Nutritional value of low-fibre and high-fat canola co-products in pigs

by

Xun Zhou

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Department of Agricultural, Food and Nutritional Science
University of Alberta

ABSTRACT

Solvent-extracted canola meal (CM) is fed to pigs as alternative to soybean meal (SBM). The relatively high dietary fibre content in CM limit its nutritional value for swine. Canola processing could produce canola co-products with less fibre and greater fat thus increasing its nutritional value. Effects of feeding low-fibre and high-fat canola co-products on pig nutrient digestibility, growth performance, carcass traits, and pork quality were evaluated. In Chapter 3, conventional *Brassica* (*B.*) *napus* and thin-hull *B. juncea* CM were air-classified to produce low-fibre light-particle fraction and high-fibre heavy-particle fraction and were included at 200 g/kg in nursery diets. Compared with *napus*, feeding *juncea* CM reduced average daily feed intake (ADFI), increased feed efficiency (G:F), but did not affect average daily gain (ADG) in weaned pigs. Feeding light-particle fraction increased G:F compared with parent CM or heavy-particle fraction, but ADFI and ADG were not affected. In Chapter 4, *napus* and *juncea* CM and their air-classified fractions were fed to ileal-cannulated grower pigs. Apparent total tract digestibility (ATTD) of gross energy (GE) and digestible energy (DE) value were greater in *juncea* than *napus* CM, and greater for light-particle fraction than parent CM or heavy-particle fraction. The standardized ileal digestibility (SID) of His, Ile, and Val were greater for *juncea* than *napus* CM. The SID amino acids (AA) was greater in light-particle fraction than parent CM or heavy-particle fraction. In Chapter 5, *juncea* canola seed was extruded and expeller-pressed to produce canola expeller (CE) with 168 g/kg ether extract (EE). Expeller included at 0, 50, 100, 150, and 200 g/kg in growing-finishing diets linearly reduced ADFI and ADG, did not affect G:F, linearly reduced carcass weight and loin depth, and linearly increased unsaturated fatty acid content in jowl fat. In Chapter 6, canola press-cake (CPC) with 204 g/kg EE was produced by merely expeller-pressing canola seed. The CPC included at 0, 50, 100, 150, and 200 g/kg in nursery

diets did not affect ADFI and ADG, but linearly increased G:F in weaned pigs. In Chapter 7, CPC and canola oil were produced expeller-pressing canola seed. True digestibility of fat was estimated to be greater in canola oil than in CPC. The total endogenous fat losses were estimated to be greater for the total tract than ileum. Canola oil inclusion increased digestibility of energy and AA in other dietary components. In conclusion, low-fibre canola co-products had greater nutritional value than conventional CM. Feeding high-fat canola co-products replacing SBM and supplemental fat in swine diets maintained growth performance when dietary glucosinolate profile was acceptable. Formulating swine diets based on NE value and SID AA content minimized the negative effect of feeding canola co-products on pig growth performance.

PREFACE

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DEDICATION

This dissertation is dedicated to my grandmother Cuilan Wang (1929–2015).

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Chapter 1 Introduction

Feed can account for up to 75% of the total cost of swine production (Zijlstra and Beltranena, 2013a). The prices of conventional energy and protein feedstuffs for swine (corn and soybean meal) have increased in the recent decades due to the increasing demand from the food and ethanol industry (Tyner and Taheripour, 2007), and is expected to reach a higher plateau in a long term (Woyengo et al., 2014). Under this situation, co-products from food and biofuel industries can be used as cost-effective alternatives for swine feeding (Zijlstra and Beltranena, 2013b). Solvent-extracted canola meal (CM), canola expeller (CE), and canola press-cake (CPC) are co-products produced from canola crushing for human food and biodiesel production. Due to the increasing canola seed production and crushing in Canada (Canola Council of Canada, 2009), the supply of canola co-products is expected to increase, which could be fed to swine as economic sources of protein, energy, and fatty acids.

Canola meal is the major co-product from canola seed crushing and has become the second-most traded protein feedstuff for animals worldwide after soybean meal (SBM). However, its nutritional value is limited by the relatively high dietary fibre content (266 g/kg total dietary fibre vs. 167 g/kg in SBM, NRC 2012). Dietary fibre cannot be digested by the endogenous enzymes of pigs and inhibits the digestion of other nutrients such as protein and fat (Grieshop et al., 2001), which contributes to its low dietary energy value. Therefore, reducing fibre content in CM may improve its nutritional value to pigs. Fibre reduction can be achieved by breeding low-fibre canola varieties such as yellow-seeded *Brassica* (*B.*) *juncea*, which has a thinner seed hull

and therefore less fibre content than conventional *B. napus* (Khajali and Slominski, 2012). Feed processing techniques such as air-classification can also be applied to produce low-fibre CM fractions (King and Dietz, 1987).

The low energy value of CM could also be attributed to oil-depletion by the solvent extraction process. The 2–3% crude fat in CM is due to adding-back of gums (Newkirk, 2009). Extracting oil by expeller-pressing the seed alone without subsequent solvent-extraction produces CE and CPC with greater remaining fat (8–22%) thus greater energy value for pigs (Grageola et al., 2013; Spragg and Mailer, 2007). However, feeding high-fat canola co-products is associated with the risk of compromising pork quality. Canola oil is high in unsaturated fatty acids that may reduce pork fat firmness, increases incidence of miscuts during pork cutting, causing color deterioration, reduced shelf life and affecting sensory attributes (Apple, 2013). Therefore, carcass fatty acid profile needs to be monitored when CE and CPC are fed to pigs. On the other hand, remaining fat in CE and CPC could be encased in the seed matrixes thus less digestible than extracted canola oil (Thacker and Petri, 2009). Such difference in fat digestibility needs to be quantified in order to accurately predict the energy value of CE and CPC.

Another limitation of feeding canola co-products to swine is the presence of glucosinolates that are the major anti-nutritional factors in canola. Glucosinolates can compromise thyroid and liver function and reduce animal feed intake by their bitter taste (Tripathi and Mishra, 2006). Canola varieties and co-products differ in glucosinolate content and profile, which need to be characterized before including into swine diets (Khajali and Slominski, 2012). Feed processing

techniques such as extrusion can be applied to reduce the negative effect of glucosinolates on pig performance and health (Liang et al., 2002).

The inclusion of these low-fibre and high-fat canola co-products into swine diets to replace SBM may reduce feed cost and net profit of swine productions. However, the feeding of canola co-products requires proper characterization of their digestible nutrient profile. The effects of feeding canola co-products on pig performance, carcass traits and pork quality also need to be validated.

1.1 Hypothesis

The hypotheses of the thesis were:

a) Feeding of low-fibre CM products would result in greater energy and amino acid (AA) digestibility, and improved growth performance in pigs.

b) Feeding increasing dietary inclusion of high-fat canola products would not affect growth performance and carcass traits when diets are formulated to equal net energy (NE) and standardised ileal digestible (SID) AA content, but unsaturated fatty acid content in pork would increase.

c) The digestibility of remaining fat in high-fat canola co-products would be lower than that in liquid extracted canola oil.

1.2 Objectives

a) To compare the growth performance and nutrient digestibility of pigs that fed low-fibre CM products and the regular- or high-fibre counterparts (Chapter 3 and 4).

b) To measure the growth performance, dressing percentage, carcass characteristics, and carcass fatty acid profile of pigs fed increasing levels of high fat canola products (Chapter 5 and 6).

c) To measure and compare the fat digestibility in high-fat canola co-products and liquid canola oil (Chapter 7).

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Chapter 2 Nutritional value of canola co-products in pig nutrition: A review

2.1 Abstract

Solvent extracted canola meal (CM), canola expeller (CE) and canola press-cake (CPC) are co-products from canola oil extraction that can be fed to swine as sources of amino acids (AA) and energy. Earlier studies often reported reduced growth performance of pigs fed canola co-products mainly due to high glucosinolate content. As glucosinolate in canola has been progressively reduced by breeding programs in recent decades, the feeding value of canola co-products needs to be re-evaluated. Recent studies that investigated the nutrient composition and feeding value of canola co-products in pigs were summarized. Research focused on increasing the feeding value of CM by processing or enzyme supplementation were also discussed. Canola meal is the major canola co-product globally; it has relatively high crude protein (CP) content with acceptable AA profile. However, its relatively high dietary fibre and low fat content limits its energy value and AA digestibility in pigs that may limit its use in swine diets. These limits can be counteracted by canola breeding, processing techniques and enzyme supplementation. Canola expeller and CPC contain more remaining fat, less fibre and generally have greater AA digestibility than CM. However, glucosinolates in CE and CPC may have greater negative effects on pig performance; their high content of unsaturated fatty acid could also deteriorate pork quality. These risks can be minimized by manipulating processing conditions and feeding strategies. In summary, canola co-products are valuable feed ingredients for swine. When dietary glucosinolate content is controlled within acceptable limits, replacing SBM with canola co-

products in swine diets could achieve similar growth performance and product quality provided that diets were formulated based on net energy (NE) system and standardized ileal digestible (SID) AA content.

2.2 Introduction

Canola is derived from rapeseed that belongs to the *Brassicaceae* family. Rapeseed was first brought into western Canada in 1928 from Poland (Daun, 2011). During 1930–1950, rapeseed oil was extracted and used to lubricate steam and marine engines (Canola Council of Canada, 1991). Edible rapeseed oil was first extracted in 1956. However, rapeseed oil was high in erucic acid (250–380 g/kg of total fatty acid) that could cause heart lesions in humans (Daun, 2011). Rapeseed meal, the solid residue after solvent-extraction of oil, could be used for animal feeding. However, it was high in glucosinolates (120–150 μmol/g), a major anti-nutritional factor (ANF) that reduces animal feed intake and health (Newkirk, 2009). To increase the value of rapeseed, breeding programs was targeted on reducing these two ANF. The first "double-low" rapeseed variety was developed in 1974 and was named "canola" as having < 20 g erucic acid/kg in the oil and < 30μmol glucosinolates/g in the meal fraction (Daun, 1993). Canola production in Canada has increased steadily from 3.7 million tonnes (MT) in 1980 to 15.5 MT in 2014 (Beckman, 2014). Canola has become the most valuable crop in Canada contributing $19.3 billion/year to the Canadian economy from 2009–2012 (Canola Council of Canada, 2014a).

Canola seed crushing in Canada increased from 3.4 to 7.0 MT from 2003–2014 (Canola Council of Canada, 2014b), producing canola oil as primary product for the food and biofuel industries. The solid protein-rich fractions remaining after oil extraction are canola co-products. Different oil-extraction procedures produce canola co-products such as solvent-extracted canola meal (CM), canola expeller (CE) and canola press-cake (CPC) that are mainly directed to feeding livestock. Canola meal is the most common canola co-product and is currently the 2nd most traded protein feedstuff after soybean meal (SBM) globally (Arntfield and Hickling, 2011). The CM can be fed to swine as cost-effective alternative to SBM, because CM is generally priced 60–75% lower (Arntfield and Hickling, 2011). However, feeding value of CM for pigs is limited by its relatively low energy value caused by high dietary fibre content and depletion of oil (Fan et al., 1996). Greater fibre content in CM also reduces digestibility of AA (Grieshop et al., 2001). In addition, ANF such as glucosinolates, phytate and phenolic compounds could reduce feed intake, nutrient utilization and health of pigs (Matthäus, 1998). To increase the feeding value of CM, efforts were made to reduce fibre and ANF content and increase nutrient digestibility in CM by breeding, processing and enzyme treatments (Hickling, 2007). Modern feed formulation based on net energy (NE) and standardized ileal digestible AA may also reduce negative effects of feeding canola co-products on pig performance (Zijlstra and Beltranena, 2013).

Canola expeller and CPC are canola co-products produced by mechanical pressing canola seed without solvent-extraction in small- to medium-scale crushing plants associated with

biodiesel production (Newkirk, 2011). Mechanical pressing is less efficient in oil removal than solvent-extraction (Seneviratne et al., 2010). Therefore, CE and CPC contain more remaining oil and thus have greater energy value than CM (Spragg and Mailer, 2007; Maison et al., 2015). The remaining oil content in CE and CPC varies (80–220 g/kg) due to seed quality and oil-extraction procedures (Newkirk, 2011; Grageola et al., 2013). Availability of AA was greater in CE and CPC than in CM (Spragg and Mailer, 2007). Thus, CE and CPC could be fed to swine as source of AA and energy. Despite these nutritional advantages of CE and CPC over CM, some concerns exist over feeding medium- to high-fat canola co-products. Dietary inclusion of CE or CPC may compromise pork quality by softening pork fat due to richness of unsaturated fatty acids in canola oil (Wood et al., 2008) and remaining oil in CE and CPC may be less digestible than the extracted canola oil due to physical encasement in the seed matrix (Thacker and Petri, 2009). Supply of CE and CPC increased recently due to increasing demand for biodiesel production (CRFA, 2013). The feeding value of CE and CPC needs to be evaluated to support their inclusion into swine diets.

The objective of this review are: to describe canola seed processing that produce canola co-products, to summarize nutritional composition and ANF in CM, CE and CPC and to discuss effects of feeding canola co-products to pigs on AA and energy digestibility, growth performance, carcass traits and pork fat quality. Special focus will be on value-added processing techniques and enzyme treatments that may increase the feeding value of CM.

2.3 Canola seed and seed processing

2.3.1 Nutritional composition of canola seed

The 3 registered canola species in Canada are *Brassica* (*B.*) *napus*, *B. juncea* and *B. rapa*. Dark-seeded *B. napus* currently accounts for 95% of canola production (Canola Council of Canada, 2015). Thus, canola seed and co-products discussed in this review generally refer to *B. napus* unless otherwise specified. On as-is basis, full-fat canola seed contains 433 g EE/kg, 231 g CP/kg, 185 g NDF/kg and 14.0 μmol glucosinolates/g (Montoya and Leterme, 2010; González-Vega and Stein, 2012; NRC, 2012; Sauvant et al., 2012; Canadian Grain Commission, 2014). The seed hull is rich in fibre and the cotyledon is rich in oil and protein (Thakor et al., 1995). Following manual separation, the hull accounted for 16% of total seed weight and cotyledons for 84% (Slominski et al., 2012). The EE, CP and total dietary fibre (TDF) content was 164, 153 and 572 g/kg in the hull and 515, 267 and 105 g/kg in the cotyledons, respectively (Slominski et al., 2012; Bell and Shires, 1982). Glucosinolates are concentrated in cotyledons rather than the hull (Matthäus, 1998; Bell and Shires, 1982). Unlike crushing of soybean, dehulling before oil removal (front-end dehulling) is usually not performed for canola due to small seed size and tight adherence between hull and cotyledons that hampers separation (McCurrdy and March, 1992). Front-end dehulling of canola may reduce oil yield by producing fine particles (Khajali and Slominski, 2012).

2.3.2 Canola seed processing

Oil in canola seed is extracted in large-scale crushing plants by pre-press solvent extraction that produces CM as co-product. This process includes seed cleaning, conditioning, flaking, cooking, expelling, solvent extraction and desolventizing (Unger, 2011). Briefly, canola seed is subjected to: 1) cleaning by aspiration and sieving to remove foreign material such as dockage; 2) conditioning (important when seed is cold) to adjust seed temperature to 35°C (Newkirk, 2009) that prevents seed from being brittle and fractures into small intact cells during later processing that reduces oil extraction (Unger, 2011); 3) flaking to rupture cell walls and release oil droplets; 4) cooking that quickly increases flake temperature to 85–95°C and maintain for 30–40 minutes that helps to coalesce oil droplets by reducing oil viscosity thus increases efficiency of subsequent oil extraction (Newkirk, 2009; Unger, 2011); 5) mechanical expelling to extract 60–70% of oil from the seed (Unger, 2011); 6) solvent-extraction (usually by hexane) to extract the remaining oil; 7) desolventization the meal by toasting at 95–115°C for 30–50 minutes to remove remaining solvents that is followed by cooling and drying (Unger, 2011). The final product was defined as solvent extracted canola meal (CM, IFN 5-05-146) in AAFCO (2015).

In small- to medium scale crushing plants in North America, canola oil is usually mechanically extracted due to lower capital cost and equipment requirements (Beshada et al., 2008), producing CE and CPC as co-products. The CE is produced by cleaning, conditioning, flaking, cooking and expelling of canola seed without solvent extraction and desolventizing that result in 80–150 g remaining oil/kg. Some crushing plants apply the expelling procedure twice to

extract more oil from the seed, producing double-pressed canola expeller as co-product (Newkirk, 2009). In contrast, CPC is produced by expelling cleaned canola seed without conditioning, flaking, cooking, solvent extraction and desolventizing that result in 150–220 g remaining oil/kg. The CE and CPC have not been officially defined in AAFCO (2015).

2.4 Nutrient composition of canola meal

2.4.1 Protein and AA

Canola meal is fed to swine mainly as a protein source. Canola protein was classified into 4 fractions based on solubility in various solvents: 1) albumin, protein fraction soluble in water; 2) globulins, soluble in dilute salt; 3) prolamins, soluble in ethanol/water solution and 4) glutelins, soluble only in dilute alkali (Aider and Barbana, 2011). Globulin and albumin are the major storage proteins in cotyledons accounting for 60 and 20% of total canola protein (Hoglund et al., 1992). Solubility of canola protein could be reduced by excessive heating during desolventizing (Naczk et al., 1985). On as-is basis, the CP, Lys, Met, Thr and Trp content in *B*. *napus* CM was 388, 21.0, 7.5, 15.8 and 4.9 g/kg (Table 2.3) compared with 477, 29.6, 6.6, 18.6 and 6.6 g/kg in SBM (NRC, 2012). The *B*. *juncea* canola was developed to be more thermo-tolerate and disease-resistant than *B*. *napus* (Khajali and Slominski, 2012). It has similar CP (391 g/kg as-is basis) and AA (21 g Lys/kg) content as *B. napus* CM. High-protein *B*. *napus* canola was developed to produce CM with similar CP (475 g/kg) and AA (27 g Lys/kg) content to SBM (Berrocoso et al.,

2015). However, the greater protein content may reduce oil yield that limits its production, because oil is the most valuable product from canola seed crushing (Barthet and Daun, 2011).

