed in the DE and ME contents of CPCE, which averaged 3,531 and 3,172 kcal/kg DM, respectively. Differences ($P < 0.05$) were noted in the apparent total tract digestibility of GE, nitrogen (**N**), as well as in the retention of DM, GE, and N in CPCE samples. In conclusion, while the chemical composition and values of DE and ME in CPCE vary among processors, the byproduct obtained through cold pressing process can be a valuable source of energy and protein for pig nutrition.

Lay Summary

Cold-pressed canola expellers (**CPCE**), a byproduct of canola oil extraction obtained without using heat or chemicals; however, there is variability in its quality due to differences in processing methods. The research aimed to understand the chemical composition and energy values of CPCE from five processing facilities in Western Canada when fed to growing pigs. Chemical analyses revealed variations in components such as protein, fiber, and gross energy content among samples, mainly attributed to the residual oil content in CPCE. The pig study found significant differences in the CPCE energy values and digestibility among processing plants. In conclusion, while CPCE offers nutritional benefits for pigs, its quality can vary depending on processing conditions.

Key words: cold-pressed canola expellers, chemical characterization, digestible energy, metabolizable energy, pig

Introduction

The use of alternative feedstuffs in pig nutrition offers several advantages. Firstly, the impact of climate change and undesirable weather conditions on crop production has led to a shortage of conventional feedstuffs (Nardone et al., 2010; Chapman et al., 2012; Rojas-Downing et al., 2017). Therefore, alternative feedstuffs, especially co-products of agri-food industry, present a viable solution to this scarcity. Secondly, alternative feedstuffs have become a means to manage the escalating feed cost, market inconsistencies, and disruptions in the supply chain affecting swine nutrition (Zijlstra and Beltranena, 2013; Woyengo et al., 2014; Agyekum and Nyachoti, 2017). Additionally, upcycling byproducts from oil and biodiesel production into high-quality nutritional co-products for swine nutrition helps mitigate the negative environmental impacts associated with their disposal. Furthermore, utilizing locally available feeds or co-products from other industries reduces the greenhouse gas emissions generated by transportation vehicles used for importing conventional feeds. Ultimately, this practice promotes sustainable swine production systems.

Canola, renowned for its role in oil production and biofuel manufacturing, yields co-products that have demonstrated potential as conventional feed in swine nutrition in several

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animal studies. These co-products are widely used, and readily available in Canada for swine production (Seneviratne et al., 2010; Woyengo et al., 2010; Heo et al., 2014; Liu et al., 2016, 2018; Pedersen et al., 2016). The primary method employed in Canadian processing plants to extract canola oil is the pre-press solvent extraction technique. The resulting canola meal (**CM**) from this process is widely utilized protein source in animal nutrition (Canola Council of Canada, 2019). However, one of the alternative approaches is cold-pressed expelling, involving mechanical crushing of canola seed without prior heat conditioning and solvent use. This method has gained attention due to its suitability for on-farm oil production, its relevance in organic farming, and its alignment with the growing demand for biodiesel. Although the cold pressing extraction method is less efficient in oil extraction, it yields a meal with a higher residual oil content (ranging from 8.0% to 15.0%) compared to CM obtained from the pre-press solvent extraction or expelling of heat-conditioned seeds (Spragg and Mailer, 2007; Zhong and Adeola, 2019). The residual oil content in cold-pressed canola expellers (**CPCE**) compared to the conventional CM enhances its metabolizable, digestible, and net energy content, therefore, CPCE could serve as a valuable energy source in swine nutrition (Ndou and Woyengo, 2020). Due to potential variations in chemical composition of CPCE sourced from different processing plants, the percentage of residual oil content varies based on whether the seeds undergo single or multiple passes through the mechanical system, thus contributing to differences among producers. The considerable variability in the processing and oil extraction methods from canola seeds impacts the nutritional value of resulting co-products, making it an essential area for study.

Although the digestible energy (DE) and metabolizable energy (ME) of CPCE fed to growing pigs have been determined (Kaldmäe et al., 2010; Seneviratne et al., 2011; Maison et al., 2015; Li et al., 2017), the research on the potential differences in the nutritive value, DE, and ME of CPCE from various producers is limited. Therefore, this study aimed to achieve the following objectives: (1) determine the chemical composition, DE and ME of CPCE obtained from different processing plants in Western Canada for growing pigs, and (2) test the hypothesis that CPCE sourced from different processing plants in Western Canada will vary in chemical composition, DE and ME.

Materials and Methods

All experimental procedures used in this study were reviewed and approved by the University of Manitoba Animal Care Committee (F18-038-1/2–AC11419), and pigs were handled in accordance with the guidelines described by the Canadian Council on Animal Care (2009). The experiment was conducted at the T.K. Cheung Center for Animal Science Research, at the University of Manitoba.

Chemical Composition of Cold-Pressed Canola Expellers

In this in vivo study, five CPCE (*Brassica napus*) samples were collected from five processing plants across Western Canada. The nutritional profile of the five CPCE samples, i.e., A, B, C, D, and E, was determined. The test CPCE products used in this study were received in different forms, i.e., meal, flakes, and cake (Figure 1). No specific details regarding the seed processing and production of CPCE were provided.

The samples were ground through a 1 mm sieve in a model 4 Thomas Wiley mill (Labwrench, Midland, ON, Canada) and thoroughly mixed before chemical analysis. The chemical composition of CPCE samples were analyzed in duplicate. The dry matter (**DM**) content (945.15), nitrogen (**N**), and crude protein (**CP**; 990.03), ether extract (**EE**; 920.39), ash (942.05), and total phosphorus (965.17) were determined using the standard by AOAC (2006) methods (Association of Official Analytical Chemists, 2006). Organic matter content was calculated as DM minus ash. The gross energy (**GE**) content was measured using a bomb calorimeter (model 6,400; Parr Instrument Co., Moline, IL) which had been calibrated using benzoic acid. Neutral detergent fiber (**NDF**) and acid detergent fiber contents were determined according to the methodology of the study by Van Soest et al. (1991) using an Ankom fiber analyzer (Ankom Technology, Macedon, NY, USA). The sugars (simple sugars, sucrose, raffinose, stachyose) were analyzed by gas-liquid chromatography as described by Slominski et al. (1994). Total starch was determined using an assay kit (Megazyme Total Starch assay kit; Megazyme International Ltd, Bray, Co. Wicklow, Ireland). The non-starch polysaccharides (NSP) were determined following the procedure described by Englyst and Cummings (1984; 1988) with some modifications (Slominski and Campbell, 1990) by gas-liquid chromatography (component sugars) and colorimetry (uronic acids; Scott, 1979). Total dietary fiber was calculated as the sum of NDF and NDF-soluble NSP (Slominski et al., 1994). The NDF-soluble NSP was calculated as the difference between total NSP and NSP present in NDF residue. The CP in NDF residue was also determined to represent the neutral detergent insoluble CP (NDICP). The lignin and polyphenols content was calculated as the difference between total dietary fiber and sum of NDCIP and NSP contents. Phytate phosphorus was determined according to Haugh and Lantzsch (1983) method and non-phytate phosphorus was calculated as the difference between total and phytate phosphorus. Glucosinolates were determined using the method described by Slominski and Campbell (1987).