2.4.2 Carbohydrates

Carbohydrates in CM include monosaccharides, disaccharides, oligosaccharides and polysaccharides (Table 2.2). The CM contains low amount of monosaccharides such as 6.4 g glucose/kg and 2.9 g fructose/kg, an intermediate to low amount of disaccharides such as 60 g sucrose/kg and 0.40 g maltose/kg. Sucrose is the main sugar in CM and with up to 90 g/kg (Slominski et al., 2012). Those sugars can be readily digested and absorbed in the small intestine to provide energy to animals (Englyst and Englyst, 2005). However, sugars can be encased in the cell wall structure in canola that inhibits their digestion and absorption (Bell, 1993). The CM contains 25 g oligosaccharide/kg with 84% stachyose and 16% raffinose (Slominski et al., 2012). Oligosaccharides cannot be digested by porcine enzymes but could be fermented by large intestine microbes to produce short-chain fatty acids (SCFA, Grieshop et al., 2001). Sugars and oligosaccharides are not major energy contributors in CM due to their low content.

Dietary polysaccharides include starch and non-starch polysaccharides (NSP). Starch content in canola is high for immature seed, but it is quickly used up as the seed develops (King et al., 1997), causing low starch content (8.8 g/kg) in CM. The NSP in CM includes cellulose, hemicellulose and pectin that are classified as dietary fibre. Lignin is not a carbohydrate, but is closely bounded with cell wall fibre and is included in fibre analyses (Lunn and Buttriss, 2007). Thus, lignin is considered part of dietary fibre. Dietary fibre in CM was analysed by detergent

fibre procedures (ADF, NDF) and enzymatic-chemical procedures (total dietary fibre, TDF and NSP). The ADF, NDF, total NSP, TDF and acid-detergent lignin (ADL) content in CM was 178, 276, 185, 285 and 74.0 g/kg (Table 2.2) that are greater than the 52.8, 82.1, 157, 167 and 11 g/kg in SBM (NRC, 2012). The cellulose (ADF – ADL) and hemicellulose (NDF – ADF) in CM were calculated to be 108 and 117 g/kg, respectively. The NSP in CM was 91% water-insoluble (Slominski et al., 2012) that may increase digesta passage rate and limits available time for nutrient digestion and absorption (Chesson, 2006). Therefore, the greater fibre content in CM was related to its reduced energy value and AA digestibility (Fan et al., 1996).

Hull and defatted cotyledons are 2 basic seed components in CM. Hull accounts for 30% of total weight of CM and is highly concentrated in fibre (~600 g TDF/kg; Bell and Shires, 1982, Slominski et al., 2012). Canola hull contains more cellulose and lignin but less hemicellulose and pectin than defatted cotyledons (Bell, 1993; Mustafa et al., 1996; Slominski et al., 2012). Cellulose and lignin in canola are not digestible and poorly fermented by gut microorganisms (Bach Knudsen et al., 2013), whereas hemicellulose and pectin are more fermentable (Urriola et al., 2010). Thus, reducing hull mass by breeding or partially removing hull by processing may increase the nutritional value of CM in pigs (Hickling, 2007). Yellow-seeded *B. juncea* has thinner hull and thus less fibre than *B. napus*. The ADF, NDF, total NSP, TDF and ADL content in *B. juncea* CM was 111, 178, 199, 243 and 28 g/kg, respectively (Table 2.2). Fibre in *B. juncea* CM contained more hemicellulose and pectin (Slominski et al., 2012) that may increase hindgut fermentability and energy value (Le et al., 2012).

2.4.3 Fat

Oil in canola seed was depleted after pre-press solvent-extraction, leaving 10–20 g residual EE/ kg of CM. However, Canadian CM contains 33.7 g EE/kg, because 10–20 g gums/kg are added back into CM (Newkirk, 2011). Gums are phospholipids, glycolipids and free fatty acids in extracted canola oil. Hydrophilic property of phospholipids causes them to bind with moisture in canola oil and settle out during transportation and storage that is undesirable for oil refining and thus must be removed (Unger et al., 2011). The gums increase the energy value of CM. Adding up to 100 g gums/kg into CM did not reduce nutrient digestibility and growth performance in pigs (McCuaig and Bell, 1981).

2.4.4 Anti-nutritional factors

2.4.4.1 Glucosinolates

Glucosinolates are sulphur-containing secondary plant metabolites in *Brassica* seed and are the major ANF in CM (Tripathi and Mishra, 2007). Although more than 120 types of glucosinolates exist (Chen and Andreasson, 2001), they have the same core molecular structure comprising of a β-D-thioglucose group, a sulphonated oxime moiety and an AA side-chain (Tripathi and Mishra, 2007). Intact glucosinolates are chemically inert and generally not harmful to animals (Liang et al., 2002). However, myrosinase in canola hydrolyses glucosinolates into isothiocyanates, nitriles and thiocyanate that cause bitter taste, disruption of thyroid and liver function and reduced feed intake and growth (Bell et al., 1991; Lönnerdal and Janson, 1973; Mithen et al., 2000; Wallig et al., 2002). In intact seed, myrosinase and glucosinolates are

contained in separate cellular compartments (Maheshwari et al., 1980). Crushing of canola seed causes contact between myrosinase and glucosinolates and triggers their reaction. Glucosinolates may also be hydrolysed by microbial enzymes in the hindgut where their break-down compounds could be absorbed (Oginsky et al 1965; Shapiro et al., 1998). Myrosinase is most active at 50–70°C with 10% moisture but would be inactivated above 90°C (Newkirk, 2009; Unger, 2011). Adjusting heat and moisture applied during canola seed processing (cooking, expeller-pressing, desolventizing) could inactivate myrosinase and decompose glucosinolates that may increase feeding value of CM (Tripathi and Mishra, 2007).

The guaranteed maximum glucosinolate content in Canadian canola is 30 μmol/g. Breeding and processing techniques have reduced glucosinolates content to 7.1 ± 4.2 μmol/g in conventional *B. napus* CM (Table 2.5). The major types of glucosinolates in *B. napus* CM are 2-OH-3-butenyl, 4-OH-3-CH3-indolyl and 3-butenyl, accounting for 37, 18 and 20% of total glucosinolates, respectively (Table 2.2). In contrast, *B. juncea* CM contains more total glucosinolates (12.0 ± 1.9 μmol/g) but is particularly high in 3-butenyl, accounting for 80% of glucosinolates (Table 2.5). The 3-butenyl is a bitter glucosinolate in CM (Kyriazakis and Emmans, 1992). Thus, feeding *B. juncea* CM would more likely reduce pig feed intake.

2.4.4.2 Phytate, sinapine and tannins

Canola meal contains 10.7 g phosphorus/kg (as-is basis) with 60% in phytate form (myo-inositol 1, 2, 3, 4, 5, 6-hexakis dihydrogen phosphate (Sauvant et al., 2004, NRC, 2012, Rodriguez et al., 2013; Adhikari et al., 2015). Phytate cannot be hydrolysed by porcine enzymes

(Nahashon et al., 1994) and may cross-link with other cations, proteins and fibre thereby reducing their digestibility or fermentability (Newkirk and Classen, 2001; Angel et al., 2002). Dietary supplementation of phytase releases phosphorus and increases phosphorus digestibility in pigs fed CM as main dietary protein source (Akinmusire et al., 2009; Woyengo et al., 2009). Phytase supplementation might also break down links between phytate and protein thereby increasing AA digestibility (Kemme et al., 1998). However, this response was inconsistent among studies and may depend on other dietary components (Adeola and Sands, 2003; Favero et al., 2014).

Sinapine is the choline ester of sinapic acid. Canola meal contains 10–20 g sinapine/kg that is mainly concentrated in de-fatted cotyledons (Matthäus, 1998; Khattab et al., 2010). Sinapine contributes to the bitterness of CM (Niu et al., 2015). Sinapine reduction has not been a major target for canola breeding programs due to its low content and limited genetic variation within *B. napus* (Mailer et al., 2008). Sinapine did not affect feed intake of pigs as much as glucosinolates (Lee and Hill, 1983).

Tannins are phenolic compounds present at 15–30 g/kg in CM (Newkirk et al., 2011). Although having limited effect on palatability of CM, tannins may form complexes with protein and inhibit digestive enzyme activity, thereby reducing AA digestibility (Martin-Tanguy et al., 1978). Unlike other ANF such as glucosinolates, sinapine and phytate that are present in cotyledons, tannins are concentrated in the hull (Matthäus, 1998). Thus, tannins are tightly associated with hull fibre and lignin, making hull protein indigestible (Bell and Shires, 1982).

Dehulled CM or CM processed from seed with thinner hull (yellow-seeded) may have reduced tannin content.

2.5 Feeding value of CM

2.5.1 Protein and AA digestibility

The coefficient of apparent ileal digestibility (CAID) and standardised ileal digestibility (CSID) have been used in literature for AA digestibility. The CAID does not correct for any endogenous loss of AA while CSID corrects for basal endogenous losses (Stein et al., 2007), making CSID closer to the true digestibility of AA. When multiple protein sources were added into a diet, the CAID of AA in the complete diet could be underestimated if calculated from CAID of AA in each ingredient (Stein et al., 2005). The poor additivity of CAID was due to interaction of endogenous AA (Xue et al., 2014). Therefore, the CSID of AA is more accurate in estimating AA digestibility in feed ingredients or diets.

The CSID of Lys, Met, Thr, Trp and CP in CM was 0.74, 0.79, 0.73, 0.77 and 0.72 in grower-finisher pigs, respectively (Table 2.4). These values are lower than the 0.90, 0.91, 0.87, 0.91 and 0.87 for SBM (Sauvant et al., 2004; NRC, 2012), respectively. The CSID of other AA were generally 0.10–0.15 units lower in CM than in SBM. The lower digestibility could be due to the greater fibre content in CM (Berrocoso et al., 2015). Canola hull is highly cellulosic and lignified that could tightly encase or bind to hull protein and thereby reduce its digestion (Bell and Shires, 1982; Mustafa et al., 1996). Cell-wall NSP (cellulose, hemicellulose, pectin) in

canola cotyledon may protect protein bodies from enzyme hydrolysis (Le Gall et al., 2009). The high insoluble fibre content in CM could reduce digesta retention time that limits protein digestion and AA absorption (Chesson, 2006). The greater fibre content in CM may trigger greater specific endogenous AA losses that are not accounted for by CSID calculations (Mosenthin et al., 1994; Stein et al., 2007) causing values of CSID of AA to be lower in CM. The *B. juncea* CM contains less fibre than the *B. napus* CM and has slightly greater CSID of AA (Table 2.4). However, some studies reported similar CSID of AA in *B. napus* and *juncea* CM (Le et al., 2012, Sanjayan et al., 2014).

Variation of CSID AA in CM among studies could be attributed to different genetic lines and growing conditions of canola (Fan et al., 1996). Dietary glucosinolates would not affect AA digestibility when their dietary concentration was below 10 μmol/g (Aumaitre et al., 1989). However, greater dietary level of glucosinolates may reduce CSID of AA in pigs (Gilani et al., 2005; González-Vega and Stein, 2012). Since inclusion of CM in pig diets usually does not exceed 300 g/kg, dietary glucosinolate content is limited to < 3 μmol/g. Thus, glucosinolates in CM may not meaningfully affect AA digestibility.

Processing conditions during oil extraction are important factors affecting AA digestibility in CM. Heat and steam applied during desolventizing may overheat CM and induce Maillard reactions (Messerschmidt et al., 2014). During Maillard reactions, the carbonyl group of reducing sugar reacts with the amino group of AA to form sugar-AA complexes such as Amadori compounds, furfural and melanoidins (Newkirk, 2002; Nursten, 2005). The AA in these

complex forms had reduced digestibility and cannot be utilized by pigs for maintenance or lean growth after being absorbed (González-Vega et al., 2012; Moughan, 2005; Newkirk et al., 2003). The rate of Maillard reactions increases greatly when temperature rises over 100°C with an optimum moisture level of 15–18% (Lea et al., 1949; Adrian, 1974). Conventional CM desolventizing usually results in processing at 100–115°C and moisture level of 15–18% that are ideal conditions for Maillard reactions (Unger, 2011). The Maillard reactions also require the presence of reducing sugars. The CM is low in glucose but has moderate amounts of sucrose. Although not a reducing sugar itself, sucrose could be degraded into glucose when heated during desolventizing thereby providing substrate for Maillard reactions (Lindberg et al., 1975). Lysine is the first limiting AA in swine diets and is particularly susceptible to Maillard reactions due to its exposed ε-amino group (Pahm et al., 2008). Excessive heating could also trigger protein-phenolic and protein-protein cross-links that further reduce AA digestibility (Newkirk, 2002). Thus, overheating during desolventizing should be avoided. However, CM produced from vacuum-assisted cold desolventizing (< 60°C) had lower CSID of AA than conventional CM desolventizing (Trindade et al., 2012). This finding indicates that an intermediate temperature (60–100°C) might be required during canola processing for protein denaturation that may increase AA digestibility (Nordheim and Coon, 1984). The AA quality in CM may also be damaged during cooking and expeller-pressing since heating is applied. Temperature and moisture during canola processing should be carefully controlled to ensure optimum AA availability.

2.5.2 Energy utilization

On as-is basis, the gross energy (GE), digestible energy (DE), metabolisable energy (ME) and net energy (NE) value of CM were 17.8, 12.5, 11.5 and 8.4 MJ/kg (Table 2.1) that were lower than 17.8, 15.1, 13.8 and 8.5 MJ/kg in SBM (Sauvant et al., 2004; NRC, 2012), respectively. The low energy value of CM can be attributed to its relatively high fibre and protein content and low fat and starch content. Dietary fibre cannot be digested by porcine enzymes and also reduces digestibility of other energy-yielding nutrients (Dégen et al., 2007), therefore causing the low DE value. Fibre is partially degraded by gut microbes and produce short-chain fatty acids (SCFA) that can yield energy upon absorption. However, some energy is lost during fermentation as gas and absorbed SCFA yield energy only 69% as efficient as absorbed glucose (Jorgensen et al., 1997). The fibre and protein in CM induce greater heat increment in pigs that further penalizes its NE value (Noblet and van Milgen, 2004). Due to the lower fibre content and greater fibre fermentability in *B. juncea* over *B. napus* CM, *B. juncea* CM has greater DE, ME and NE values that were 13.7, 12.5 and 9.3 MJ/kg, respectively (Table 2.1).

2.5.3 Growth performance and carcass quality

Soybean meal is the major protein source for feeding livestock globally and determines the pricing of other protein feedstuffs (Willis, 2003). The CM is usually priced at 55–75% of the SBM price and generally replaced SBM to control feed cost (Kim et al., 2014). However, in earlier studies feed intake and growth of weaned and growing-finishing pigs was reduced when

CM replaced SBM in diets (Baidoo et al., 1986, 1987; Bell et al., 1988; Corino et al., 1991; McIntosh et al., 1986). The reduced performance was attributed to the high level of glucosinolates and fibre in CM that reduced feed intake and nutrient digestibility. Consequently, maximum inclusion of CM in swine diets was initially limited to 180 g/kg for finishing pigs, 120 g/kg for growing pigs and 50 g/kg for weaned pigs (Brand et al., 2001; Newkirk, 2009).

Canadian CM contains < 30 μmol glucosinolates/g but this level may still reduce pig performance. Breeding programs continued to develop canola with lower glucosinolate content (Bell, 1993). Glucosinolate content in *B. napus* CM could be as low as 1.0 μmol/g recently that would allow its greater inclusion in swine diets (Thacker and Newkirk, 2005). Moreover, early studies usually formulated diets based on DE or ME value and total AA content of feedstuffs that overestimated their available energy and AA contribution, especially for co-products such as CM that are rich in protein and fibre (Noblet, 2007; Noblet and LeGoff, 2001). The NE value and SID AA content in feedstuffs better reflects the available of energy and AA that can actually be used by pigs for maintenance and growth (Lynch et al. 2007; Zijlstra and Beltranena, 2013). Thus, formulating diets based on NE and SID AA could minimize negative effects of feeding CM on growth performance of pigs (Zijlstra and Beltranena, 2013).

Increasing dietary inclusion of low-glucosinolate (3.7–5.0 μmol/g) CM up to 150–250 g/kg by replacing SBM did not reduce average daily feed intake (ADFI), average daily gain (ADG) and feed efficiency (G:F) in weaned pigs (Brand et al., 2001; King et al., 2001; Landero et al., 2011; Seneviratne et al., 2011b). However, increasing dietary inclusion of CM with 8–15 μmol

glucosinolates/g up to 400 g/kg reduced ADFI linearly in weaned pigs (Parr et al., 2015). Apparently, pigs can tolerate up to 2.0–2.5 μmol glucosinolates/g from *B. napus* CM in the diet (Schone et al. 1997a; Schone et al. 1997b). The *B. juncea* CM generally has greater total glucosinolate and more bitter taste than *B. napus* CM. Weaned pigs preferred *B. napus* over *juncea* when given a choice (Landero et al., 2012). Without choice, weaned pigs fed *B. juncea* CM had lower ADFI than pigs fed *B. napus*. However, feeding *B. juncea* CM may increase G:F due to reduced fibre content and increased nutrient digestibility. Increasing dietary inclusion of *B. juncea* CM up to 240 g/kg replacing SBM reduced ADFI, ADG and G:F linearly (Landero et al., 2013). However, performance was not reduced when feeding pigs up to 250 g *B. juncea* CM/kg (Sanjayan et al., 2014). Different glucosinolate profile among studies may explain varying results. Breeding programs or processing techniques should further reduce the glucosinolate content in *B. juncea* canola to support greater inclusion of *B. juncea* CM in swine diets.