Animals, Housing, and Experimental Diets

Thirty-six growing barrows [(Yorkshire × Landrace) × Duroc] with an average initial body weight of 19.2 ± 1.0 kg (mean ± SD) were obtained from Glenlea Swine Research Unit, University of Manitoba. All experimental pigs were housed individually in adjustable metabolism crates (1.8 × 0.6 m) with smooth transparent plastic sides in a temperature-controlled room (23 ± 1 °C) throughout the experiment. The metabolism crates had plastic-covered expanded metal sheet flooring and underneath the flooring was a screen for fecal collection and a stainless-steel urine tray underneath the fecal screen, which allowed for the total, but separate, collection of feces and urine from each pig.

The diets used in this experiment were mixed and acquired from the Glenlea Research Station feed mill, University of Manitoba. The six experimental diets included a corn-SBM-based Basal diet (100%) and five (5) Experimental diets in which 18% of the Basal diet was substituted with CPCE from different producers (Table 1). As illustrated in Figure 1, test materials were received in different forms and, therefore, to ensure that pigs received the test material in the same form, the CPCE samples were ground through a 2 mm sieve to standardize the particle size and aid proper mixing with the Basal diet. The DE and ME of CPCE were determined using

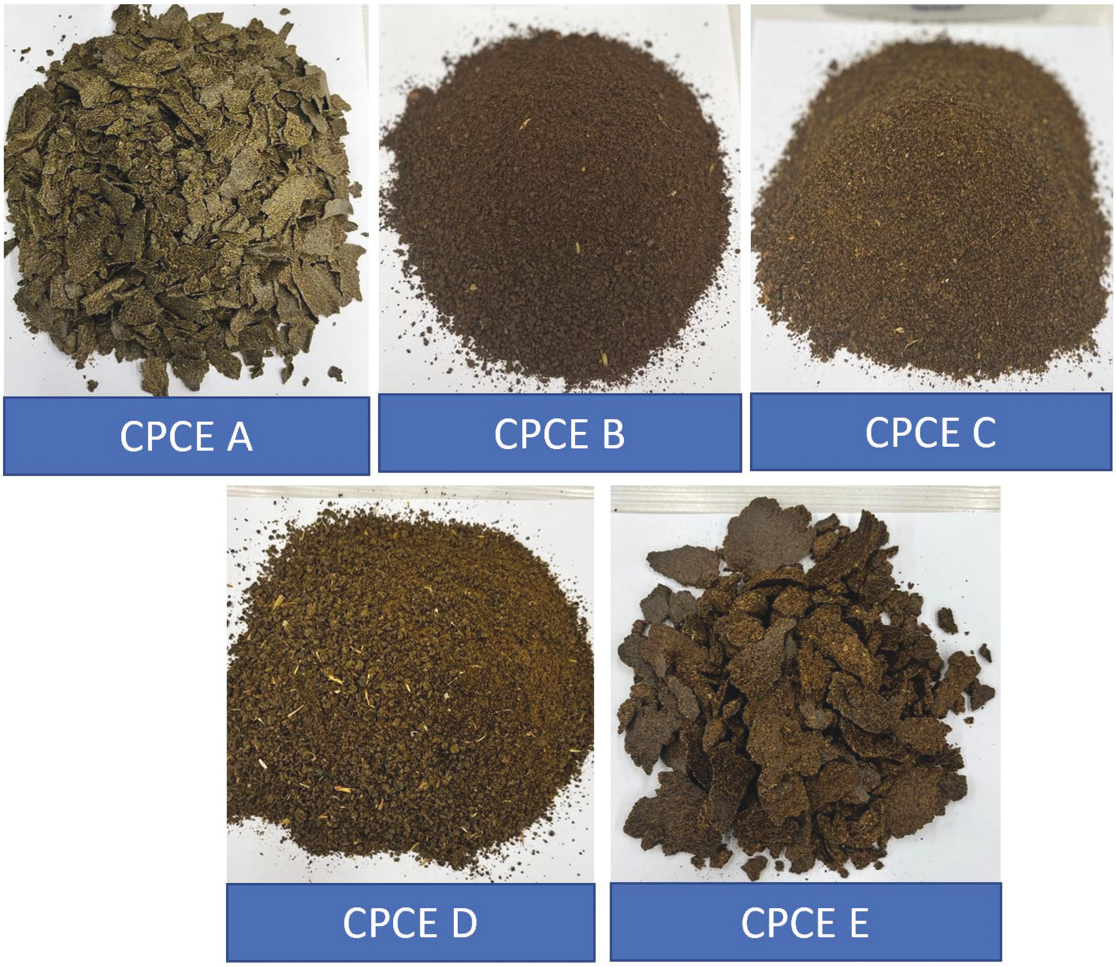

Figure 1. Cold-pressed canola expellers samples used in the current study (as-received form).

the corn-SBM diet as a Basal diet. All experimental diets were supplemented with vitamins and minerals to meet or exceed the requirements of growing pigs (NRC, 2012).

Experimental Design and Procedure

This experiment was conducted in two consecutive periods (18 pigs per period) using the same facility and similar experimental conditions and procedures due to limited metabolism crates. Pigs were assigned to one of the six experimental diets in a completely randomized design with three replicates (pigs) per diet (per period). Each experimental period lasted 10 d and pigs were fed experimental diets for 10 d, including 5 d for adaptation to the environmental conditions and diets and 5 d for total but separate collection of urine and feces. Daily feed intake was set at 550 kcal ME/kg metabolic weight (body weight$^{0.60}$) based on body weight of pigs registered on days 1 and 5, which has been reported to be close to ad libitum intake (Noblet et al., 1994). During the experiment, pigs were fed once daily at 0800 hours and trained to consume their daily feed allowance within 1 h after feeding. Pigs were given access to fresh water at ad libitum via a low-pressure nipple drinker throughout the experimental period. On day 6 of feeding period, total, but separate fecal and urine collection started for the determination of DE and ME as previously described by Kim and Nyachoti (2017) and lasted for 5 d. From days 6 to 10, urine and feces were collected once daily at 0800 hours, and were further weighed, and stored at −20 °C. Urine was also collected in jugs containing 20 mL of 3 *N* HCl to minimize nitrogen losses, once daily in the morning.

Sample Preparation and Chemical Analysis

Fecal samples were dried in a forced-air drying oven at 60 °C for 5 d, weighed, and pooled separately per pig. The CPCE and diet samples were ground through a 1-mm screen in a model 4 Thomas Wiley mill (Lab wrench, Midland, ON, Canada) and thoroughly mixed before chemical analysis, whereas dried fecal samples were finely ground in a coffee grinder (Smart Grind; Applica Consumer Products, Inc., Miami Lakes, FL) for chemical analysis. Urine samples from metabolism crates were thawed and pooled separately for each pig per period, filtered through glass wool, and transferred into a plastic bottle. All samples were analyzed in duplicate. Diets were analyzed for DM, GE, CP (N × 6.25), EE, starch, NDF, non-phytate phosphorus, and organic matter content as described above. Fecal and urine samples were analyzed for DM, GE, N, and organic matter contents as described above. The DM of urine was determined by mixing 1 mL of urine with 0.5 g of cellulose and the resulting urine-cellulose mixture with a sample of pure cellulose were dried in an oven at 50 °C for 24 h while GE of the pure celluloses and dried urine-cellulose mixtures was determined as described above. Then the GE and DM

Table 1. Ingredient composition, calculated and analyzed nutrient composition of basal diet (g/kg, as-fed basis)

Ingredient	Basal diet
Corn	644.6
Soybean meal	295.0
Vegetable oil	15.9
Limestone	11.1
Monocalcium phosphate (Biofos)	10.3
Salt NaCl	6.6
Lys-HCl	4.0
DL-Methionine	1.4
L-Threonine	1.2
Vitamin-mineral premix[1]	10.0
Calculated nutrient[2]	
Metabolizable energy, kcal/kg	3,352
Crude protein	198.0
SID protein	163.7
SID Lysine	12.2
SID Methionine	4.0
SID Methionine + cysteine	6.8
SID Threonine	7.2
STTD Phosphorus	3.4
Analyzed nutrient	
Dry matter	889.2
Gross energy, kcal/kg	3,965
Metabolizable energy, kcal/kg	3,332
Crude protein	197.5
Ether extract	41.8
Starch	380.8
Neutral detergent fiber (NDF)	84.7
Non-phytate phosphorus	3.8

[1]The vitamin–mineral premix supplied the following per kilogram of complete diet: vitamin A, 3,080 IU; vitamin D, 200 IU; vitamin E, 200 IU, vitamin K, 2 mg, thiamin, 1 mg; riboflavin, 10 mg; pantothenic acid, 23 mg; choline, 323 mg; niacin, 34 mg; vitamin B_6, 2 mg; vitamin B_{12}, 10 mg, biotin, 3 mg; folic acid, 1 mg; I, 0.4 mg as $Ca(IO_3)_2$, Cu, 10 mg as $CuSO_4$, Fe, 120 mg as $FeSO_4 \cdot H_2O$; Mn, 10 mg as MnO; Se, 0.3 mg as Na_2SeO_3; and Zn, 103 mg as ZnO.
[2]Calculated from NRC (2012) values.
SID, standardized ileal digestible; STTD, standardized total tract digestible.

contents in urine were calculated by different methods as previously described by Kim and Nyachoti (2017) and Fleischer et al. (1981).

Calculations and Statistical Analysis

Apparent total tract nutrient digestibility and nutrient retention were determined by the total collection method using the following equations as described by Woyengo et al. (2010):

$$\text{Total tract nutrient digestibility } (\%) = 100 \times [(\text{NI} - \text{O}_{\text{feces}})/\text{NI}] \quad (1)$$

$$\text{Nutrient retention } (\%) = 100 \times \left[\frac{(\text{NI} - \text{NO}_{\text{feces}} - \text{NO}_{\text{urine}})}{\text{NI}}\right] \quad (2)$$

where NI is the nutrient intake (g), NO_{feces} is the nutrient output in feces (g), and NO_{urine} is the nutrient output in urine (g).

The apparent total tract digestibility (ATTD) and apparent retention of nutrients for CPCE were determined by the difference method (Fan and Sauer, 1995), with the corn-SBM-based Basal diet, using the following equation:

$$D_A = \frac{D_D - D_B \times S_B}{S_A} \quad (3)$$

where D_A is the digestibility or retention of a nutrient (%) in an assay feedstuff (CPCE), D_D is the digestibility or retention of a nutrient (%) in an experimental diet (corn-SBM and CPCE-based diet), D_B is the digestibility or retention of a nutrient (%) in the basal feedstuff (corn-SBM-based Basal diet), S_B is the contribution of a nutrient (decimal percentage) from corn-SBM to the experimental diet, and S_A is the contribution of a nutrient (decimal percentage) from CPCE to the corn-SBM and CPCE-based diet.

The DE and ME contents of CPCE were determined using the following equations according to Woyengo et al. (2010):

$$\text{DE } (kcal/kg) = \frac{[(\text{total tract GE digestibility for CPCE, \%}) \times (\text{GE content in } CPCE, \ kcal/kg)]}{100} \quad (4)$$

$$\text{ME(kcal/kg)} = \frac{[(\text{GE retention for CPCE, \%}) \times (\text{GE content in CPCE, kcal/kg})]}{100} \quad (5)$$

All data were analyzed using the MIXED procedure of SAS 9.4 (2018) (SAS Institute, Cary, NC, USA) with the individual pig as the experimental unit and CPCE as the only fixed effect in the model since the effect of period was not significant ($P > 0.05$). The least-square means procedure was used to calculate mean values, and the pairwise difference option of SAS was used to separate means. Homogeneity of the variances among treatments was tested using the UNIVARIATE procedure. Scatter plots of Excel software were used to determine the correlations between EE and DE and EE and ME.