Growing-finishing pigs may tolerate greater level of glucosinolates (Corino et al., 1991). Increasing CM inclusion up to 120–350 g/kg (1.0–20.0 μmol total glucosinolates/g) did not reduce growth performance in growing-finishing pigs (Kim et al., 2014; King et al., 2001; Little et al., 2015; McDonnell et al., 2010; Mullan et al., 2000; Thacker and Newkirk, 2005). However, feeding increasing level of CM up to 300 g/kg along with other fibrous co-products such as distiller dried grain with solubles (DDGS) reduced growth performance in growing-finishing pigs (Smit et al., 2014a; Smit et al., 2014b). Supposedly, even a low dietary level of glucosinolates could still reduce ADFI if fed longer (Smit et al., 2014b). Information on feeding

CM to sows is scarce. Feeding up to 100 g CM/kg to gestating sows did not affect litter size, weight, first postpartum estrus and ovulation rates (Flipot and Dufour, 1977). Feeding up to 202 g CM/kg to lactating sows did not reduce feed intake (King et al., 2001). More research is required to further validate the inclusion of CM in sow diets.

Pigs fed CM may have similar ADG and body weight as pigs fed SBM. However, viscera weight relative to live weight may be greater in pigs fed CM (Parr et al., 2015). Feeding high-fibre feedstuffs such as CM may increase gut fill and the weight of the pig gut (Kerr and Shurson, 2013). Glucosinolates may increase liver weight by causing cell hypertrophy (Busato et al., 1991; Little et al., 2015). Kidney weight relative to live weight also increased with increasing CM inclusion (Little et al., 2015). On the other hand, glucosinolates could reduce iodine absorption and utilization in the thyroid, causing hyperthyroidism, reduced secretion of thyroid hormones that are responsible for muscle growth (Tripathi and Mishra, 2007; Hocquette et al., 1998). Therefore, feeding CM may cause reduced dressing percentage and lean yield. Indeed, increasing inclusion of either *B. napus* or *juncea* CM (5.8 and 12.3 μmol/g total glucosinolates, respectively) up to 300 g/kg along with 150 g/kg wheat-corn DDGS linearly reduced carcass weight, dressing percentage, and loin depth in growing-finishing pigs (Smit et al., 2014b). However, these reduction was minor (< 2% of reduction). Other studies found carcass traits not being affected by up to 240 g/kg inclusion of CM with total glucosinolate content ranged 4.0–20.0 μmol/g (Smit et al., 2014a; Mullan et al., 2000; McDonnell et al., 2010; Little et al., 2015; King et al., 2001). It is

expected that CM with lower fibre and glucosinolates would have less detrimental effects on carcass traits of pigs.

2.6 Further processing of CM

The feeding value of CM is limited by its high dietary fibre content and presence of ANF. Further processing of CM could reduce these undesirable substances or reduce their negative effect on nutrient digestibility, performance and health (Hickling, 2007). Processing techniques include hydrothermal, physical and chemical processing and enzyme supplementation. Extrusion, sieving, air-classification and protein extraction may increase nutrient composition of CM.

2.6.1 Hydrothermal and physical processing

2.6.1.1 Extrusion

Extrusion is the process of forcing feedstocks through a shaped opening using single or twin screws within a cylindrical barrel (Serrano, 1997). The decreasing channel between screw and barrel combined with the reducing flight helix angle create high shearing force, pressure and thus generate autogenous heat on feedstuffs (Lusas et al. 1988). Steam and other additives may also be added during extrusion to assist the cooking (Fenwick et al., 1986; Serrano, 1997).

Depending on type of extruders and processing conditions, temperature of extrudates may rise to 90–150°C during extrusion that may inactivate myrosinase in CM thereby limiting hydrolysis of glucosinolates (Fenwick et al., 1986; Allan and Booth, 2004). The heat could also decompose 28–75% of glucosinolates in CM that would reduce total glucosinolate content in

CM (Fenwick et al., 1986; Keady and O'Doherty, 2000). The break-down products from glucosinolates as result from heat differed from those produced by myrosinase hydrolysis (Fenwick et al., 1986; Liang et al., 2002) and seemed to be less toxic, because pig growth performance was increased when feeding extruded CM compared to raw CM (Keady and O'Doherty, 2000). The addition of alkali, formic acid, ammonium sulphate or formaldehyde during extrusion could further reduce glucosinolate content in CM. However, these additives were not widely used due to their detrimental effect on protein digestibility (Fenwick et al., 1986). The high temperature during extrusion may damage protein quality. However, the feedstuff passes through the extruder quickly (5–30 seconds) so protein quality is not likely affected (Harper, 1978; Keady and O'Doherty, 2000).

Extrusion could increase the nutritional value of feedstuffs with complex fibre structure such as CM (Anguita et al., 2006; Ahmed et al., 2014). Heat, pressure and shear force during extrusion may rupture cell-wall materials (Nasi, 1991), partially break the weak binding among NSP molecules and glycoside link within NSP molecules (de Vries et al., 2014), making NSP more soluble (Anguita et al., 2006) and increase protein denaturation (Camire et al., 1991) that eventually leads to greater digestibility of protein, fat and minerals. Extrusion of CM using single-screw extruder with added steam at 160ºC increased the apparent digestibility of AA, CP and GE in pigs (Ahmed et al., 2014). Feeding 200 g CM/kg extruded at 120°C did not affect ADFI but increased ADG and G:F in pigs compared with pigs fed raw CM (Keady and O'Doherty, 2000). The ideal processing conditions (screw speed, moisture level, ammonia level,

temperature) for extruding CM need to further investigation to increase nutritional value while avoiding potential detrimental effects.

2.6.1.2 Sieving

Dry fractionation separates seed components by their physical properties such as particle size, density or shape. In CM, the hull is more rigid than defatted cotyledons (Wolf et al., 2002). Thus, cotyledons with less fibre and more protein are more easily shattered into smaller particles during milling than hull that contains more fibre and less protein (Clark et al., 2001). By vibratory screening finely milled CM through a series of sieves, CM particles with different sizes would be separated into fractions with different chemical composition. McCurdy and March (1992) tempered the moisture content of CM to 16% (to loosen binding between hull and cotyledons), grounded it to < 300 micron particle size and sieved it through 210 micron sieve. The fine fraction contained more CP (404 vs. 373 g/kg) and glucosinolates (18.0 vs. 16.1 μmol/g) and less NDF (157 vs. 218 g/kg) than parent CM. Clark et al. (2001) followed the same sieving procedure and found similar increase of CP (372 vs 353 g/kg), glucosinolates (1.8 vs. 1.6 μmol/g). Mejicanos (2015) created 2 fine CM fractions with particle size < 250 micron and 250–355 micron that contained 417 and 396 g CP/kg, 214 and 267 g TDF/kg, 48 and 73 g lignin with polyphenols/kg and, 9.6 and 9.6 μmol glucosinolates/g, comparing with 369, 300, 100 g/kg and 9.2 μmol/g in the parent CM, respectively. Feeding these fine fractions at 150 g/kg did not affect ADFI but increased G:F and ADG of weaned pigs compared with pigs fed parent CM (Mejicanos, 2015). The minor enrichment of glucosinolates in the fine fractions did not affect

feed intake while the reduced fibre content and reduced particle size increased nutrient utilization. However, fine fractions with less fibre than the parent CM has limited yields. Fractions with < 335 micron particle size only accounted for 22.5% of the weight of parent CM (Mejicanos, 2015) that would limit their supply for swine feeding. Also, if AA in CM are heat damaged, the damaged AA may be concentrated in the fine fractions and reduce its nutrient digestibility and availability (Yáñez et al., 2014).

2.6.1.3 Air-classification

Air-classification is dry fractionation that separates particles based on their density and shape using streams of air (Seth and Clandinin, 1973). After milling of CM, the high-fibre hull particles are denser than low-fibre cotyledon particles. The air-flow would lift the lighter particles up while heavier particles would fall. Thus, air-classification produces a light- and a heavy-particle fraction that differ in chemical composition (Fedec, 2003). The light-particle fraction contained less fibre and more CP than the parent CM (Leslie et al., 1973). Notably, sieving and air-classification result in incomplete separation of hull and cotyledon. The tight adherence between hull and cotyledons prevents their physical separation (McCurrdy and March, 1992). Fine grinding of parent CM before air-classification or sieving is crucial for breaking the bonds between hull and cotyledons and increase efficiency for shifting protein or fibre (King and Dietz, 1981). However, the feeding value of air-classified CM fractions has not been studied in pigs. Dry fractionation such as sieving and air-classification of CM can be regarded as tail-end dehulling techniques that reduce negative effects of hull fibre on nutrient digestibility and growth

performance of pigs (Mejicanos, 2015). However, the fibre reduction and protein enrichment are moderate for dry-fractionation. Wet fractionation of CM could produce canola protein concentrates and isolates that further increase its nutritional value.

2.6.2 Chemical processing

Chemical processing could produce canola protein concentrates or isolates with greater protein, less fibre and ANF content than raw CM. Canola protein concentrates are produced by washing raw CM with water or solvents to remove ANF while keeping protein in the solid form (Xu and Diosady, 2012). Firstly, hull removal is performed on raw CM by either front-end or tail-end dehulling. Dehulled meal will then be heated to inactivate myrosinases, preventing it from hydrolysing glucosinolates. Then, glucosinolates and sinapine would be solubilized by water or solvents and be removed from the meal (Xu and Diosady, 2012). Washing dehulled CM with hot acid (90°C) combined with ethanol reduced glucosinolate and sinapine content by 97 and 92% in raw CM (McCurdy and March, 1992). However, intensive alcohol wash should be avoided because it may reduce protein solubility (Xu and Diosady, 2012). Phytase can be added during washing to eliminate phytate in CM (CanPro, 2015). Cell-wall degrading enzymes, methanol and ammonia could be added during washing to hydrolyse fibre and solubilize ANF. Nutrient composition of canola protein concentrate varies depending on solvents used during washing and other processing conditions. In general, after solvent removal, the resulting canola protein concentrates contain 500–650 g CP/kg, 36.4 g crude fibre/kg and 0.6–3.4 μmol

glucosinolates/g that could be fed to pigs as highly-digestible specialty protein ingredients (McCurdy and March., 1992; CanPro, 2015).

Canola protein isolate is typically produced by dissolving protein in alkaline solution, removing solid impurities and then recover protein by isoelectric precipitation (Xu and Diosady, 2012). Dilute NaOH solution with pH 10.5–12 could solubilize 90% of CM protein (Tzeng et al., 1990). However, CM that has been exposed to excessive heat during desolventization (>130°C) would have lower solubility in alkaline solution. After removing insoluble solids, reducing the pH of canola protein solution from 11.0 to 3.6 precipitated 65.7% of protein (El Nockrashy et al., 1977). Different types of canola protein have various isoelectric points, so specific proteins could be precipitated at a specific isoelectric point (Xu and Diosady, 2012). The canola globulins could be precipitated at pH 6 and 8 while albumin is highly soluble over the entire pH range and could not be precipitated by pH adjustment (Xu and Diosady, 1994). Thus, this method produces 2 fractions of canola protein isolate: a solid fraction and an aqueous fraction. The albumin aqueous fraction could be further isolated by membrane ultra-filtration with smaller molecules (glucosinolates, phytate and sinapines) passing through the membrane while larger albumin molecules would be collected (Tzeng et al., 1990). Both isolate fractions may contain > 900 g CP/kg and negligible glucosinolates (Tzeng et al., 1990). However, producing canola protein isolate is costly and is mainly targeted for food and beverage consumption. Compared with dry processing, chemical wet processing of CM could produce canola products with more

concentrated digestible nutrient content. However, these procedures would increase processing cost associated with equipment, solvents and spray-drying (Beltranena and Zijlstra, 2011).

2.6.3 Enzymatic treatments

Dietary supplementation of exogenous NSP-degrading enzymes may reduce negative effects of dietary fibre on nutrient digestibility and growth performance in pigs (Olukosi and Adeola, 2013). The CM is rich in NSP such as cellulose, hemicellulose (mainly arabinoxylan) and pectin (Slominski and Campbell, 1990). Thus, supplementation of cellulase, xylanase or pectinase may break down these fibre components and increase digestibility of NSP in CM that would also open the cell-wall fibre matrixes and increase endogenous enzyme access to AA and other nutrients that are encapsulated (Fang et al., 2007). Supplementation of a mixture of xylanase and β-glucanase may increase digesta passage rate and stomach emptying that could increase pig fed intake when dietary DE was limited (Zijlstra et al., 2004). *In vitro* digestibility of DM, CP and NDF increased in CM when either cellulase, xylanase or pectinase was added to the diet (Fang et al., 2007; Fang et al., 2008). Xylanase and cellulase had a synergic effect on nutrient digestibility (Fang et al., 2008). Supplementing multi-carbohydrase or combination of carbohydrases, protease and oligosaccharidases also increased apparent total tract digestibility of GE, DM and CP in CM for weaned and growing pigs (Soria-Flores et al., 2009; Sanjayan et al., 2014). Carbohydrase supplementation may increase growth performance of pigs when CM was included in diets (Omogbenigun et al., 2004; Zijlstra et al., 2004). However, this response was inconsistent among studies (Thacker, 2001; Olukosi et al., 2007; Sanjayan et al., 2014). The

increased nutrient digestibility caused by enzyme supplementation may not convert into growth performance when diets were well-balanced for digestible nutrient content (Sanjayan et al., 2014). Also, exogenous carbohydrase supplementation usually led to moderate increases in nutrient digestibility that might be insufficient to meaningfully affect growth performance. The combination of CM processing (extrusion, dehulling) and enzyme supplementation may increase nutrient digestibility more (Vries et al., 2014; Fang et al., 2008).

2.7 Nutrient composition of canola expeller (CE) and canola press-cake (CPC)

2.7.1 Fat

The low energy value in CM can be partly attributed to oil depletion during solvent extraction (Seneviratne et al., 2011b). Mechanical pressing the seed alone is less effective in oil removal than combined with solvent extraction and would leave more remaining oil in the meal (Grageola et al., 2013). The CE contains on average 102 g EE/kg (as-is basis) that varies moderately (79.1–138 g/kg, Table 2.6) due to seed quality, cooking temperature and number of passes through the expeller (Woyengo et al., 2010a; Toghyani et al., 2014). By leaving out conditioning, flaking and cooking, the CPC contains even more remaining fat (179 g EE/kg as-is) but varies greatly (86.8–275 g/kg, Table 2.6) due to equipment and processing conditions (Grageola et al., 2013). By applying 2 levels of screw speeds (44 and 103 rpm) and barrel temperatures (53 and 60°C), Seneviratne et al. (2011a) created 4 CPC samples with 87.0–227 g EE/kg. Consequently, increasing screw speed at high and low temperature could reduce and

increase EE content in CPC, respectively. The greater remaining fat content in CE and CPC increased their energy value in pigs (Brand et al., 2001). Remaining fat in CE is highly unsaturated. The saturated fatty acid (SFA), monounsaturated fatty acid (MUFA) and polyunsaturated fatty acid (PUFA) content in CE were 81, 605 and 313 g/kg of total remaining fat (Spragg and Mailer, 2007) that was similar to 71.0, 586 and 296 g/kg in purified canola oil (NRC, 2012), respectively. A portion of fatty acids in CE might be oxidized during cooking and expelling with excessive heat (Liu et al., 2014b). The remaining oil in CPC may be less oxidized due to less heat exposure and contains more PUFA and less SFA than CE (Ghazani et al., 2014).

2.7.2 Protein and AA

Despite the greater remaining fat content that is expected to dilute protein and AA content in CE, the CP, Lys, Met, Thr and Trp content in CE was 357, 19.5, 6.4, 14.2 and 3.8 g/kg (as-is basis), respectively (Table 2.7), which are similar to those in CM. The AA content in CM could be reduced by excessive heat during desolventizing (Newkirk et al., 2003; Woyengo et al., 2010a). Production of CE does not involve desolventizing; thus, more AA are preserved in the cake. However, cooking and expelling also generate heat. Temperature during expeller-pressing ranges 100–120°C but could rise to 160°C when intensive expelling pressure is applied to maximize oil extraction (Spragg and Mailer, 2007; Newkirk, 2009). The chemical availability of Lys is 89% in CE compared with 81% in CM. This indicates that cooking and expelling could still cause heat damage to Lys that can be exacerbated by desolventizing process.

On as-is basis, the CP, Lys, Met, Thr and Trp content in CPC was 338, 14.1, 5.0, 11.2 and 3.4 g/kg (Table 2.7), respectively that were lower than in CM and CE due to dilution by more remaining fat (Grageola et al., 2013). The CP content in CPC produced at various processing conditions varied greatly (Seneviratne et al., 2011a). The processing temperature for CPC was 50–60°C that would limit Maillard reactions (Leming and Lember, 2005). The chemical lysine availability was above 91% (Grageola et al., 2013).