Results

All pigs adapted well to their respective diets and environmental conditions, remained healthy, and readily consumed their daily feed allowance during the experimental period.

Physical Form and Color of CPCE Material

Upon the visual assessment of the CPCE samples, distinguished differences in their shapes and appearance were observed (Figure 1). Two products, i.e., CPCE A and CPCE E, were in the flake-like structure. While the former resembled crushed and pressed canola seed, the latter appeared much darker in color, reminiscent of roasted or overheated appearance. Three other CPCE samples, labeled B, C, and D, were in the form of a meal, though displaying different colors. These variations in color or saturation can be attributed to differences in oil content and/or to the influence of the heat generated during the expelling process.

Chemical Composition of CPCE

The analyzed composition of CPCE is presented in Table 2. Differences ($P < 0.05$) were observed across all chemical

Table 2. Chemical composition of cold-pressed canola expellers from different processors (g/kg, dry matter basis)[1]

Item	Cold-pressed canola expellers (CPCE)					SEM	*P* value
	A	B	C	D	E		
Moisture content	50.97^{b}	48.5^{b}	80.2^{a}	78.9^{b}	80.7^{b}	1.31	<0.0001
Ether extract	84.9^{d}	128.9^{c}	134.7^{c}	160.1^{b}	177.2^{a}	1.30	<0.0001
Gross energy, kcal/kg	5,027^{e}	5,272^{d}	5,318^{c}	5,460^{b}	5,635^{a}	6.46	<0.0001
Crude protein (N × 6.25)	419.4^{a}	383.1^{b}	361.5^{c}	376.7^{c}	351.4^{d}	2.54	<0.0001
Carbohydrates							
Simple sugars [2]	0.61^{e}	10.8^{c}	15.1^{a}	9.39^{d}	13.8^{b}	0.17	<0.0001
Sucrose	80.0^{a}	33.7^{c}	37.1^{c}	50.0^{b}	36.2^{c}	0.82	<0.0001
Oligosaccharides [3]	21.9^{a}	12.8^{b}	14.5^{b}	20.1^{a}	12.4^{b}	0.50	<0.0001
Starch	2.40^{c}	6.51^{a}	3.49^{bc}	3.71^{b}	2.46^{bc}	0.23	0.0003
Fiber fractions							
Neutral detergent fiber (NDF)	230.7^{d}	278.8^{b}	292.6^{a}	248.5^{c}	300.1^{a}	2.94	<0.0001
Total dietary fiber	327.0^{b}	371.2^{a}	373.2^{a}	325.5^{b}	369.2^{a}	2.37	<0.0001
Non-starch polysaccharides (NSP)	204.4^{ab}	188.4^{c}	207.5^{a}	191.0^{c}	194.9^{bc}	2.06	0.0044
Xylose	15.1	14.4	14.8	14.9	13.5	0.39	0.1562
Mannose	3.03	3.15	3.11	3.09	2.99	0.079	0.6299
Arabinose	42.5^{a}	34.2^{b}	38.6^{ab}	39.3^{ab}	37.8^{ab}	1.01	0.0172
Galactose	13.0	13.1	13.9	13.4	13.0	0.27	0.1893
Glucose	62.0^{b}	62.7^{b}	68.4^{a}	62.4^{b}	63.7^{ab}	0.92	0.0199
Uronic acids	68.9^{a}	60.8^{bc}	68.5^{a}	58.0^{c}	63.8^{ab}	0.91	0.0013
Lignin and polyphenols	92.7^{b}	106.5^{a}	108.6^{a}	84.9^{c}	109.9^{a}	1.27	<0.0001
Glycoproteins (NDICP)[4]	29.9^{e}	76.3^{a}	57.0^{c}	49.6^{d}	64.4^{b}	0.54	<0.0001
Ash	64.5^{a}	63.6^{ab}	64.7^{a}	62.0^{b}	58.3^{c}	0.38	0.0004
Total phosphorus	11.1^{a}	10.3^{ab}	10.4^{ab}	10.6^{ab}	9.68^{b}	0.18	0.0233
Phytate phosphorus	6.42^{a}	5.49^{b}	5.83^{ab}	6.01^{ab}	5.84^{ab}	0.14	0.0354
Non-phytate phosphorus	4.65	4.78	4.62	4.60	3.84	0.22	0.1427
Total glucosinolates (GLS), µmol/g	9.69^{a}	6.29^{bc}	6.34^{bc}	7.37^{b}	5.01^{c}	0.40	0.0032
Gluconapin	1.99^{a}	1.33^{b}	1.22^{bc}	1.49^{b}	0.99^{c}	0.055	0.0004
Glucobrassicinapin	0.26^{bc}	0.30^{ab}	0.21^{cd}	0.37^{a}	0.14^{d}	0.015	0.0007
Progoitrin	3.52^{a}	3.20^{ab}	2.79^{b}	3.13^{ab}	2.15^{c}	0.091	0.0009
Glucobrassicin	0.35^{a}	0.18^{b}	0.21^{b}	0.18^{b}	0.13^{b}	0.022	0.0058
OH-Glucobrassicin	3.18^{a}	1.12^{b}	1.66^{b}	1.91^{ab}	1.39^{b}	0.23	0.0084
Neoglucobrassicin	0.38^{a}	0.15^{c}	0.25^{abc}	0.29^{ab}	0.22^{bc}	0.023	0.0070

[1]n = 2 for all nutrients except neutral detergent fiber; total dietary fiber; glycoproteins; lignin and polyphenols with n = 3.
[2]Includes fructose and glucose.
[3]Includes raffinose and stachyose.
[4]Neutral Detergent-Insoluble Crude Protein.
[a,b,c,d,e]Within a row, means without common superscript differ (P < 0.05).

components of CPCE except xylose, mannose, galactose (NSP component sugars), and non-phytate phosphorus among the five processing plants. The EE content in CPCE samples is primarily influenced by processing, resulting in a range of 84.9 to 177.2 g/kg on DM basis. The content of CP in CPCE varied between 351.4 to 419.4 g/kg on DM basis. Notably, CPCE A had the highest CP content at 419.4 g/kg, while registering the lowest EE content at 84.9 g/kg among the evaluated samples. Conversely, CPCE E showcased the highest EE (177.2 g/kg) but the lowest CP value (351.4 g/kg) among the samples. The overall mean values for EE and CP for CPCE from five processing plants were 137.2 and 378.4 g/kg, respectively, DM basis.