2.7.3 Carbohydrates

Some off-graded canola seed is usually included to produce CE and CPC due to profitability considerations in small- to medium-scale processing plants (Beltranena and Zijlstra, 2011). Off-graded seed could be immature (green seed) or heated by microbial activity during storage that may have contain less oil and more fibre than regular canola seed (Seneviratne et al., 2011a; NRC, 2012; Woyengo et al., 2014). This could led to greater fibre content in CE or CPC. However, the ADF, NDF, total NSP, TDF and ADL content in *B. napus* CE was 171, 237, 178, 258 and 71.7 g/kg on as-is basis (Table 2.6) that are lower than in CM. This could be due to more remaining fat in CE that diluted its fibre content. The Maillard reactions caused by excessive heat during desolventizing CM produces insoluble proteins (neutral detergent insoluble protein, NDIP) that would be analysed as NDF (Van Soest, 1994). The CE production does not involve desolventizing and thus contained less NDF (Newkirk et al., 2003). Due to the thinner seed hull, the ADF, NDF and TDF content in *B. juncea* CE was 127, 195 and 257 g/kg that were lower than in *B. napus* CE (Le et al., 2014). The fibre profile in CPC has not been studied

extensively. In general, more remaining fat and less heat exposure resulted in less fibre in CPC than CE (Grageola et al., 2013). On as-is basis, CPC contained 162 g ADF/kg and 242 g NDF/kg (Table 2.6). Fibre reduction by tail-end dehulling may not be applicable for CE and CPC due to their high content of fat that sticks particles together and hinders their separation by sieving or air-classification.

2.7.4 Glucosinolates

Due to the absence of desolventizing, more myrosinase might remain active in CE and CPC and hydrolyses glucosinolates to exert anti-nutritional effects. Myrosinase in CE could be partially inactivated during cooking when temperature rises above 90°C (Newkirk, 2009). Total glucosinolate content in *B. napus* and *juncea* CE was 10.2 and 10.9 μmol/g, respectively (Table 2.9; Le et al., 2014). Glucosinolates in *B. napus* CE contained 42, 32 and 29% of 2-OH-3-butenyl, 4-OH-3-CH3-indolyl and 3-butenyl, respectively (Table 2.9), while 89% of glucosinolates in *B. juncea* CE was the bitter 3-butenyl (Le et al., 2014).

Processing temperature of CPC is 60°C that falls into the optimum temperature range for myrosinase activity (Unger, 2011). Thus, pig feed intake should be monitored when CPC is included in swine diets. The total glucosinolate content in CPC was 3.2–12.6 μmol/g among studies (Table 2.9). Glucosinolate profile in CM, CE and CPC should be compared when all these products are produced from the same seed to investigate effects of processing and avoid confounding from varieties and growing conditions.

2.8 Feeding value of canola expeller (CE) and canola press-cake (CPC)

2.8.1 Protein and AA digestibility

The CSID of Lys, Met, Thr, Trp and CP in CE was 0.74, 0.85, 0.73, 0.83 and 0.79, respectively (Table 2.8) that are generally greater than values for CM. This may be due to lower processing temperature for CE by omitting desolventization that leads reduced Maillard reactions (Woyengo et al., 2010). However, temperature during cooking should also be carefully controlled to limit potential AA damage while still inactivating myrosinase. Expeller-pressing may further increase meal temperature by generating frictional heat (Spragg and Mailer, 2007). However, mechanical pressing is a relatively fast process compared with cooking or desolventizing (Landero et al., 2013) and will likely not cause extensive AA damage. The AA digestibility in CE might interact with its remaining fat content (Maison and Stein, 2014). The greater EE content in CE might decrease digesta passage rate in the gut (Valaja and Siljander-Rasi, 2001), thus providing more time for AA digestion and absorption and increase AA digestibility (Kil and Stein, 2011). Greater AA digestibility of CE compared with CM could also be attributed to the lower content of fibre that reduces digestion of AA (Grageola et al., 2013).

The CSID of Lys, Met, Thr and Trp in CPC was 0.81, 0.86, 0.81 and 0.85, respectively (Table 2.8). These values are greater than those for CE and CM that may be due to reduced fibre and processing temperature and more fat remaining in CPC (Grageola et al., 2013). Seneviratne et al. (2011a) reported that reducing processing temperature from 60 to 53°C reduced the SID of AA and CP in CPC. This result might indicate that a sufficiently high processing temperature

needs to be reached to denature protein and increase AA digestibility in CPC while remaining below the temperature that may cause Maillard reactions (Nordheim and Coon, 1984).

2.8.2 Energy utilization

On as-is basis, GE, DE, ME and NE in CE averaged 20.1, 13.5, 13.1 and 9.5 MJ/kg, respectively (Table 2.6). The energy value of CE is greater than of CM mainly due to the greater EE content and diluted protein and fibre content (Brand et al., 2001; Landero et al., 2012). The ATTD of ADF and NDF in CE were 46 and 54% and similar to 43 and 52% in CM (Maison et al., 2015), respectively. This indicates low fermentability of fibre in CE that could be due to the high insoluble fibre content in CE that is less fermentable than soluble fibre (Bach Knudsen, 1997). The average GE, DE, ME and NE in CPC was 21.6, 16.6, 14.5 and 10.9 MJ/kg. These values are greater than that in CE but varies greatly due to variations in fibre and remaining fat content (Leming and Lember, 2005; Seneviratne et al., 2011a). The CE and CPC could be fed to pigs as AA and energy source. The remaining fat in CE and CPC is a major contributor of their energy values. The cost per MJ of NE from remaining fat in CE and CPC was less than that from supplementing feed grade canola oil, other vegetable fat or animal fat (Beltranena and Zijlstra, 2011). However, fat present in CE and CPC is in an inherent form might not be as digestible as fat from canola oil in an extracted form (Thacker, 1998). The inherent fat in CE and CPC may be encased in the seed matrix that physically inhibits access for lipase (Adams and Jensen, 1984). Thus, the energy value of remaining fat could be lower than the same amount of extracted fat.

This difference needs to be taken into consideration when calculating the NE value of CE and CPC using prediction equations.

2.8.3 Growth performance, carcass quality and fatty acid profile

Most canola seed is processed in Canada by pre-press solvent extraction with 3% of seed being expeller-pressed (Landero et al., 2012). Production of CE and CPC is increasing recently due to greater production of canola seed (Beckman, 2014), increased mandate for biodiesel production (CRFA, 2013) and greater demand for virgin canola oil for human consumption (Maison et al., 2015). Feeding of medium- to high-fat canola co-products may offer animal husbandry advantages such as dust suppression (Keith and Bell, 1991). Feeding diets high in supplemental purified fat/oil may cause bridging in feed bins and feeders and "oil out" of diets during storage (Pettigrew, 1981). Including CE or CPC with remaining fat in diets may partially spare supplementation of fat/oil to reduce these risks while maintaining dietary energy value.

Using diets balanced for NE value and SID AA content, including 150 g CE/kg (11.0 μmol glucosinolates/g) into nursery diets by replacing SBM did reduce ADFI slightly but did not affect ADG or G:F (Seneviratne et al., 2011b). Increasing CE (10.9 μmol glucosinolates/g) inclusion from 0–200 g/kg in nursery diets at the expense of SBM did not reduce ADFI, ADF or G:F (Landero et al., 2012). However, feeding up to 225 g CE/kg linearly reduced final body weight (BW), AFDI and ADG, but linearly increased G:F of grower-finisher pigs under commercial environment (Seneviratne et al., 2010). This reduction could be due to the greater glucosinolate content in CE (22.2 μmol glucosinolates/g) used in this study that reduced growth by reducing

feed intake. The increased G:F may be attributed to better dietary AA balance with greater CE inclusion. Apparently, feeding pigs up to 200 g CE/kg based on NE system and SID AA content would not affect growth performance as long as dietary glucosinolate content remained below 2.5 μmol/g (Schone et al., 1997a; Schone et al., 1997b). However, the tolerable level of glucosinolates from *B. juncea* CE may be lower than 2.5 μmol/g due to the high level of 3-butenyl in *B. juncea* glucosinolates that has a bitterer taste. Canola breeding programs need to reduce the 3-butenyl content in *B. juncea* to increase dietary inclusion of its meal or cake (Kyriazakis and Emmans, 1992). To our knowledge, no studies have been conducted evaluating the growth response of any types of pigs to dietary CPC inclusion. The feeding value of CPC needs to be evaluated.

Dietary fibre and glucosinolates in CE and CPC may compromise carcass yield of pigs. Inclusion of 292 g CE/kg in diets reduced dressing percentage of grower-finisher pigs but did not affect back fat depth and lean yield (Brand et al., 2001). Feeding up to 180 g CE/kg to growing-finishing pigs also reduced carcass weight, back fat depth and lean yield (Seneviratne et al., 2010) that was attributed to the relatively high glucosinolate content in CE that reduced feed intake. Even when glucosinolate content has been reduced in canola co-products recently, it could still reduce feed intake and carcass yield after prolonged feeding during the growing-finishing period (Mullan et al., 2000). Progressively reducing the inclusion of CE over the growing–finishing period may alleviate its negative effect on growth performance and carcass traits (Seneviratne et al., 2010).

The fatty acid composition in pork reflects the fatty acid profile in feed (Wood et al., 2008). Feeding diets high in fat may suppress *de novo* fatty acid synthesis in pigs (Bee et al., 2002). Thus, feeding pigs CE and CPC that contain more unsaturated fatty acids may increase pork fat unsaturation and reduce carcass fat firmness. This could increase the incident of miscuts during pork cutting, reduce bacon yield, pork shelf life and deteriorate sensory variables (Apple, 2013). Jowl fat can be sampled to represent the carcass fatty acid profile since it is cheap and reflects changes to dietary fat similar to back fat (Benz et al., 2011). Feeding increasing level of CE (127 g EE/kg) up to 180 g/kg did not affect jowl fatty acid profile and iodine value (Seneviratne et al., 2010). However, CE with more remaining fat may have more influence on jowl fatty acid profile. The accepted iodine value for pork fat was below 70–75 g per 100 g fat (Benz et al. 2010). Feeding CE at 180 g/kg in the diet resulted in iodine value of 67.1 g/100 g jowl fat (Seneviratne et al., 2010) that was within the acceptable limit.

2.9 Conclusions

Supply of canola co-products is expected to increase globally due to greater demand of canola oil for human consumption and biodiesel production. Canola co-products such as CM, CE and CPC are produced by various oil-extraction procedures. Canola meal is the major canola co-product. The nutritional value of CM is limited by: 1) relatively high dietary fibre content that reduces nutrient digestibility, growth performance and carcass yield; 2) presence of ANF such as glucosinolates, phytate, sinapine and tannins that reduce feed intake, nutrient digestibility and

animal health; 3) excessive heat exposure during oil extraction (cooking, expelling, desolventization) that causes Maillard reactions and reduced AA digestibility and availability. These limits can be minimized by: 1) canola breeding to produce seed low in fibre and ANF; 2) further processing (extrusion, tail-end dehulling, wet fractionation) of CM and enzyme treatments to reduce negative effects of fibre and glucosinolates on nutrient digestibility and growth; 3) controlling conditions during pre-press solvent extraction to avoid AA damage while inactivating ANF.

The CE and CPC contain more remaining fat than CM. However, digestibility of remaining fat may be lower in CE and CPC than in liquid canola oil. Production of CE does not involve desolventizing, resulting in less heat damage and greater AA availability. By excluding conditioning, flaking and cooking, CPC is produced at even lower temperatures that may preserve AA. However, lower temperature during processing may not be sufficient to inactivate myrosinase. Feeding CE or CPC could increase unsaturated fatty acid content in carcass fat causing undesirable soft pork. Thus, inclusion of CE and CPC in diets for finishing pigs may need to be limited. The CE and CPC were usually produced from down-graded canola seed causing greater variation in nutrient profile. Proper quality evaluation is required before formulating these co-products into swine diets. Combined, canola co-products can be successfully included into swine diets to replace SBM while maintaining growth performance and reduce feed cost. Formulating diets based on NE values and SID AA content in feed

ingredients may minimize negative effects of feeding these co-products on growth performance and carcass quality.

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Table 2.1 Proximate nutrient content and energy value of *B. napus* and *B.juncea* canola meal.

	B. napus (1–6, 8–10, 12–32)					*B. juncea* (2, 7, 11, 18, 22, 24, 25, 29, 31, 32)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
Proximate nutrients (g/kg as-is)										
DM	901	1.5	872	940	51	908	0.90	889	923	12
CP	388	4.0	326	494	46	391	1.7	377	426	7
EE	32	0.86	16	51	36	21	0.36	17	26	5
Ash	72	0.68	61	87	21	71	0.38	65	74	5
Energy value (MJ/kg as-is)										
GE	17.8	0.49	16.3	18.6	18	18.8	1.2	17.8	19.9	4
DE	12.5	0.92	10.8	14.4	22	13.6	0.44	13.1	14.3	9
ME	11.5	1.5	9.4	14.0	10	12.5	-	-	-	1
NE	8.4	1.2	6.3	9.9	9	9.3	0.69	7.8	9.8	7

-, no value reported; DM, dry matter; CP, crude protein; EE, ether extract; GE, gross energy; DE, digestible energy; ME, metabolizable energy; NE, net energy; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

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Table 2.2 Carbohydrate content of *B. napus* and *B. juncea* CM (g/kg as-is).

	B. napus (1–6, 8–9, 11–28)					*B. juncea* (2, 7, 10, 15, 19, 21, 22, 26, 27, 28)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
Glucose	6.4	3.0	1.8	8.3	4	2.7	-	-	-	1
Sucrose	60	13	43	79	6	78	14	62	88	3
Maltose	0.40	-	-	-	1	-	-	-	-	-
Starch	7.7	5.9	2.9	15	5	2.7	-	-	-	1
Oligosaccharides	25	0.38	23	28	2	27	7.6	22	32	2
ADF	174	3.0	92	220	37	111	36	58	134	4
NDF	268	5.5	151	365	39	178	25	147	204	6
ADL	72	13	42	86	14	28	9.9	14	35	4
Soluble NSP	15	1.9	14	16	2	19	1.3	18	20	2
Insoluble NSP	157	13	148	166	2	167	10	160	175	2
Total NSP	185	2.1	183	187	3	199	29	180	250	5
Individual sugar, % of total NSP										
Rhamnose	1.1	0.07	1.1	1.2	2	1.1	0.14	1.0	1.2	2
Fructose	1.1	0.14	1.0	1.2	2	1.0	0.28	0.80	1.2	2
Arabinose	24	1.6	22.9	25.2	2	25	1.1	24	26	2
Xylose	9.0	0.07	9.0	9.1	2	8.3	1.1	7.5	9.1	2
Mannose	2.4	0.28	2.2	2.6	2	1.8	0.42	1.5	2.1	2
Galactose	8.6	0.99	7.9	9.3	2	8.1	0.64	7.7	8.6	2
Glucose	29	1.3	27.8	30	2	28	0.64	28	28	2
Uronic acid	25	1.7	24.2	27	2	27	4.7	24	30	2
TDF	286	20	27	32	6	243	11	232	257	5

-, no value reported; ADF, acid detergent fibre; NDF, neutral detergent fibre; ADL, acid-detergent lignin; NSP, non-starch polysaccharides; TDF, total dietary fibre; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Adeola and Kong (2014), (2) Adhikari et al. (2015), (3) Almeida et al. (2014), (4) Berrocoso et al. (2015), (5) González-Vega et al. (2013), (6) González-Vega and Stein (2012), (7) Heo et al. (2014), (8) Kim et al. (2014), (9) Landero et al. (2011), (10) Landero et al. (2013), (11) Little et al. (2015), (12) Liu et al. (2014a), (13) Maison and Stein 2014, (14) Messerschmidt et al. (2013), (15) Montoya and Leterme (2009), (16) Montoya and Leterme (2010), (17) Parr et al. (2015), (18) Rodriguez et al. (2013), (19) Sanjayan et al. (2014), (20) Seneviratne et al. (2011),

(21) Slominski et al. (1994), (22) Slominski et al. (2012), (23) Smit et al. (2014a), (24) Smit et al. (2014b), (25) Thacker and Newkirk (2005), (26) Trindade Neto et al. (2012), (27) Zhou et al. (2013), (28) Zhou et al. (2015).

Table 2.3 Protein and amino acid content in *B. napus* and *B. juncea* CM (g/kg as-is).

	B. napus (1–7, 9–21)					*B. juncea* (8, 16, 18, 21)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
CP	388	39.7	326	494	46	391	1.7	377	426	7
Indispensable AA										
Arginine	22.4	2.51	18.5	28.7	38	25.6	1.86	23.6	28.1	4
Histidine	10.3	1.19	8.6	13.1	38	10.3	1.00	9.6	11.8	4
Isoleucine	14.8	1.58	12.3	18.9	38	15.4	2.59	12.0	18.3	4
Leucine	26.4	2.57	22.4	33.1	38	28.6	2.23	26.4	31.7	4
Lysine	21.0	2.53	17.2	26.7	38	20.6	1.56	19.2	22.8	4
Chemical available lysine	17.0	2.51	13.4	20.9	10	19.1	-	-	-	1
Methionine	7.5	0.77	6.3	9.1	38	7.6	0.77	7.0	8.7	4
Phenylalanine	15.0	1.57	12.9	19.0	38	15.7	1.78	14.0	18.2	4
Threonine	15.8	1.28	13.8	18.5	38	16.9	1.17	16.1	18.6	4
Tryptophan	4.9	0.92	3.6	7.1	36	4.0	0.30	3.7	4.3	3
Valine	19.1	2.00	16.3	24.8	37	19.0	2.57	15.2	20.7	4
Dispensable AA										
Alanine	16.3	1.35	14.1	19.2	38	17.8	1.10	17.1	19.1	3
Aspartic acid	26.5	2.54	23.2	33.5	38	30.3	1.68	29.2	32.2	3
Cysteine	9.0	1.27	7.4	12.1	38	8.1	0.97	7.3	9.2	3
Glutamic acid	62.4	7.12	52.5	76.5	38	67.5	8.89	59.1	76.8	3
Glycine	18.7	1.52	16.7	22.0	38	19.9	1.85	18.5	22.0	3
Proline	22.7	2.56	19.6	28.4	38	22.6	1.83	21.0	24.6	3
Serine	14.5	1.92	11.3	17.5	38	16.7	2.15	14.5	18.8	3
Tyrosine	10.4	0.89	9.2	12.4	30	10.7	1.11	9.5	11.7	3

-, no value reported; CP, crude protein; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Almeida et al. (2014), (2) Berrocoso et al. (2015), (3) González-Vega and Stein (2012), (4) Heo et al. (2014), (5) Kim et al. (2014), (6) King et al., (2001), (7) Landero et al. (2011), (8) Landero et al. (2013), (9) Little et al. (2015), (10) Liu et al. (2014a), (11) Maison et al. (2015), (12) Maison and Stein 2014, (13) Mariscal-Landin et al. (2008), (14) Messerschmidt et al. (2013), (15) Parr et al. (2015), (16) Sanjayan et al. (2014), (17) Smit et al. (2014a), (18) Trindade Neto et al. (2012), (19) Upadhaya amd Kim (2015), (20) Zhou et al. (2013), (21) Zhou et al. (2015).

Table 2.4 Coefficients of standardized ileal digestibility of crude protein and amino acids in *B. napus* and *B. juncea* canola meal for pigs.

	B. napus (1–11)					*B. juncea* (9, 10, 11)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
CP	0.72	0.073	0.60	0.82	18	0.78	0.023	0.76	0.80	3
Indispensable AA										
Arginine	0.82	0.063	0.71	0.94	25	0.89	0.048	0.83	0.92	3
Histidine	0.83	0.052	0.74	0.93	25	0.87	0.046	0.82	0.91	3
Isoleucine	0.77	0.060	0.66	0.86	25	0.80	0.066	0.73	0.86	3
Leucine	0.77	0.049	0.69	0.88	25	0.81	0.062	0.74	0.86	3
Lysine	0.74	0.079	0.59	0.89	25	0.79	0.047	0.75	0.84	3
Methionine	0.79	0.066	0.64	0.88	25	0.86	0.041	0.81	0.89	3
Phenylalanine	0.77	0.055	0.70	0.88	25	0.76	0.874	0.68	0.86	3
Threonine	0.73	0.073	0.59	0.88	25	0.76	0.072	0.70	0.84	3
Tryptophan	0.77	0.083	0.64	0.90	22	0.77	-	-	0.77	1
Valine	0.76	0.068	0.64	0.84	25	0.79	0.054	0.73	0.84	3
Dispensable AA										
Alanine	0.75	0.059	0.64	0.89	25	0.80	0.067	0.74	0.87	3
Aspartic acid	0.72	0.071	0.59	0.89	25	0.78	0.067	0.71	0.85	3
Cysteine	0.73	0.069	0.60	0.84	25	0.88	0.075	0.69	0.84	3
Glutamic acid	0.80	0.068	0.69	0.95	25	0.88	0.049	0.82	0.92	3
Glycine	0.77	0.084	0.61	0.88	25	0.77	0.070	0.71	0.84	3
Proline	0.84	0.153	0.65	1.15	25	0.83	0.061	0.79	0.87	2
Serine	0.75	0.065	0.64	0.91	25	0.81	0.100	0.72	0.91	3
Tyrosine	0.77	0.033	0.73	0.86	19	0.81	0.034	0.78	0.85	3

-, no value reported; CP, crude protein; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Almeida et al. (2014), (2) Berrocoso et al. (2015), (3) González-Vega and Stein (2012), (4) Little et al. (2015), (5) Liu et al. (2014a), (6) Maison and Stein 2014, (7) Messerschmidt et al. (2013), (8) Parr et al. (2015), (9) Sanjayan et al. (2014), (10) Trindade Neto et al. (2012), (11) Zhou et al. (2015).

Table 2.5 Glucosinolate content and profile in *B. napus* and *B. juncea* canola meal (μmol/g as-is).

	B. napus (1–5, 7–16)					*B. juncea* (6, 10, 12, 15, 16)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
Total glucosinolates	7.11	4.21	1.01	16.0	23	12.00	1.93	10.03	15.10	5
Allyl	-	-	-	-	-	0.23	0.09	0.15	0.36	4
2-OH-3-butenyl	2.64	1.05	0.54	4.19	12	0.50	0.26	0.14	0.71	4
4-OH-3-CH3-indolyl	1.28	0.87	0.04	3.19	11	0.19	0.03	0.16	0.24	4
3-butenyl	1.43	0.54	0.22	2.03	12	9.92	0.89	8.96	10.72	4
Phenylethyl	0.53	0.82	0.05	2.13	10	0.15	0.05	0.12	0.22	4
3-CH3-indolyl	0.39	0.42	0.10	1.29	10	0.06	0.01	0.06	0.07	3
2-OH-4-pentenyl	0.14	0.16	0.01	0.42	6	-	-	-	-	-
4-pentenyl	0.21	0.15	0.01	0.47	6	0.39	0.06	0.33	0.48	4
CH3-thiobutenyl	0.06	0.06	0.02	0.13	2	-	-	-	-	-
CH3-thiopentenyl	0.06	-	-	-	2	-	-	-	-	-

-, no value reported; CP, crude protein; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Almeida et al. (2014), (2) Caine et al. (2007), (3) González-Vega and Stein (2012), (4) King et al., (2001), (5) Landero et al. (2011), (6) Landero et al. (2013), (7) Liu et al. (2014a), (8) Messerschmidt et al. (2013), (9) Parr et al. (2015), (10) Sanjayan et al. (2014), (11) Seneviratne et al. (2011b), (12) Smit et al. (2014a), (13) Smit et al. (2014b), (14) Thacker and Newkirk (2005), (15) Zhou et al. (2013), (16) Zhou et al. (2015).

Table 2.6 Proximate nutrient content, fibre content, energy value and glucosinolate profile in *B. napus* canola expeller and canola press-cake

	Canola expeller (1–14)					Canola press-cake (2, 5, 8, 12)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
DM	944	27	899	981	22	909	21	873	936	7
CP	357	31	254	398	23	338	56	258	407	7
EE	102	2.1	79	138	21	179	63	87	275	7
Ash	63	3.8	55	69	18	67	14	45	91	7
ADF	171	19	150	233	17	162	37	114	204	7
NDF	237	33	188	327	19	242	60	153	285	7
ADL	72	7.8	64	84	5	-	-	-	-	-
Soluble NSP	37	-	-	-	1	-	-	-	-	-
Insoluble NSP	141	-	-	-	1	-	-	-	-	-
Total NSP	178	-	-	-	1	-	-	-	-	-
TDF	282	33	258	305	2	-	-	-	-	-
Energy values										
GE	20.1	0.82	18.0	20.9	14	21.6	0.88	21.0	22.2	2
DE	13.5	0.74	12.8	15.1	9	16.2	3.1	11.9	19.9	5
ME	13.1	1.2	12.0	15.4	7	14.5	-	-	-	1
NE	9.5	0.65	9.0	10.2	3	10.9	2.7	7.8	13.9	4

-, no value reported; DM, dry matter; CP, crude protein; EE, ether extract; ADF, acid detergent fibre; NDF, neutral detergent fibre; ADL, acid-detergent lignin; NSP, non-starch polysaccharides; TDF, total dietary fibre; GE, gross energy; DE, digestible energy; ME, metabolizable energy; NE, net energy; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Brand et al. (2001), (2) Grageola et al. (2013), (3) Keith and Bell (1991), (4) Landero et al. (2012), (5) Leming and Lember (2005), (6) Maison and Stein (2014), (7) Mullan et al. (2000), (8) Seneviratne et al. (2010), (9) Seneviratne et al. (2011a), (10) Seneviratne et al. (2011b), (11) Spragg and Mailer (2007), (12) Thacker and Petri (2009), (13) Toghyani et al. (2014), (14) Woyengo et al. (2010), (15) Woyengo et al. (2011).

Table 2.7 Protein and amino acid content in *B. napus* canola expeller and canola press-cake (g/kg as-is).

	Canola expeller (1–8, 10, 11)					Canola press-cake (1, 6, 9)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
CP	357	31	254	398	23	338	56	258	407	7
Indispensable AA										
Arginine	20.2	1.54	17.0	22.4	14	15.9	1.94	13.3	19.1	6
Histidine	9.1	1.33	5.7	11.5	14	6.7	1.86	5.3	10.3	6
Isoleucine	14.4	2.95	12.0	24.1	14	18.3	5.71	10.5	23.9	6
Leucine	23.1	1.95	18.3	26.1	14	17.6	2.39	14.5	21.6	6
Lysine	19.5	1.79	15.5	23.1	20	14.1	2.42	10.9	17.8	6
Chemical available lysine	17.3	1.88	13.5	20.6	12	13.7	-	-	-	1
Methionine	6.4	0.57	5.3	7.4	14	5.0	0.34	4.7	5.4	5
Phenylalanine	13.6	0.72	12.5	14.7	14	12.5	1.35	10.3	14.2	6
Threonine	14.2	1.03	11.8	16.2	14	11.2	1.58	9.0	13.3	6
Tryptophan	4.2	0.34	3.9	4.9	10	3.4	-	-	-	1
Valine	17.9	1.57	15.4	21.5	14	16.0	4.13	9.6	9.5	6
Dispensable AA										
Alanine	14.8	0.92	13.9	16.6	13	13.5	0.52	12.6	13.9	5
Aspartic acid	24.3	1.51	21.4	26.9	13	22.6	3.00	19.7	26.1	5
Cysteine	8.1	0.91	7.0	10.1	13	9.2	1.34	7.0	10.4	5
Glutamic acid	56.8	6.68	47.6	70.6	13	61.1	10.9	50.8	73.6	5
Glycine	17.1	1.05	15.4	18.6	13	17.6	2.07	15.4	19.7	5
Proline	19.9	2.67	13.6	24.5	12	13.6	-	-	-	1
Serine	12.7	2.28	7.5	16.9	13	9.0	2.18	7.0	11.9	5
Tyrosine	9.3	0.61	7.8	10.2	13	7.6	1.03	6.6	9.3	5

-, no value reported; CP, crude protein; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Grageola et al. (2013), (2) Keith and Bell (1991), (3) Landero et al. (2012), (4) Maison and Stein (2014), (5) Mullan et al. (2000), (6) Seneviratne et al. (2010), (7) Seneviratne et al. (2011a), (8) Spragg and Mailer (2007), (9) Thacker and Petri (2009). (10) Woyengo et al. (2010), (11) Woyengo et al. (2011).

Table 2.8 Coefficients of standardized ileal digestibility of crude protein and amino acids in *B. napus* canola expeller and canola press-cake.

	Canola expeller (1–5)					Canola press-cake (1, 4)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
CP	0.79	0.024	0.77	0.83	6	-	-	-	-	-
Indispensable AA										
Arginine	0.88	0.036	0.81	0.92	9	0.87	0.003	0.87	0.88	3
Histidine	0.83	0.013	0.81	0.85	9	0.85	0.007	0.84	0.85	3
Isoleucine	0.78	0.041	0.73	0.85	9	0.84	0.080	0.75	0.91	3
Leucine	0.80	0.051	0.70	0.87	9	0.85	0.057	0.78	0.89	3
Lysine	0.74	0.030	0.71	0.78	9	0.81	0.020	0.79	0.83	3
Methionine	0.85	0.029	0.80	0.89	9	0.86	0.055	0.82	0.92	3
Phenylalanine	0.81	0.059	0.76	0.94	9	0.86	0.074	0.78	0.91	3
Threonine	0.73	0.042	0.66	0.79	9	0.81	0.081	0.72	0.89	3
Tryptophan	0.83	0.017	0.81	0.87	7	0.85	-	-	-	1
Valine	0.74	0.053	0.67	0.84	9	0.83	0.086	0.73	89.1	3
Dispensable AA										3
Alanine	0.78	0.047	0.70	0.85	9	0.85	0.050	0.79	0.88	3
Aspartic acid	0.76	0.045	0.68	0.82	9	0.82	0.065	0.75	0.88	3
Cysteine	0.73	0.036	0.67	0.80	9	0.87	0.038	0.83	0.90	3
Glutamic acid	0.85	0.029	0.81	0.92	9	0.89	0.029	0.86	0.91	3
Glycine	0.74	0.107	0.53	0.86	9	0.81	0.025	0.78	0.83	3
Proline	0.77	0.180	0.47	1.09	7	-	-	-	-	-
Serine	0.75	0.047	0.69	0.85	9	0.78	0.047	0.73	0.81	3
Tyrosine	0.80	0.074	0.74	0.98	9	0.80	0.040	0.76	0.84	3

-, no value reported; CP, crude protein; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Grageola et al. (2013), (2) Maison and Stein (2014), (3) Seneviratne et al. (2010), (4) Seneviratne et al. (2011a), (5) Woyengo et al. (2010).

Table 2.9 Glucosinolate content and profile in *B. napus* canola expeller and canola press-cake (μmol/g as-is).

	Canola expeller (1–8, 10, 11)					Canola press-cake (1, 6, 9)				
	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
Total glucosinolates	10.17	4.58	5.26	22.18	15	6.05	3.40	3.17	12.67	6
Allyl	0.07	0.03	0.05	0.09	2	-	-	-	-	-
2-OH-3-butenyl	4.25	0.89	2.72	5.00	5	1.53	0.60	0.95	2.54	6
4-OH-3-CH3-indolyl	3.23	0.98	2.30	4.40	5	2.96	2.49	1.06	7.67	6
3-butenyl	2.59	0.81	1.50	3.27	5	0.90	0.27	0.47	1.23	6
Phenylethyl	0.15	0.03	0.13	0.20	5	0.14	0.05	0.05	0.20	6
3-CH3-indolyl	0.29	0.06	0.23	0.37	5	0.24	0.07	0.15	0.34	6
2-OH-4-pentenyl	0.08	0.01	0.07	0.08	3	0.04	-	-	-	1
4-pentenyl	0.23	0.05	0.16	0.30	5	0.13	0.06	0.06	0.20	6
CH3-thiobutenyl	0.11	0.06	0.05	0.17	4	0.05	0.01	0.05	0.06	2
CH3-thiopentenyl	0.10	0.06	0.06	0.17	3	-	-	-	-	-

-, no value reported; SD, standard deviation; Min, minimum; Max, maximum; n, number of observations.

References: (1) Grageola et al. (2013), (2) Keith and Bell (1991), (3) Landero et al. (2012), (4) Mullan et al. (2000), (5) Seneviratne et al. (2010), (6) Seneviratne et al. (2011a), (7) Seneviratne et al. (2011b), (8) Spragg and Mailer (2007), (9) Thacker and Petri (2009), (10) Toghyani et al. (2014), (11) Woyengo et al. (2011).

Chapter 3 Effects of feeding high- and low-fibre fractions of air-classified, solvent-extracted canola meal on diet nutrient digestibility and growth performance of weaned pigs

3.1 Abstract

The dietary energy value of solvent-extracted canola meal (CM) is limited by its relative high fibre content. The fibre-rich hull of canola is denser than the oil-free cotyledons, so these seed components partially fractionate in a stream of air. Air classification thus separates CM into a low-fibre, light-particle fraction and a high-fibre, heavy-particle fraction of interest for feeding monogastric and ruminant species, respectively. Crude fibre, acid detergent fibre and neutral detergent fibre in light-particle fraction were reduced by 96, 34 and 28% compared with CM. *Brassica (B) napus, B. juncea*, or their fractions were evaluated feeding 288 weaned pigs (7.1 kg) for 37 d as a 2 × 3 factorial with 12 replicate pens per treatment. Wheat-based diets including 200 g test feedstuff/kg provided 2.5 and 2.4 Mcal net energy (NE)/kg and 5.3 and 4.8 g standardised ileal digestible lysine/Mcal NE and were fed for 9 and 28 d, respectively. Pen feed added, orts, and individual pig body weight were measured weekly to calculate average daily feed intake (ADFI), average daily gain (ADG), and feed efficiency (G:F). Pen faecal samples were collected on d 16 and 17 to calculate diet apparent total tract digestibility coefficients (CATTD) of dry matter (DM), gross energy (GE), crude protein (CP) and digestible energy (DE) value. Pigs fed *B. juncea* had 3 and 2% higher ($P<0.001$) CATTD of DM and GE than pigs fed *B. napus*. Feeding the light-particle fraction increased ($P<0.001$) CATTD of DM, GE, and CP by 4,

3 and 3% compared with CM, respectively. For the entire trial, pigs fed *B. juncea* consumed 33 g/d less ($P<0.001$) feed, had 0.02 g:g higher ($P<0.05$) G:F, but ADG was not different ($P>0.05$) compared to pigs fed *B. napus*. Feeding pigs the light-particle fractions did not affect ADFI ($P>0.05$), increased ($P<0.05$) G:F 0.02 g:g and tended to increase ($P=0.07$) ADG by 18 g/d compared to CM. In conclusion, air classification of canola meal increased diet nutrient digestibility, but only modestly increased G:F of weaned pigs due to dietary fibre reduction.

3.2 Introduction

Solvent-extracted canola meal (CM) is the major co-product from canola seed crushing for human oil production. Canola meal is only second to soybean meal as the most commonly fed protein feedstuff in animal diets around the world (Newkirk, 2009). Due to record canola seed production in Canada (15.7 Mt; Beckman, 2012), the supply of CM for animal feeding continues increasing, yet remains cost-competitive with other co-products such as distillers dried grains with solubles.