The carbohydrate components of CPCE include simple sugars (i.e., glucose and fructose), sucrose, raffinose family oligosaccharides (i.e., raffinose and stachyose), starch, and NSP. Among the CPCE samples, differences (P < 0.05) were observed in the contents of simple sugars, which ranged from 0.61 to 15.1 g/kg (DM basis), and raffinose family oligosaccharides, ranging from 12.4 to 21.9 g/kg, (DM basis). Sucrose content varied between 33.7 (in CPCE B) and 80.0 g/kg (in CPCE A) on a DM basis. The higher (P < 0.05) sucrose content was in the CPCE A sample compared to the other samples. The sucrose contents of CPCE B, C, and E were not different but lower (P < 0.05) than both CPCE A and D. The CPCE A not only showcased the highest sucrose and oligosaccharide content but was also the lowest (P < 0.05) in glucose and simple sugars, which includes glucose and fructose. The difference in the oligosaccharide content aligned with the differences in sucrose levels. Starch content in CPCE samples ranged from 2.40 to 6.51 g/kg. Furthermore, CPCE's dietary fiber and its components varied between samples from different seed processing facilities (P < 0.05). The NDF content among the CPCE

samples varied ($P < 0.05$), reaching as low as 230.7 g/kg in CPCE A and highest value of 300.1 g/kg, DM basis in CPCE E. Considering all the CPCE samples from five processing plants, the overall mean NDF for was 270.1 g/kg on DM basis. The variation in total dietary fiber and its components was observed ($P < 0.05$). Total dietary fiber ranged from 325.5 to 373.2 g/kg on DM basis. Specifically, the NSP content in CPCE C was the highest and did not differ from that of CPCE A but the lowest NSP content was observed in CPCE B and D which were not different from CPCE E. The glycoprotein, or NDICP, demonstrated variability ($P < 0.05$) among the samples. CPCE A showed the lowest NDICP content (29.9 g/kg) while CPCE B was the highest (72.6 g/kg on DM basis). The lignin and polyphenols content ranged between 84.9 and 109.9 g/kg on a DM basis among the samples.

There was no difference in the non-phytate phosphorus content of the samples. In CPCE, the non-phytate phosphorus portion accounted for 39.7% to 46.4% of the total phosphorus content. The lowest total GLS content was present in CPCE E while the highest total GLS content was analyzed in CPCE A (5.0 and 9.69 µmol/g on a DM basis, respectively). On average, among all processing plants, the total GLS content in CPCE was 6.94 µmol/g on a DM basis.

Nutrient Digestibility and Energy Values of Expeller/ Cold-pressed Canola

Among the experimental diets differences ($P < 0.05$) were observed in the ATTD of DM, OM, GE, and N (Table 3). Similarly, differences were noted in the apparent retention of DM, GE, and N ($P < 0.05$) among these diets. Interestingly, the retained N by pigs, regardless of whether they were fed the Basal diet or Experimental diets with different CPCE samples, showed no differences. Results presented in Table 4 show the DE, ME, and the ratio of ME to DE (ME:DE) in the experimental diets containing different CPCE samples. The inclusion of various CPCE samples in these diets affected DE, ME, and ME:DE values, with differences ($P < 0.05$) ranging from 3834 to 3917 kcal/kg DM, 3628 to 3747 kcal/kg DM, and 0.946 to 0.957, respectively. Specifically, CPCE B and E demonstrated statistical comparability to the Basal diet in terms of DE, ME, and ME:DE ($P < 0.05$).

As the residual oil content can impact energy value, correlations between EE and both DE and ME were determined. Positive correlations were observed between DE and EE contents ($R^2 = 0.10$; Figure 2), as well ME and EE contents ($R^2 = 0.34$; Figure 3).

The ATTD of GE and N and apparent retention of DM, GE, and N were different ($P < 0.05$) among the different sources of CPCE (Table 5). However, no difference was noticed in the ATTD of DM and organic matter. The CPCE A demonstrated the highest ATTD of GE, while CPCE E had the highest retention of GE among the samples, i.e., 70.7% and 62.1%, respectively. The DE and ME of CPCE samples for pigs ranged from 3,333 to 3,759 kcal/kg DM and 2,935 to 3,501 kcal/kg DM, respectively. On average, among the five different processing plants, the DE and ME of CPCE were 3,531 and

Table 3. Apparent total tract digestibility (ATTD) and retention of dry matter, OM, gross energy, and N of experimental diets fed to growing pigs[1]

Item	Diet						SEM	*P*-value
	Basal	CPCE A	CPCE B	CPCE C	CPCE D	CPCE E		
ATTD, %								
DM	88.9[a]	84.2[b]	84.9[b]	84.4[b]	83.9[b]	84.8[b]	0.32	<0.0001
OM[2]	90.2[a]	86.6[b]	86.6[b]	85.4[b]	86.9[b]	86.6[b]	0.60	<0.0001
GE	87.8[a]	84.8[b]	84.1[bc]	83.3[c]	83.5[c]	84.0[bc]	0.26	<0.0001
N	85.9[a]	82.8[bc]	82.2[c]	82.9b[c]	83.4[b]	83.4[b]	0.27	<0.0001
Retention, %								
DM	83.7[a]	78.6[c]	80.1[b]	79.0[bc]	78.5[c]	79.9[bc]	0.32	<0.0001
GE	84.0[a]	80.0[b]	79.8[b]	78.8[b]	79.3[b]	80.1[b]	0.32	<0.0001
N	67.2[a]	64.7[b]	64.1[b]	63.0[c]	63.6[bc]	64.5[b]	0.25	<0.0001
N retained, g/d	18.7	19.6	16.9	19.0	20.0	19.8	1.20	0.486

[1]CPCE A to CPCE E are diets containing expeller/ cold-pressed canola (CPCE) samples A to E; each value represents the mean of 6 observations.
[2]OM: Organic matter.
[a,b,c]Within a row, means without a common superscript differ ($P < 0.05$).

Table 4. Energy values of experimental diets[1] fed to growing pigs

Item	Diets						SEM	*P*-value
	Basal	CPCE A	CPCE B	CPCE C	CPCE D	CPCE E		
DE, kcal/kg DM	3,917[a]	3,863[ab]	3,892[a]	3,834[b]	3,875[ab]	3,903[a]	12.87	0.0012
ME, kcal/kg DM	3,747[a]	3,646[cd]	3,693[abc]	3,628[d]	3,679[bcd]	3,719[ab]	13.83	<0.0001
Energy utilization								
ME/DE	0.957[a]	0.944[b]	0.949[ab]	0.946[b]	0.949[ab]	0.953[ab]	0.0022	0.0049

[1]CPCE A to CPCE E are diets containing expeller/cold-pressed canola (CPCE) samples A to E; each value represents the mean of six observations.
[a,b,c,d]Within a row, means without a common superscript differ ($P < 0.05$).

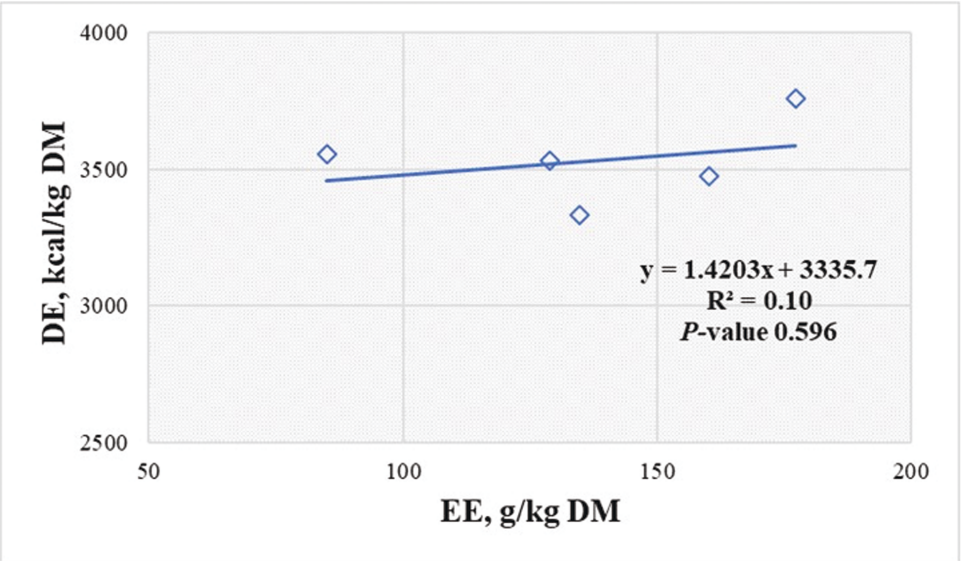

Figure 2. Relationship between digestible energy and ether extract in cold-pressed canola expellers.

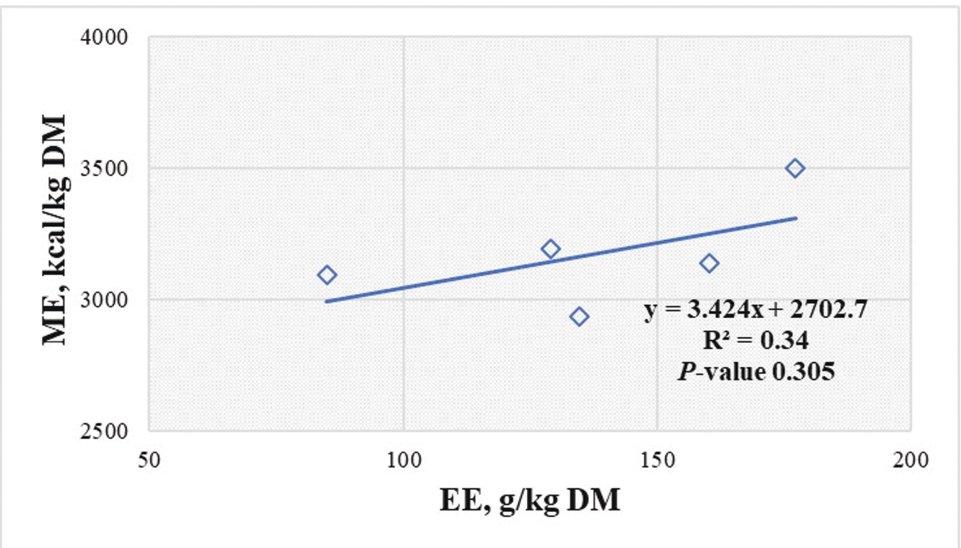

Figure 3. Relationship between metabolizable energy and ether extract in cold-pressed canola expellers.

3,172kcal/kg DM, respectively. CPCE E recorded the highest DE and ME, while CPCE C had the lowest, but both were not different from values seen in CPCE B and D. CPCE A had significantly lower ME values than CPCE E.

Discussion

The primary objective of this study was to characterize the chemical composition of CPCE from different processing facilities in Western Canada and investigate relationships between CPCE components and DE and ME values.

In the production of canola oil for human consumption and crude canola oil extraction for small-scale biodiesel production, canola seeds undergo mechanical pressing. The mechanical pressing of canola seeds without heat preconditioning and moisture, generates a canola oil coproduct known as CPCE. This method, termed expeller/cold pressing of canola seeds (Spragg and Mailer, 2007), differs from conventional solvent-extracted meal process, as CPCE is not subjected to desolventizing/toasting, which is the primary source of heat that can affect quality of the traditional solvent-extracted meal. Despite the absence of induced heat, the expelling process generates friction, elevating meal temperature up to 160 °C. The low moisture content and short duration, generally help preserve protein quality (Mauron, 1981; Newkirk et al., 2003a, 2003b; Almeida et al., 2014). However, prolonged exposure to high temperatures or delayed cooling after extraction can negatively impact protein quality (Khajali and Slominski, 2012; Adewole et al., 2016; Agyekum and Woyengo, 2022). Compared to expeller-pressed canola and conventional CM, CPCE typically retains more residual oil due to inefficient oil recovery from canola seeds (Leming and Lember, 2005), which also dilutes the concentration of other components of CPCE. This higher residual oil content in CPCE may increase its digestible and ME levels relative to solvent-extracted canola meal, thereby making it a valuable energy

Table 5. Apparent total tract digestibility (ATTD) and retention of nutrients, and digestible energy and metabolizable energy of cold-pressed canola expellers from different processors fed to growing pigs[1]