Some constrains of feeding CM to monogastric species exist. Apart from lipid depletion during oil extraction, the relatively high fibre content of CM [117 g crude fibre (CF)/kg] places a penalty on its dietary energy yield and limits its inclusion in pig diets (Fan et al., 1996). Dietary fibre may have functional properties (Buttriss and Stocks, 2008), but cannot be digested by the endogenous enzymes of pigs. Fibre in CM also constrains digestion of other nutrients such as protein and minerals (Fan et al., 1996; Grieshop et al., 2001). The relatively high fibre content in

CM therefore dilutes the energy density of diets and compromises pig growth, especially for young pigs with limited appetite. The current recommended maximum inclusion level of CM in starter diets is only 50 g/kg (Newkirk, 2009). Reducing the fibre content of CM by breeding or processing could increase its dietary energy value and lead to greater inclusion levels in feed (Hickling, 2007).

Yellow-seeded *Brassica (B.) juncea* is a novel canola species targeted to grow in regions where thermotolerance, disease resistance, and adaptation to dry agronomic conditions are required. *B. juncea* has a thinner seed coat and thus less hull fibre than conventional dark-seeded *B. napus* CM [190 vs. 260 g neutral detergent fibre (NDF)/kg], but also slightly less lysine (20 vs. 22 g/kg), and greater glucosinolate content (11 vs. 5 μmol/g; Beltranena and Zijlstra, 2011). To support its cultivation and potentially greater inclusion in swine diets, *B. juncea* CM requires feed quality evaluation.

Air classification is a continuous dry fractionation technique that shifts the fibre content in oilseed meals using a stream of air (Seth and Clandinin, 1973). Air classification of CM yields a low-fibre, light-particle fraction and a high-fibre, heavy-particle fraction from the parent CM. The low-fibre fraction may have better feeding value for monogastric animals while the high-fibre fraction could be intended for feeding ruminants. Research focused on the effects of feeding air-classified CM fractions to weaned piglets has not been published to our knowledge.

The present study tested the hypothesis that nutrient digestibility and growth performance would not differ among weaned pigs fed diets containing air-classified low- or high-fibre *B.*

napus or *B. juncea* CM fractions or the parent stock meals. The objectives of the study were therefore to determine the apparent total tract digestibility coefficients (CATTD) of gross energy (GE), crude protein (CP), dry matter (DM) and digestible energy (DE) value of diets including *B. napus* and *B. juncea* and to compare the growth performance of weaned pigs fed air-classified fractions or parent CM.

3.3 Materials and methods

3.3.1 Test articles, grinding and air classification

B. napus and *B. juncea* were grown in southern Saskatchewan and Manitoba during the 2010 growing season. The seed oil was pressed and the expellers solvent extracted as per typical commercial procedures at Bunge, Altona, MB, Canada that fall. The parent meals were further processed at Agri-Food Discovery Place, University of Alberta (Edmonton, AB, Canada) to produce the fractions (Table 3.1). Particle size was reduced using a model 15 Mikro-ACM mill (Hosokawa Micron Powder, Summit, NJ, USA) equipped with a rotor fitted with 4 J-shape hammers and a separator wheel of the short type. Process air flow was 600 cfm, feed rate 1.5 kg/min, rotor speed 7000 rpm, and separator speed 3700 rpm. Air classification was subsequently conducted using a model 20 Alpine Turboplex ATP classifier (Hosokawa Micron Powder). Process air flow was 600 cfm, secondary air flow 200 cfm, feed rate 1.5 kg/min, separator speed 3700 rpm. Particle size of parent CM and fractions was determined in triplicates

using a sieve shaker (model RX-30; W.S. Tyler, Mentor, OH, USA) and a laser diffraction analyser (model LS 13 320; Beckman Coulter Inc., Mississauga, ON, Canada), respectively.

3.3.2 Animals and diets

The animal procedures were reviewed by the University of Alberta Animal Care and Use Committee for Livestock, and followed principles established by the Canadian Council on Animal Care (CCAC, 2009). The study was conducted at Swine Research and Technology Centre, University of Alberta.

In total, 288 pigs (Duroc × Large White/Landrace F_1; Hypor, Regina, SK, Canada) were weaned at 19 ± 1 days of age, were selected based on daily weight gain during the first 5 d post weaning and body weight (BW; 7.1 ± 1.1 kg). Pigs were divided within gender into heavy and light BW. One heavy and one light barrow and gilt were randomly placed in one of 72 pens, 4 pigs per pen.

After weaning, pigs were fed a common commercial phase 1 diet for 5 days. Six pelleted wheat-based diets including 200 g/kg of either *B. napus* or *B. juncea* parent CM, air-classified light- or heavy-particle fractions were formulated to provide 2.5 and 2.4 Mcal net energy (NE)/kg and 5.3 and 4.8 g standardised ileal digestible (SID) lysine/Mcal NE and were fed for 9 (phase 2; Table 3.2) and 28 d (phase 3; Table 3.3), respectively. Other amino acids were formulated as an ideal ratio to lysine (NRC, 1998) using calculated NE values from EvaPig (Noblet et al., 2011) and SID amino acids (AA) coefficients from Buchet et al. (2011). Premixes were added to exceed vitamin and mineral requirements for weaned pigs (NRC, 1998). Phase 3

diets included 80 g acid-insoluble ash (Celite 281; World Minerals, Santa Barbara, CA, USA)/kg as indigestible marker.

3.3.3 Experimental design and measurements

The study was conducted as a randomised complete block design with 72 pens in 4 nursery rooms filled 2 weeks apart. Pens of pigs within block representing areas within room were randomly allocated to be fed one of 6 diet regimens during the 37-day study for a total of 12 replicate pens per treatment. Pens (1.1 m × 1.5 m) were equipped with a 4-space dry feeder (model N4-424; Crystal Spring, MB, Canada), a nipple drinker, polyvinyl chloride partitions, and plastic deck flooring. The rooms ventilated using negative pressure, were maintained within the thermo-neutral zone for the pigs, and provided a 12-h light (0600-1800 h), 12-h dark cycle. Pigs had continuous access to feed and water.

To calculate average daily weight gain (ADG), average daily feed intake (ADFI), and feed efficiency (G:F), individual pigs were weighted, pen feed added and orts were weighed weekly. To calculate CATTD of DM, GE, CP, and DE value, freshly voided faeces were collected from 0800 to 1600 h by grab sampling from pen floors on d 16 and 17. Faeces were pooled by pen and frozen at –20°C for storage. Faeces were thawed after, homogenised, sub-sampled and oven-dried at 55ºC.

3.3.4 Chemical analyses

Test ingredients, diets and lyophilized faeces were ground through a 1-mm screen in a centrifugal mill (model ZM200; Retsch GmbH, Haan, Germany). The parent CM and air-

classified light- and heavy-particle fractions of each were analysed for GE using an adiabatic bomb calorimeter (model 5003; Ika-Werke GMBH & Co. KG, Staufen, Germany), DM (method 930.15), CP (method 984.13A-D), ether extract (EE), CF, ash (method 942.05), acid detergent fibre (ADF) inclusive of residual ash (method 973.18), NDF (Holst, 1973), calcium (method 968.08), phosphorus (method 946.06), AA (method 982.30E), available lysine (method 975.44) as per AOAC (2006). Glucosinolate profiles of parent CM and air-classified fractions were determined by gas chromatography (Daun and McGregor, 1981) at POS Bio-Sciences, Saskatoon, SK, Canada. Diets were analysed for DM, GE, CP, EE, ash, CF, ADF, NDF, AA, available lysine and acid-insoluble ash (McCarthy et al., 1974). Faeces were analysed for DM, CP, acid-insoluble ash content and GE. Based on results of chemical analyses, CATTD of DM, GE, and CP were calculated from acid-insoluble ash concentration of faeces relative to feed using the indicator method (Adeola, 2001). Diet DE values were calculated by multiplying diet GE by CATTD.

3.3.5 Statistical analyses

Digestibility and growth performance data were analysed as a 2 × 3 factorial arrangement using the MIXED procedure of SAS (version 9.1, SAS Inst. Inc., Cary, NC, USA). Pen was considered the experimental unit. Models included the fixed effects of canola species, parent stock or air-classified fractions, and the two-way interactions; block was the random term. Growth performance data were also analysed as repeated measures with week as the repeated

term. Initial BW was tested as a covariate and excluded unless significant. To test the hypothesis, $P<0.05$ was considered significant; $P<0.1$ was considered a trend.

3.4 Results

Particle size of *B. napus* and *B. juncea* CM was 636 ± 2.14 and 640 ± 2.29 µm, respectively. Upon air classification, yield of light- and heavy-particle fractions was 46 and 54% for *B. napus*, and 47 and 53% for *B. juncea*, respectively. Particle size for light- and heavy-particle fractions were 21.60 ± 22.18 and 71.01 ± 40.16 µm for *B. napus*, 16.12 ± 17.29 and 81.14 ± 65.31 µm for *B. juncea*, respectively. *B. juncea* had 30, 36 and 25% reduced CF, ADF and NDF content compared with *B. napus* CM, respectively (Table 3.1). Compared with parent CM, content of crude fibre, ADF and NDF in light-particle fractions was reduced by 97, 35 and 24% in *B. napus* and 95, 33 and 33% in *B. juncea*, respectively. Compared with parent CM, content of CF in heavy-particle fractions was reduced by 10% in *B. napus*, but increased by 23% in *B. juncea*; ADF and NDF were increased 28 and 16% in both heavy-particle fractions. Crude fat content in light-particle fractions increased by 81% and decreased by 6% in heavy-particle fractions compared with parent CM. Protein content was only enriched by 7% in light-particle fractions and decreased by 5% in heavy-particle fractions compared with parent CM. Glucosinolates in *B. juncea* were about 2 fold higher than in *B. napus* CM. Air classification did not enrich glucosinolate content in either light- or heavy-particle fractions.

No interactions between canola species and parent CM or air-classified fractions for digestibility and performance variables were observed (P>0.05). Feeding diets including *B. juncea* resulted in 3 and 2% greater (P<0.001) CATTD of DM and GE than *B. napus* (Table 3.4). Feeding diets including the light particle fractions increased (P<0.001) CATTD of DM, GE, and CP by 4, 3 and 3% compared with feeding parent CM, respectively. Pigs fed diets including heavy-particle fractions had greater (P<0.001) CATTD of DM than those fed parent CM.

Final BW on trial d 37 between pigs fed *B. napus* or *B. juncea* (25.2, 25.3 kg, respectively; SEM 0.19) or among those fed parent CM, light- or heavy-particle fractions (25.1, 25.7, 25.0 kg, respectively; SEM 0.21) was not different (P>0.05). Feeding *B. juncea* lowered ADFI compared with *B. napus* for the entire trial (P<0.001), d 23-30 (P<0.05) and d 30-37 (P<0.05) by 33, 61 and 57 g/d, respectively (Table 3.5). The ADG did not differ (P>0.05) between pigs fed *B. juncea* and *B. napus* overall or for each weekly period, except for d 23-30 in which feeding *B. napus* resulted in 41 g/d higher (P<0.05) ADG than feeding *B. juncea*. For the entire trial and d 16-23, G:F was 0.02 and 0.04 g:g higher (P<0.05) for pigs fed *B. juncea* than *B. napus*, respectively. Feeding parent CM or fractions did not affect (P>0.05) ADFI of pigs for any trial period or overall. Feeding light-particle fractions tended to increase (P=0.07) overall ADG by 18 g/d compared with feeding parent CM or heavy-particle fractions. However, pigs fed light-particle fractions had 0.02 g:g higher (P<0.05) overall G:F by than those fed parent CM or heavy-particle fractions.

3.5 Discussion

3.5.1 Air classification of canola meal

Air classification effectively separated CM into 2 fractions with different physical properties and nutrient content, consistent with previous research (Andersson et al., 2000). Canola seeds are made up of fibrous hulls and cotyledons containing oil and protein (Thakor et al., 1995). During oil-extraction, seeds are crushed, expeller-pressed and solvent-extracted to yield oil and CM with hull and oil-free cotyledons (Newkirk, 2009). Grinding CM partially breaks adherence between these seed components. The rigid hull is resistant to grinding and stays in larger particles (Wolf et al., 2002), while cotyledons are more easily shattered into smaller particles (Clark et al., 2001). Canola hull particles have greater density than cotyledons. During air classification, the air flow lifts lighter particles up while heavier particles fall (Fedec, 2003), thereby partially separating hull from cotyledons and concentrating fibre into the heavy-particle fraction. Air classification of solvent-extracted oilseed meals thus serves as processing back-end or tail-end dehulling.

Compared with parent CM, reduction of CF and ADF in light-particle fractions was greater than reduction of NDF. The same effect was noted by Mustafa et al. (1996) sieving to dehull CM that reduced ADF and NDF by 25 and 8% in the low-fibre fraction, respectively. Bell and Shires (1982) reported 43, 33 and 19% reduction of CF, ADF and NDF, respectively, conducting front-end dehulling of rapeseed. Similarly, Kracht et al. (2004) obtained 39, 35 and 28% lower CF, ADF and NDF, respectively, in dehulled vs. parent seed. Canola meal includes hull fibre rich in cellulose and lignin and cell wall fibre from cotyledons rich in hemicellulose and pectin (Mustafa

et al., 1996; Bell, 1984). Because air classification segregates hull fibre from the parent meal into the heavy-particle fraction while shifting the cell wall fibre into the light-particle fraction (Elkowicz and Sosulski, 1982), higher reduction of CF and ADF compared with NDF was achieved in light-particle fraction due to inclusion of hemicellulose in NDF. It must be emphasized that air classification is not an absolute fractionation process. Lighter hull particles may also be shifted into the light-particle fraction.

In the present study, indispensable and dispensable amino acids and available lysine content were increased in light-particle fractions compared with parent CM. However, air classification only slightly enriched CP in the light-particle fraction (7%). Mustafa et al. (1996) indicated that tail-end dehulling of CM was more effective in reducing fibre than increasing protein content in the fine fraction, similar to sieving to dehull CM (de Lange et al., 1998; Clark et al. 2001). The limited enrichment of CP can be attributed to the low starch content of CM (Elkowicz and Sosulski, 1982). Also, due to the incomplete dehulling by air classification, some hull fibre remained in light-particle fractions while some cotyledon protein bodies adhere tightly to hull and stay in the coarse fraction (Mustafa et al., 1996). Compared to dry fractionation, wet fractionation using aqueous washing and extraction greatly enriches CP and reduces anti-nutritional factors producing canola protein concentrate and isolate ranging from 540 to 910 g CP/kg (Mwachireya et al., 1999; Thacker and Petri, 2009; Thiessen et al., 2004). However, dry fractionation has the advantage over wet fractionation in that it is a continuous rather than a

batching process devoid of costly spray-drying (Beltranena and Zijlstra, 2011). Fractionation cost can be a determining factor limiting dietary inclusion in least-cost formulated nursery feeds.

Particle size influences the efficiency of air classification. Cell components are more efficiently separated when particle size is sufficiently small (King and Dirtz, 1987). Intensive milling is needed for air classification to yield protein-rich fractions (Sosulski and Zadernowski, 1981). King and Dietz (1987) used wet milling and achieved 70 and 75% of meal particles smaller than 15 μm, which is finer than obtained for the present study. Subsequent air classification enriched CP by 26% and reduced ADF and NDF by 49 and 46%, respectively, in light-particle fractions with particle size 3.5 to 7.5 μm. In comparison, de Lange et al. (1998) sieved coarser CM grounded through a 35 mesh (514 μm) screen and obtained only minor reduction of fibre and enrichment of protein content. Although fine grinding increases the efficiency of air classification and the yield of light-particle fraction, it also increases processing time and power requirements.

A challenge in dehulling CM is the tight adherence of hull and cotyledons, the binding of which is further strengthen by expeller pressing (McCurrdy and March, 1992). Hydrothermal treatment before dehulling loosens this binding and increases the efficiency of dehulling. Proper moisture and heating conditions may make cotyledons more susceptible to shattering resulting in easier hull separation (Thakor et al., 1995; Clark et al., 2001). Tempering defatted canola meal to 16% moisture before milling increased the efficiency of tail-end dehulling by “toughening” the canola hull and increasing its resistance to grinding (McCurdy and March, 1992). Fewer hull

particles would shift into the fine fraction and higher protein enrichment could be expected. Compared with our results, the preceding study achieved greater dehulling efficiency evident by 14% CP enrichment, 49.3 and 46.4% ADF and NDF reduction, respectively, in fine fraction. The same study also showed that dehulling non-toasted meal had lower fractionation efficiency than dehulling toasted meal. Although loosed adjunction between hull and cotyledons would make separation of seed components easier, prolonged heating can cause amino acid damage, and increase fractionation costs of products intended for animal feeding.

3.5.2 Glucosinolates

Glucosinolates are the major anti-nutritional factor in CM. By affecting liver function and inhibiting thyroid hormone production, hydrolysed glucosinolates reduce animal growth and health (Newkirk, 2009). Their bitter taste may reduce feed intake (Bourdon and Aumaitre, 1990). Glucosinolates are mostly concentrated in cotyledons instead of the hull. Minkowski (2002) manually dehulled rapeseed that contained 19 μmol/g and reported 6 and 21 μmol/g total glucosinolates in rapeseed hull and cotyledons, respectively. Matthaus (1998) found 9, 10 and 3 μmol/g glucosinolates in rapeseed, manually-dehulled cotyledons and hulls, respectively. Therefore, we assumed that air classification of CM would enrich glucosinolates in the light-particle fraction and reduce them in the heavy-particle fraction; however, we did not observe such a change. Similar results were reported by Clark et al. (2001), McCurdy and March (1992) who sieved CM to reduce fibre content. The lack of shifting of glucosinolates content can be attributed partly to the mixture of seed components in different fractions. Regardless of

processing, canola breeding programs have continued to reduce glucosinolates meal content over the last 30 years (Newkirk, 2009).