Item	CPCE A	CPCE B	CPCE C	CPCE D	CPCE E	SEM	*P*-value
ATTD, %							
DM	63.1	66.6	63.8	61.0	66.0	1.77	0.2022
OM[2]	70.0	70.3	63.4	72.1	70.2	3.51	0.4691
GE	70.7^{a}	67.0^{ab}	62.7^{b}	63.6^{b}	66.7^{ab}	1.45	0.0050
N	68.5^{ab}	65.3^{b}	68.9^{ab}	71.8^{a}	72.8^{a}	1.30	0.0037
Retention, %							
DM	55.4^{b}	63.7^{a}	57.7^{ab}	54.9^{b}	62.2^{ab}	1.83	0.0054
GE	61.6^{ab}	60.5^{ab}	55.2^{b}	57.5^{ab}	62.1^{a}	1.63	0.0278
N	52.9^{a}	49.8^{a}	43.7^{b}	47.0^{ab}	52.2^{a}	1.46	0.0008
Energy values, kcal/kg DM							
DE	3,556^{ab}	3,532^{ab}	3,333^{b}	3,473^{ab}	3,759^{a}	77.32	0.0123
ME	3,095^{b}	3,190^{ab}	2,935^{b}	3,140^{ab}	3,501^{a}	87.17	0.0022

[1]Difference method by subtracting the energy contribution of the Basal diet from the energy content of the diets containing the different CPCE samples (Woyengo et al., 2010).
[2]Organic matter.
[a,b,c]Within a row, means without a common superscript differ ($P < 0.05$).

and amino acids source in swine diets. However, variability in the nutritional content arises from different processing conditions and systems used by processors, contributing to differences in CPCE sourced from various processing plants.

The initial step in evaluating the quality of CPCE involves assessing its physical appearance, i.e., form, particle size, shape, and color. It is known that processed feed ingredients, such as canola meal or distillers' dried grain with solubles, can be perceived as of lower value when they appear dark. Darker appearance might indicate overheating during processing, potentially leading to lower protein quality due to the Maillard reactions between reducing sugars and amino acids, particularly lysine (Newkirk and Classen, 2002; Khajali and Slominski, 2012; Adewole et al., 2016). In this study, a comparison of test CPCE samples obtained from different canola seed processing plants revealed distinctions among the samples. While two samples were in flake form, they appeared to be different in color, hardness, and flake size. Similarly, the remaining three CPCE samples in meal form exhibited varying appearances. The presence of residual oil could influence the color saturation, but the heat that was generated during the expelling process might also impact the appearance of CPCE, subsequently affecting their chemical composition and nutritional quality.

The results of this research demonstrated variations in the chemical composition and energy content among the CPCE samples sourced from different processing plants. While some nutrients showed wide-ranging differences, others demonstrated only slight variations. The EE content of CPCE ranged from 84.9 to 177.2 g/kg on DM basis, indicating variability in residual oil among the CPCE samples. This variation is likely attributed to diverse processing conditions and equipment used by different producers. Similar findings were observed by Seneviratne et al. (2011), who also recorded EE values widely ranging from 96.0 to 242.0 g/kg (DM) among different CPCE samples produced from four cold pressing processing conditions. The average EE of CPCE in this study is 137.2 g/kg on DM basis, which is greater than in expeller-pressed canola (116.0 g/kg DM) recorded by Grageola et al. (2013) and conventional CM (35.0 g/kg DM) by Adewole et al. (2016). The CPCE A, with lower EE content, appeared to be lighter in color compared to the other test CPCE samples, particularly CPCE E, which was also in the flake form.

The average of the GE value for the five CPCE samples used in this study (5,342 kcal/kg on DM basis) was lower than those reported by Grageola et al. (2013) (6,086 kcal/kg on DM basis) but similar to the value reported by Seneviratne et al. (2011) (5,285 kcal/kg, on DM basis).

Variation in simple sugars, sucrose, and raffinose family oligosaccharides within CPCE samples might be attributed to seed quality determinants such as maturity, seed size, and cleanness, along with the processing conditions (Slominski et al., 2012). The presence of simple sugars and sucrose can contribute to the energy of CPCE, thus a significant variation among samples from different processors could potentially affect energy availability. Again, CPCE A appears to have a favorable quality having highest sucrose content, suggesting mild or gentle seed processing. Traditionally, raffinose family oligosaccharides, or galactooligosaccharides, were perceived as antinutritive, but in fact, they might exert a prebiotic property. These sugars could be utilized by beneficial bacteria in the gastrointestinal tract and converted to short-chain fatty acids, and potentially contributing to the energy content of the feedstuffs (Khajali and Slominski, 2012). The CPCE A contained more raffinose and stachyose compared to other CPCE samples, and it was similar to the content in conventional CM (Khajali and Slominski, 2012; Adewole et al., 2016). However, on average, their content in CPCE samples remained lower than that found in CM. Starch content in canola seeds is generally low, suggesting a negligible contribution to energy of CPCE.

The average NDF content of CPCE in this study was lower (270.1 g/kg, DM) than that of conventional CM (294 g/kg, DM) as reported by Adewole et al. (2016). Individually, CPCE samples demonstrated a wide range, from 230.7 to 300.1 g/kg, DM. The high NDF content of CPCE E, C, and B (300.1, 292.6, and 278.8 g/kg on DM basis, respectively) indicates the possibility of either high temperature generated due to friction or the use of the off-grade seeds (small seeds, immature seeds, contaminated with chaff and other fibrous debris).

Cold pressing would be anticipated to result in high-quality CPCE by reducing exposure to heat, thereby minimizing the formation of Maillard reaction products and preventing the accumulation of dietary fiber (Khajali and Slominski, 2012; Almeida et al., 2014; Adewole et al., 2016). However, the chemical composition results from various CPCE samples in this study demonstrated that the benefits of cold pressing were not that evident due to the higher levels of NDICP, and lignin and polyphenols in certain samples (CPCE B, C, and E). Based on the results, it could be concluded that the quality of the CPCE A is considered superior to the other counterparts. Such a conclusion is supported by the lowest content of glycoproteins or NDICP, the compound that has been proposed to be a marker for protein damage in processed feed ingredients (Newkirk and Classen, 2002). Specifically, NDICP was present at 29.9 g/kg in CPCE A, while in CPCE B, E, C, and D at 76.3, 64.4, 57.0, and 49.6 g/kg DM basis, respectively. The appearance of the CPCE B, which was darker than other samples and also has the highest NDCIP, suggests potential exposure to excessive heat, either due to generated friction or prolonged exposure to the otherwise mild heat. The variation in NDICP content contributed to the differences in total dietary fiber, ranging from 327.0 g/kg on DM basis in CPCE A to 373.2 g/kg on DM basis in CPCE C. In essence, the observed variation in the total dietary fiber, NDF, and lignin contents could potentially result from Maillard reactions occurrence during processing. The potential impact of exposure to heat during processing can be indicated in the GLS content, due to their sensitivity to heat treatment (Campbell and Slominski, 1990; Khajali and Slominski, 2012). The CPCE A contained the highest GLS level, suggesting their lesser decomposition compared to other CPCE samples. Remarkably, the highest GLS content in this sample coincided with the lowest NDF content. In contrast, CPCE E characterized by the highest NDF content, showcased the lowest GLS content among the CPCE samples. In this study, the average GLS level in CPCE was higher than in the conventional CM, i.e., 6.94 µmol/g vs. 4.60 µmol/g DM (Adewole et al., 2016), indicating that overall, canola seeds in cold pressing were likely processed at lower temperatures.

The NSPs are composed of cellulose and non-cellulosic polysaccharides, referred to as hemicellulose and pectic polysaccharides. The diverse types of polysaccharides may be rationalized from the component sugar profile. The relatively high concentration of uronic acids along with glucose residues indicates that pectic-type substances and cellulose are the major cell wall constituents of CPCE. Although cellulose and pectic polysaccharides would predominate, some amounts of arabinoxylans, and arabinogalactans are also present.

The experimental diet incorporated CPCE at an 18% inclusion rate, resulting in an overall average CP of 231.6 g/kg on an as-fed basis. It was observed that the CP of the experimental diet fell within the requirement for growing pigs due to the high protein quality of CPCE. Consequently, exceeding the 18% inclusion of CPCE in the diet might lead to an oversupply of protein. The average CP content of CPCE in this study (378.4 g/kg DM) was similar to the 409.5 g/kg DM reported by Seneviratne et al. (2011).

The quality of CPCE varies vastly due to inconsistencies in the processing conditions among processors. For instance, producers might use different screw press speeds during canola seed crushing, which likely yields differing qualities of CPCE. In a study by Seneviratne et al. (2011) evaluating CPCE cake processed using four different conditions, it was observed that increasing screw speed raised the EE content in cold-pressed canola cake. This increase occurred because the canola seed had less time to be crushed. This could be one of the many discrepancies in the processing methods and systems adopted by several processors, contributing to the diverse nutrient compositions observed in CPCE sourced from different crushing plants.

Differences in nutrient digestibility among CPCE samples in this experiment likely came from variations in nutrient composition and diverse processing conditions applied. The presence of greater fiber content decreased the apparent ileal digestibility and ATTD of nutrients in CPCE cake when processed at slow screw speed (Seneviratne et al., 2011). In this study, CPCE A, having the lowest NDF content, had the high ATTD of organic matter and GE, as well as N retention. However, CPCE E, with the highest NDF content, showed high ATTD of N that was not different from CPCE A. These discrepancies could be attributed to the inherent properties of the canola seeds and diet composition. Despite the lowest EE and GE content, CPCE A demonstrated the greater ATTD of GE, potentially due to its lower NDF content compared to other CPCE samples, making it more digestible in the pig's gastrointestinal tract. When energy loss through urine was accounted for in energy retention analysis, it revealed that CPCE with the highest residual oil (CPCE E) had the highest energy retention, although not different from CPCE A, B, and D. The CPCE A, initially presumed to have superior quality, had N and GE digestibility not different from CPCE B and E, and GE and N retention not different from CPCE B, D and E. Understanding the link between differences in digestibility/retention of nutrients and the physical form or chemical composition of the CPCE samples in this study remains challenging. This could be due to the limitations associated with the digestibility method employed, as ATTD and retention may not fully consider the contribution of intestinal metabolism, potentially affecting accuracy of nutrient digestibility in CPCE.

The DE and ME values of the CPCE samples varied from 3,333 to 3,759 kcal/kg and 2,935 to 3,501 kcal/kg (DM basis), respectively. The CPCE E had the highest DE and ME values among the CPCE samples, possibly due to its greater GE value and EE content. The DE and ME values of test ingredients are derived from GE content, and energy digestibility and retention, respectively. On average, the DE value of the CPCE used in this study (3,531 kcal/kg DM) was lower than the value (4,521 kcal/kg, DM basis) reported by Grageola et al. (2013) for finishing pigs. This discrepancy in DE values between studies might be related to the age of the animals (finishing versus growing pigs) and the EE content (137.2 vs. 231.4 g/kg), including the ATTD of GE for CPCE used in the former study compared with the latter (66.1% vs. 74.3%). Also, the average ME value in CPCE (3,172 kcal/kg DM) in this study was lower than the value recorded in an Estonian study (3,631 kcal/kg DM; Kaldmäe et al., 2010). Nevertheless, the DE and ME contents of CPCE in this study surpassed those for conventional CM by 13% and 9% (DM basis), respectively (Kim et al., 2018). These greater energy values in CPCE compared with conventional CM indicate the presence of more EE remaining in CPCE, resulting from lower oil extraction efficiency.

The lack of significant correlation between DE and EE or ME and EE might be due to relatively small number of

observations, because in this study we only analyzed five CPCE samples. A more extensive sample set could potentially allow establishment a detectable relationship between these variables. It is worth noting that the total glucosinolates content observed in CPCE used in this study (ranging from 5.01 to 9.69 µmol/g, DM basis) fell within the tolerable range for pigs and likely did not affect nutrient digestibility.

In summary, cold pressing proves to be less efficient in extracting oil from canola seeds compared to other industry methods. Nonetheless, the residual oil content in CPCE will vary among processors employing cold pressing. The residual oil present in CPCE will dilute the concentrations of CP and NDF, with higher EE content inversely correlating with these constituents. Furthermore, variations in heat-sensitive compounds such as glucosinolates and NDICP were independent of EE contents, suggesting differences in processing conditions as the likely cause. On average, CPCE provides 3,531 kcal/kg of DE and 3,172 kcal/kg of ME (on DM basis), with a range spanning from 3,333 to 3,759 kcal/kg of DE and from 2,935 to 3,501 kcal/kg of ME for pigs. Due to the limited number of CPCE samples, research failed to demonstrate a significant correlation between EE content and DE and ME. However, it was demonstrated that the residual oil content influenced the GE energy value of CPCE, suggesting it could be considered as the primary predictor of energy value.

In conclusion, while the chemical composition and values of DE and ME in CPCE vary among processors, the by-product obtained through the cold pressing process can be a valuable source of energy and protein for pig nutrition.

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Conflict of interest statement

The authors declare no competing financial interest.

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