3.5.3 Nutrient digestibility

Feeding *B. juncea* instead of *B. napus* increased CATTD of DM and GE. This difference can be explained by the thinner seed coat of *B. juncea* reducing fibre in CM (Montoya and Leterme, 2009). In the present study, feeding light-particle fractions increased CATTD of DM, GE and CP compared with feeding parent CM and heavy fractions. The increased nutrient digestibility is similar to previous studies dehulling canola or rapeseed (Bourdon and Aumaitre, 1990; de Lange et al., 1998; Kracht et al., 2004). Fibre resists digestion in pigs and reduces digestibility of associated protein and minerals (Bell, 1984). Therefore, the reduced fibre content explains the increased digestibility and greater digestible nutrient density in diets including light-particle fractions. Compared with Landero et al. (2011, 2012), who fed 20 and 24% solvent-extracted *B. napus* and *B. juncea* CM to weaned pigs, respectively, CATTD of DM and GE of light-particle fractions in our study exceeded previous values indicating that air classification can increase the nutritional value of diets with lower digestibility. In our trial, feeding high-fibre fractions resulted in similar CATTD of GE and CP as parent CM. The CATTD of DM in pigs fed heavy-particle fractions was even higher than pigs fed parent CM, which can be explained by the reduced particle size of heavy-particle fractions that offset the negative effects of higher fibre on digestibility.

3.4.4 Growth performance

Although feeding light-particle fractions increased CATTD of nutrients, air classification had little effect on growth performance of weaned pigs. Pigs fed parent CM had similar ADFI, ADG and G:F compared with Landero et al. (2011, 2012) feeding 20 and 24% *B. napus* and *B. juncea* CM to weaned pigs, respectively. The ADFI did not differ between pigs fed the two air-classified fractions in the present study, which could be explained by similar glucosinolate level between fractions. The greater G:F for pigs fed light-particle fractions might be due to lower fibre and thus greater digestible nutrient content in light-particle fractions. Similar results were reported by McCurrdy and March (1992), Clark et al. (2001), and Zeb et al. (2002) for poultry and fish indicating that feeding dehulled canola meal had lesser effect on growth performance than digestibility. In the present study, SID amino acids and major energy yielding ingredients were equalized among diets. Thus, differences in energy value among diets should be attributed to the energy value of parent CM and fractions. Yet, the DE value of diets containing low-fibre fractions did not increase. Advantages of feeding low-fibre fractions might be greater if comparisons were made at higher dietary inclusions. Although small increases of pig growth performance limit the economic advantage of feeding low-fibre CM fraction (Shires et al., 1983), the higher nutrient density of dehulled fraction may reduce supplemental fat inclusion in diets to increase dietary energy, which would lower feed cost (Clark et al., 2001).

3.5 Conclusion

Air classification is a continuous dry fractionation process capable of reducing the dietary fibre content of canola meal. Compared to *B. napus* and *B. juncea* parent meals, feeding low-fibre fractions to weaned piglets increased CATTD of DM, GE and CP of diets, but had little effect on growth performance. Additional studies with young animals are needed to validate air classification as tail-end processing step to increase the feeding value of solvent-extracted CM.

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Table 3.1 Analysed nutrient (g/kg as-is) and glucosinolate content of *Brassica (B) napus* and *B. juncea* solvent-extracted canola meals[a] and their light- and heavy-particle fractions produced by air classification[b].

	B. napus			*B. juncea*		
	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Moisture	105.5	77.3	83.2	110.7	77.9	85.5
Crude protein	392.1	419.2	373.3	383.9	409.9	372.0
Crude fat	22.0	41.0	20.7	18.1	31.8	17.1
Crude fibre	97.2	2.6	87.3	68.1	3.7	83.5
Acid detergent fibre	201.2	131.3	255.8	128.8	85.8	165.2
Neutral detergent fibre	272.2	206.0	315.2	203.6	136.4	234.8
Ash	75.7	77.1	76.0	72.8	71.7	75.6
Calcium	6.0	5.4	6.6	6.4	5.6	7.3
Phosphorus	11.2	11.8	10.1	11.6	12.3	10.9
Indispensable amino acid						
Arginine	20.8	25.2	21.9	24.0	26.5	22.5
Histidine	9.2	11.2	9.8	9.8	10.8	9.1
Isoleucine	14.4	17.4	15.4	15.7	17.9	14.8
Leucine	24.7	29.8	26.1	27.1	29.9	25.3
Lysine	19.5	23.6	20.5	19.3	21.1	18.1
Available lysine	18.1	22.2	19.4	18.3	19.2	16.7
Methionine	7.0	8.4	7.4	7.1	7.7	6.5
Phenylalanine	13.8	16.8	14.6	14.9	16.4	14.0
Threonine	14.3	17.2	15.4	15.4	16.8	14.6
Tryptophan	5.1	5.6	4.8	4.2	5.1	3.8
Valine	18.2	22.0	19.3	19.1	21.2	18.0
Dispensable amino acid						
Alanine	15.2	18.3	16.1	16.6	18.2	15.5
Aspartic acid	24.3	29.0	26.0	28.0	30.5	26.3
Cysteine	8.2	9.7	8.7	7.6	8.1	7.1
Glutamic acid	57.8	68.9	60.7	59.3	65.4	55.8
Glycine	17.5	21.2	18.5	18.8	20.7	17.7
Proline	20.0	24.7	21.8	19.6	21.6	18.9
Serine	12.6	15.0	13.5	13.1	14.1	12.7
Tyrosine	9.4	11.9	9.7	10.5	11.0	10.1
Total amino acids	318.3	383.2	336.6	334.8	367.6	316.7
Glucosinolates, µmol/g						

	B. napus			*B. juncea*		
	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Allyl	-	-	-	0.36	0.17	0.15
3-butenyl	1.92	1.71	1.35	10.72	8.77	8.01
4-pentenyl	0.18	0.12	0.13	0.48	0.34	0.3
2-OH-3-butenyl	4.19	2.81	2.4	0.49	0.72	0.66
2-OH-4-pentenyl	0.1	0.06	0.05	-	-	
CH3-thiobutenyl	0.13	0.09	0.07	-	-	-
Phenylethyl	0.12	0.13	0.12	0.22	0.11	0.11
CH3-thiopentenyl	0.06	-	-	-	-	-
3-CH3-indolyl	0.27	0.2	0.19		0.05	0.05
4-OH-3-CH3-indolyl	1.12	0.98	0.81	0.24	0.1	0.17
Total aliphatics	6.39	4.71	3.92	11.69	9.83	8.97
Density, g/1000 mL ± SD[c]	532 ± 16	381 ± 15	595 ± 21	555 ± 31	405 ± 49	625 ± 14

[a] Processed at Bunge, Altona, MB, Canada.

[b] Ground (Model 15 Mikro-ACM) prior to air classification (Model 200 Alpine ATP).

[c] Standard deviation based on 5 replicates.

Table 3.2 Ingredient composition and analysed nutrient content (g/kg as fed) of phase 2 nursery diets containing 200 g/kg solvent-extracted *Brassica (B) napus* or *B. juncea* canola meal or their air-classified light- or heavy-particle fractions fed to weaned pigs from d 0 to 9 of the trial.

	B. napus			*B. juncea*		
	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Ingredient composition						
Wheat, ground	458.5	459.5	459.2	458.1	458.0	458.7
B. napus parent meal	200.0	-	-	-	-	-
B. napus light-particle fraction	-	200.0	-	-	-	-
B. napus heavy-particle fraction	-	-	200.0	-	-	-
B. juncea parent meal	-	-	-	200.0	-	-
B. juncea light-particle fraction	-	-	-	-	200.0	-
B. juncea heavy-particle fraction	-	-	-	-	-	200.0
Lactose	100.0	100.0	100.0	100.0	100.0	100.0
Soybean meal, 460 g CP/kg	50.0	50.0	50.0	50.0	50.0	50.0
Pea protein isolate, 780 g CP/kg	25.0	25.0	25.0	25.0	25.0	25.0
Soy protein concentrate, 560 g CP/kg	25.0	25.0	25.0	25.0	25.0	25.0
Herring fish meal, 700 g CP/kg	25.0	25.0	25.0	25.0	25.0	25.0
Canola oil	70.0	70.0	70.0	70.0	70.0	70.0
Limestone	10.0	10.0	10.0	10.0	10.0	9.0
Mono-di-calcium phosphate	10.0	10.0	10.0	10.0	10.0	10.0
L-Lysine HCl	5.4	5.0	5.1	5.5	5.7	5.7
Vitamin premix[a]	5.0	5.0	5.0	5.0	5.0	5.0
Mineral premix[b]	5.0	5.0	5.0	5.0	5.0	5.0
Salt	5.0	5.0	5.0	5.0	5.0	5.0
L-Threonine	2.3	2.0	2.1	2.2	2.2	2.3
Choline chloride 600 g/kg	2.0	2.0	2.0	2.0	2.0	2.0
DL-Methionine	1.5	1.2	1.3	1.7	1.7	1.8
L-Tryptophan	0.3	0.3	0.3	0.5	0.4	0.5
Analysed nutrients						
Moisture	99.5	85.6	89.2	89.6	84.9	93.5
Crude protein	244.4	246.5	235.5	241.8	244.6	239.4
Ether extract	88.0	97.7	94.5	92.7	92.8	90.1
Ash	60.3	59.1	59.8	59.8	58.8	57.9
Crude fibre	35.1	12.0	31.6	23.0	11.4	19.0
Acid detergent fibre	63.2	46.6	73.6	48.9	38.6	54.6
Neutral detergent fibre	117.4	83.3	122.4	98.8	82.0	108.5

[a] Supplied per kilogram of diet: 3,750 IU of vitamin A, 750 IU of vitamin D, 50 IU of vitamin E, 37.5 mg of niacin, 15 mg of pantothenic acid, 2.5 mg of folacin, 5 mg of riboflavin, 1.5 mg of pyridoxine, 2.5 mg of thiamine, 2000 mg of choline , 4 mg of vitamin K, 0.25 mg of biotin and 0.02 mg of vitamin B12.

[b] Supplied per kilogram of diet: 125 mg of Zn, 50 mg of Cu, 75 mg of Fe, 25 mg of Mn, 0.5 mg of I and 0.3 mg of Se.

Table 3.3 Ingredient composition and analysed nutrient content (g/kg diet as fed) of Phase 3 nursery diets containing 200 g/kg solvent-extracted *Brassica (B) napus* or *B. juncea* canola meal or their air-classified light- or heavy-particle fractions fed to weaned pigs from d 9 to 37 on trial.

	B. napus			*B. juncea*		
	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Ingredient composition						
Wheat, ground	578.7	579.0	579.1	578.7	579.1	578.3
B. napus						
Parent meal	200.0	-	-	-	-	-
Light-particle fraction	-	200.0	-	-	-	-
Heavy-particle fraction	-	-	200.0	-	-	-
B. juncea						
Parent meal	-	-	-	200.0	-	-
Light-particle fraction	-	-	-	-	200.0	-
Heavy-particle fraction	-	-	-	-	-	200.0
Soybean meal, 460 g CP/kg	125.0	125.0	125.0	125.0	125.0	125.0
Limestone	10.0	11.0	10.0	10.0	10.0	10.0
Mono-di-calcium phosphate	7.5	7.2	7.7	7.5	7.0	7.5
Salt	5.0	5.0	5.0	5.0	5.0	5.0
Canola oil	50.0	50.0	50.0	50.0	50.0	50.0
L-Lysine HCl	4.6	4.1	4.3	4.7	4.8	4.9
Vitamin premix[a]	4.0	4.0	4.0	4.0	4.0	4.0
Mineral premix[b]	4.0	4.0	4.0	4.0	4.0	4.0
L-Threonine	1.3	1.0	1.1	1.2	1.2	1.3
Choline chloride 600 g/kg	1.0	1.0	1.0	1.0	1.0	1.0
DL-Methionine	0.9	0.7	0.8	0.9	0.9	1.0
Celite 281[c]	8.0	8.0	8.0	8.0	8.0	8.0
Analysed nutrients						
Moisture	102.8	105.1	104.0	98.7	94.1	94.8
Crude protein	235.6	241.4	235.7	234.9	239.3	238.8
Ether extract	71.4	70.7	74.2	74.2	74.3	72.6
Ash	67.3	71.6	64.6	66.5	69.9	65.5
Crude fibre	36.0	16.8	36.3	29.5	17.3	23.2
Acid detergent fibre	74.8	59.2	83.5	58.6	47.9	66.3
Neutral detergent fibre	131.0	114.0	143.3	117.0	104.9	123.8
Gross energy (MJ/kg)	17.6	17.5	17.5	17.9	17.5	17.5

[a] Supplied per kilogram of diet: 3,750 IU of vitamin A, 750 IU of vitamin D, 50 IU of vitamin E, 37.5 mg of niacin, 15 mg of pantothenic acid, 2.5 mg of folacin, 5 mg of riboflavin, 1.5 mg of pyridoxine, 2.5 mg of thiamine, 2000 mg of choline, 4 mg of vitamin K, 0.25 mg of biotin and 0.02 mg of vitamin B12.

[b] Supplied per kilogram of diet: 125 mg of Zn, 50 mg of Cu, 75 mg of Fe, 25 mg of Mn, 0.5 mg of I and 0.3 mg of Se.

[c] World Minerals Inc., Santa Barbara, CA, USA.

Table 3.4 Apparent total tract digestibility[a] (CATTD) of dry matter, gross energy, crude protein, and digestible energy (DE) values of nursery diets including 200 g/kg of solvent-extracted *Brassica (B) napus* or *B. juncea* canola meal or their air-classified light- or heavy-particle fractions fed to weaned pigs, 3 weeks post-weaning.

	Species			Fractions				P-value		
	B. napus	*B. juncea*	SEM	Parent	Light	Heavy	SEM	Species	Fraction	Species × fraction
CATTD										
Dry matter	0.794	0.817	0.001	0.793[c]	0.824[a]	0.800[b]	0.002	<0.001	<0.001	0.110
Gross energy	0.820	0.835	0.001	0.818[b]	0.844[a]	0.820[b]	0.002	<0.001	<0.001	0.385
Crude protein	0.775	0.780	0.003	0.767[b]	0.790[a]	0.774[b]	0.003	0.112	<0.001	0.110
DE, MJ/kg	14.55	14.52	0.060	14.58	14.57	14.46	0.070	0.725	0.436	0.802

[a] Least-squares means based on 12 pen observations of 4 pigs each per treatment.

Table 3.5 Effects of feeding nursery diets incluing 200 g/kg solvent-extracted *Brassica(B) napus* or *B. juncea* canola meal or their air-classified light- or heavy-particle fractions on average daily feed disappearance (ADFI), daily weight gain (ADG), and gain:feed (G:F) of weaned pigs[a].

	Species			Fractions				P value		
	B. napus	*B. juncea*	SEM	Parent	Light	Heavy	SEM	Species	Fraction	Species × fractions
ADFI, g/d										
Day 0–9	216.3	208.6	3.4	207.2	217.7	212.5	4.2	0.118	0.207	0.167
Day 9–16	519.7	516.0	9.3	510.1	525.6	517.9	11.3	0.783	0.631	0.136
Day 16–23	779.6	745.5	12.6	745.1	767.4	775.1	15.3	0.061	0.362	0.264
Day 23–30	1027.2	966.1	14.3	1005.0	991.5	993.5	17.5	0.004	0.842	0.440
Day 30–37	1235.2	1178.2	16.8	1214.0	1201.6	1204.5	20.5	0.020	0.905	0.844
Day 0–37	755.6	722.9	5.6	736.3	740.8	740.7	6.8	<0.001	0.866	0.082
ADG, g/d										
Day 0-9	185.2	181.4	4.0	178.0	191.5	180.3	4.9	0.508	0.122	0.648
Day 9-16	381.5	388.8	9.5	373.9	391.2	390.4	11.6	0.591	0.495	0.121
Day 16-23	561.9	563.3	11.2	545.4	581.8	560.6	13.7	0.933	0.182	0.291
Day 23-30	688.5	646.8	11.0	679.8	673.3	649.9	13.4	0.010	0.261	0.288
Day 30-37	752.0	736.8	15.1	730.2	757.2	745.8	18.1	0.456	0.554	0.968
Day 0-37	513.8	503.4	4.7	501.3	519.2	505.4	5.7	0.121	0.070	0.147
G:F										
Day 0-9	0.853	0.869	0.012	0.859	0.879	0.845	0.014	0.360	0.240	0.617
Day 9-16	0.733	0.753	0.012	0.731	0.745	0.754	0.015	0.244	0.539	0.114
Day 16-23	0.721	0.757	0.010	0.732	0.759	0.726	0.012	0.015	0.140	0.648
Day 23-30	0.671	0.670	0.008	0.678	0.681	0.653	0.010	0.910	0.098	0.549
Day 30-37	0.611	0.627	0.012	0.604	0.633	0.621	0.015	0.369	0.392	0.780

	Species			Fractions				P value		
	B. napus	*B. juncea*	SEM	Parent	Light	Heavy	SEM	Species	Fraction	Species × fractions
Day 0-37	0.718	0.735	0.005	0.721[b]	0.739[a]	0.720[b]	0.006	0.013	0.034	0.921

[a] Least-squares means based on 12 pen observations of 4 pigs each per treatment.

Chapter 4 Nutrient digestibility of solvent-extracted *B. napus* and *B. juncea* canola meals and their air-classified fractions fed to ileal-cannulated grower pigs

4.1 Abstract

Energy and nutrient digestibility of solvent-extracted canola meal (CM) is limited in pigs by its relatively high fiber content. The seed hull, which greatly contributes to the fiber content of CM, is denser than the oil-free cotyledon. By utilizing streams of air, air classification partially separates these seed components based on their different size and density to produce a low-fiber, light-particle fraction and a high-fiber, heavy-particle fraction. Compared with parent CM, ADF, and NDF were reduced by 31.9 and 29.5% in the light-particle fraction and enriched by 16.5 and 9.0% in the heavy-particle fraction, respectively (DM basis). Particle size of parent CM, light- and heavy-particle fraction was 638, 18.9 and 76.1μm, respectively. To determine the nutrient digestibility of CM and their air-classified fractions, *Brassica* (*B.) napus* and *B. juncea* CM and their 2 air-classified fractions were evaluated in a 2 × 3 factorial arrangement together with a basal diet and an N-free diet. The experiment was conducted as an 8 × 8 Latin square feeding diets containing 40% *B. napus* or *B. juncea* CM or their air-classified fractions and 60% basal diet. Digesta data from pigs fed the N-free diet served to subtract basal endogenous AA losses. Eight ileal-cannulated barrows (32 kg initial BW) were fed the 8 diets at 2.7 × maintenance DE for eight 11-d periods. At the end of each period, feces were collected for 48 h and ileal digesta for two 12 h periods. The DE and calculated NE value and the apparent total tract digestibility (ATTD) of GE were 6.3, 10.0 and 7.8% greater ($P < 0.001$) for *B. juncea* than *B. napus* CM; 6.1, 10.8 and 5.3% greater ($P < 0.001$) for the light-particle fraction than parent CM; and 5.4, 7.2 and 3.8% lower ($P < 0.001$) for the heavy-particle fraction than parent CM, respectively. The

standardized ileal digestibility (SID) of His, Ile, Val, Asp, and Tyr were greater ($P < 0.05$) for *B. juncea* than *B. napus* CM. The SID of CP and AA were greater ($P < 0.01$) in light-particle fraction than heavy-particle fraction. The SID of Trp, Glu, Pro, and Tyr were greater ($P < 0.05$) in the light-particle fraction than parent CM. In conclusion, *B. juncea* CM had greater energy and AA digestibility than *B. napus* CM due to reduced fiber content. Air classification of CM increased its energy and AA digestibility in light-particle fraction for pigs due to the reduced dietary fiber content and decreased particle size.

4.2 Introduction

Solvent-extracted canola meal (CM), together with rapeseed meal, is the second most traded protein feedstuff for animals worldwide after soybean meal (SBM, Newkirk, 2009). Substitution of SBM by CM in swine diets may reduce feed cost (Woyengo et al., 2013). However, the relatively high dietary fiber content in CM (32% total dietary fiber, TDF) limits its energy and nutrient availability for pigs (González-Vega and Stein, 2012). Reducing fiber content by further processing CM may improve its feeding value (Hickling, 2007).

Brassica (B.) juncea is a yellow-seeded novel canola species with a thinner seed coat and therefore less fiber content than traditional dark-seeded *B. napus* (Slominski et al., 2012). However, energy and AA digestibility of *B. juncea* need to be evaluated to support its meal inclusion in swine diets. Air classification is a constant, dry fractionation process that primarily shifts fiber content in oilseed meals using streams of air and gravity (Seth and Clandinin, 1973). Air classification of CM results in a low-fiber, light-particle fraction and a high-fiber, heavy-particle fraction from the parent meal. The low-fiber fraction may have better feeding value for young monogastric animals while the high-fiber fraction may be more appropriate for feeding

gestating sows, broiler breeders, or ruminants. Dietary inclusion of air-classified CM fractions requires precise knowledge of their energy and AA digestibility to obtain predictable animal performance and reduce nutrient excretion. Dietary energy and nutrient digestibility values of air-classified CM fractions have not been published.

The hypotheses of this study were that *B. juncea* CM would have greater energy and AA digestibility than *B. napus* CM, and that low- and high-fiber CM fractions would have greater and lower energy and AA digestibility than the parent meal, respectively. The objective was to determine and compare the energy and AA digestibility of *B. napus* and *B. juncea* CM and their air-classified fractions.

4.3 Materials and methods

4.3.1 Test articles, grinding and air classification

Brassica juncea and *B. napus* canola were grown in southern Saskatchewan and Manitoba, respectively, during the 2010 growing season. The seed was expeller-pressed and the oil solvent extracted using typical commercial procedures at Bunge North America (Altona, MB, Canada) that fall. The parent meals were further processed at Agri-Food Discovery Place, University of Alberta (Edmonton, AB, Canada) to produce the fractions (Table 4.1). Particle size was first reduced using a model 15 Mikro-ACM mill (Hosokawa Micron Powder, Summit, NJ) equipped with a rotor fitted with 4 J-shape hammers and a separator wheel of the short type. Process air flow was 600 cfm, feed rate 1.5 kg/min, rotor speed 7,000 rpm, and separator speed 3,700 rpm. Air classification was subsequently conducted using a model 20 Alpine Turboplex ATP classifier (Hosokawa Micron Powder). Process air flow was 600 cfm, secondary air flow 200 cfm, feed rate 1.5 kg/min, separator speed 3,700 rpm. Particle size of the parent CM was determined in

triplicate using a sieve shaker (model RX-30; W.S. Tyler, Mentor, OH) and of the fractions in a laser diffraction analyzer (model LS 13 320; Beckman Coulter Inc., Mississauga, ON, Canada).

4.3.2 Experimental diets and design

Effects of feeding canola species (*B. napus* and *B. juncea*) and air-classified fractions (parent CM, light-particle fraction and heavy-particle fraction) were tested in a 2 × 3 factorial arrangement together with a basal diet and an N-free diet. The 8 mash diets were fed as an 8 × 8 Latin square to 8 pigs for 8 observations for each treatment. The basal diet was formulated to reflect a typical western Canadian grower diet (wheat, barley, field pea-based; Table 4.1) that provided approximately 18% CP and exceeded NRC (1998) requirements for most nutrients (Table 4.3). Test diets were prepared by mixing 40% of each test parent CM or fractions with 60% of basal diet. The N-free diet was formulated as per Stein et al. (2007) and was used exclusively to correct for basal endogenous losses of AA. As indigestible marker, TiO_2 was used.

4.3.3 Experimental procedures

The animal procedures were reviewed by the University of Alberta Animal Care and Use Committee for Livestock, and followed principles established by the Canadian Council on Animal Care (CCAC, 2009). The animal study was conducted at the Swine Research and Technology Centre (Edmonton, AB, Canada).

Eight crossbred barrows (initial BW 31.9 ± 2.0 kg; Duroc × Large White/Landrace F1; Genex Hybrid; Hypor, Regina, SK, Canada) were housed in individual metabolism pens that allowed freedom of movement (1.2 m wide, 1.2 m long, and 0.9 m high). Pens were equipped with a stainless-steel feeder attached to the front of the pen, cup drinker next to the feeder, polyvinyl chloride walls with windows, and slatted flooring in a temperature-controlled room (22.0 ± 2.5ºC). During a 10-d adaptation to pens, barrows had free access to an 18% CP diet.

Pigs were then surgically fitted with a simple T-cannula at the distal ileum, approximately 5 cm prior to the ileocecal sphincter. Cannula dimensions, surgical procedure, and modifications were described previously (Sauer et al., 1983; de Lange et al., 1989). Pre-and post-operative care was also described previously (Li et al., 1993). After surgery, barrows recovered for 7 d with a gradual increase in feed allowance, and were then switched to the first assigned experimental diet. Daily feed allowance was adjusted to 2.7 times the maintenance requirement for DE (2.7 × 110 kcal of DE/kg of $BW^{0.75}$; NRC, 1998), which was fed in 2 equal meals at approximately 0800 and 1500 h. Each 11-d experimental period consisted of a 7-d acclimation to the experimental diets, followed by a 2-d collection of feces and a 2-d collection of ileal digesta. Pigs had free access to water throughout the experiment.

Feces were collected using plastic bags attached to the skin around the anus (Van Kleef et al., 1994) continuously for 48 h. Digesta samples were collected for 2 d from 0800 to 2000 h using soft plastic tubes (length, 20 cm; i.d., 4 cm) containing 15 mL of 5% formic acid that were attached to the opened barrel of the cannula with a rubber band. Tubes were replaced as soon as filled or after 20 min (Li et al., 1993). Collected feces and digesta were pooled for each pig within experimental period and frozen at -20ºC. Prior to analyses, feces and digesta were thawed, homogenized, sub-sampled, and freeze-dried.

4.3.4 Chemical analyses

Test diets and lyophilized feces and digesta were ground through a 1-mm screen in a centrifugal mill (model ZM200; Retsch GmbH, Haan, Germany). The parent CM and air-classified light- and heavy-particle fractions of each were analyzed for GE using an adiabatic bomb calorimeter (model 5003; Ika-Werke GMBH & Co. KG, Staufen, Germany), DM (method 934.01), CP (method 984.13A-D), ether extract (EE, method 920.39A), ash (method 942.05),

ADF (method 973.18A-D), NDF (Van Soest et al., 1991), Ca (method 968.08), P (method 946.06), AA (method 982.30E), and available Lys (method 975.44) content as per AOAC (2006) without further grinding at the Agricultural Experiment Station Chemical Laboratories, University of Missouri-Columbia, MO, USA. Glucosinolate profile of parent CM and air-classified fractions were determined by GLC (Daun and McGregor, 1981) at POS Bio-Sciences, Saskatoon, SK, Canada. Experimental diets were analyzed for DM, GE, CP, EE, ash, CF, ADF, NDF, AA, available lysine, and TiO_2 (Myers et al., 2004; latter analysed at University of Alberta) content. Feces were analyzed for DM, GE, CP, EE, ash, CF, ADF, NDF and TiO_2 content. Digesta were analyzed for DM, GE, CP, AA, and TiO_2 content.

4.3.5 Calculations

The index method was used to calculate the digestibility of components in the experimental diets. The apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of relevant nutrients in the diet was calculated using the following equation (Adeola, 2001):

ATTD or AID, % = 100 – [100 × (concentration of TiO_2 in feed × concentration of component in feces or digesta / concentration of TiO_2 in feces or digesta × concentration of component in feed)]

The basal ileal endogenous loss (I_{end}) of an AA or CP (g/kg of DM intake) was calculated by the equation for the N-free diet (Eq. 3, Stein et al., 2007):

$$I_{end} = [\text{AA or CP in digesta} \times (TiO_2 \text{ in feed} / TiO_2 \text{ in digesta})]$$

Standardized ileal digestibility (SID) values for each indispensable AA were then calculated by correcting the AID for basal ileal endogenous losses by the equation (Eq. 7, Stein et al., 2007):

$$SID = [AID + (I_{end} / \text{AA in feed})]$$

Digestibility of test ingredients was calculated according to the difference method (Eq. 2, Bureau et al., 1999):

$$D_{\text{test ingredient}} = D_{\text{test diet}} + [(D_{\text{test diet}} - D_{\text{basal diet}}) \times (0.6 \times N_{\text{basal}} / 0.4 \times N_{\text{ingredient}})]$$

Where: $D_{\text{test ingredient}}$ = % digestibility of the test ingredient; $D_{\text{test diet}}$ = % digestibility of the test diet; $D_{\text{basal diet}}$ = % digestibility of the basal diet; 0.6 means 60% of basal diet in the test diets; 0.4 means 40% of test ingredient in the test diets; N_{basal} = % nutrient (or MJ/kg GE) of basal diet (DM-basis); $N_{\text{ingredient}}$ = % nutrient (or kJ/g GE) of test ingredient (DM-basis).

NE values were calculated using Eq. 5 in Noblet et al., (1994) based on analytical values.

4.3.6 Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (ver. 9.3, SAS Inst. Inc., Cary, NC) as a 2 × 3 factorial arrangement. Normality (PROC UNIVARIATE) and homogeneity of variance (PROC GLM, Hovtest = Levene) were confirmed first. The model included canola species, fraction, and species × fraction interaction as fixed effects. Diet fed in the previous period was used as covariate to test for carry-over effects. Period and pig were random terms. Least-square means for each nutrient were reported. Multiple comparisons between least-square means were achieved using the PDIFF statement with TUKEY adjustment. Significance level was declared at $P < 0.05$.

4.4 Results

Pigs remained healthy during the experiment. Orts were not collected as pigs consumed their daily feed allowance throughout the experiment regardless of the diet offered.

Particle size of *B. napus* and *B. juncea* CM was 636 and 640 µm (Table 4.2), respectively. Upon air classification, yield of light- and heavy-particle fractions was 45 and 55% for *B. napus* CM; 46 and 54% for *B. juncea* CM, respectively. Particle size for light- and heavy-particle fractions was 21.6 and 71.0 µm for *B. napus* CM, and 16.1 and 81.1 µm for *B. juncea* CM,

respectively. *B. juncea* CM had 37.9 and 28.0% lower ADF and NDF content than *B. napus*, respectively (DM basis). Compared with parent CM, content of ADF and NDF in light-particle fractions was reduced by 32.4, and 31.7% for *B. napus,* and 31.4 and 27.2% for *B. juncea* CM, respectively (DM basis). Compared with parent CM, content of ADF and NDF in heavy-particle fractions was increased by 14.0 and 7.8% for *B. napus*, and 19.0 and 10.2% for *B. juncea* CM, respectively (DM basis). Compared to the parent CM, CP content was enriched by 4.3 and 2.1% in light-particle fractions, and decreased by 2.9 and 5.2% in heavy-particle fractions for *B. napus* and *B. juncea* CM, respectively (DM basis). The AA content in the light- and heavy-particle fraction was generally greater and lower than that in the parent CM, respectively. Glucosinolates in *B. juncea* CM were about 2-fold greater than in *B. napus* CM. Air classification did not enrich glucosinolate content in either light- or heavy-particle fractions (DM basis).

Carry-over effects were not observed ($P > 0.05$) among periods for digestibility variables. Interactions between canola species and parent CM or air-classified fractions for digestibility variables were not observed ($P > 0.05$), except for ATTD of OM of experimental diets (Table 4.4).

Brassica juncea CM had 8.8, 7.8, 63.2, 45.5, and 8.4% greater ($P < 0.001$, Table 4.5) ATTD of DM, GE, ADF, NDF, and OM than *B. napus* CM, respectively. The DE and calculated NE value of *B. juncea* CM was 6.3 and 10.0% greater ($P < 0.001$) than *B. napus* CM. The ATTD of CP did not differ ($P > 0.05$) between *B. napus* and *B. juncea* CM. The light-particle fraction had 5.3, 29.4 and 5.1% greater ($P < 0.001$) ATTD of GE, ADF, and OM than parent CM, respectively. However, the light-particle fraction had 5.1% lower ($P < 0.001$) ATTD of CP than parent CM. The heavy fraction had 5.4, 3.8, 5.8, 14.2 and 4.8% lower ($P < 0.001$) ATTD of DM, GE, CP, ADF, and OM than parent CM, respectively. The DE and NE value of the light-particle

fraction was 6.1 and 10.8% greater ($P < 0.001$) than those of parent CM. The DE and NE value of the heavy-particle fraction was 5.4 and 7.2% lower ($P < 0.001$) than those of parent CM. The ATTD of NDF did not differ ($P > 0.05$) between the parent CM and fractions (Table 4.5).

The AID of gross energy and nutrients in test diets (Table 4.6) and the SID of crude protein and amino acids in test diets (Table 4.7) were generally similar to test ingredients (Table 4.8). The *B. juncea* CM had 17% greater ($P = 0.05$, Table 4.8) AID of DM than *B. napus* CM. The AID of GE did not differ ($P > 0.05$) between *B. napus* and *B. juncea* CM. The Light-particle fraction had 37.5 and 37.2% greater ($P < 0.001$) AID of DM and GE than parent CM. The Heavy-particle fraction had similar ($P > 0.05$) AID of DM and GE as parent CM.

Brassica juncea CM had greater ($P < 0.05$, Table 4.8) SID of His, Ile, Val, Asp, Pro, and Tyr than *B. napus* CM. The SID of other AA, CP, and total AA did not differ between *B. juncea* and *B. napus* CM. The Light-particle fraction had greater ($P < 0.001$) SID for every AA and total AA than the heavy-particle fraction. The SID of AA and total AA did not differ ($P > 0.05$) between the light-particle fraction and parent CM, except for Trp, Glu, Pro, and Tyr that were greater ($P < 0.05$) in light-particle fraction. The SID content of AA did not differ ($P > 0.05$; Table 4.8) between parent CM and heavy-particle fraction, except for Arg, Lys, and total AA that were greater ($P < 0.05$) in the parent CM.

4.5 Discussion

4.5.1 Air classification of CM

Air classification separates CM into 2 fractions with different physical properties and nutrient content (Andersson et al., 2000). Canola seed is composed of hull and cotyledons containing oil and protein (Thakor et al., 1995). Hull accounts for approximately 30% of the

weight of CM and contains about 60% of total dietary fiber (Bell and Shires, 1982; Slominski et al., 2012), which greatly contributes to the fiber content of CM. During oil-extraction, seeds are crushed, expeller-pressed and the remaining oil is solvent-extracted to yield CM with hull and oil-free cotyledons (Newkirk, 2009). Grinding of CM partially breaks the adherence between these two seed components. The rigid hull is resistant to grinding and stays in larger particles (Wolf et al., 2002), while cotyledons are more easily shattered into smaller particles (Clark et al., 2001). Canola hull particles have greater density than cotyledons. During air classification, air flow lifts suspended lighter particles up while heavier particles fall (Fedec, 2003), thereby partially separating hull from cotyledons and shifting fiber to the heavy-particle fraction and reducing fiber in the light-particle fraction. Air classification of solvent-extracted oilseed meals thus can serve as one of the last plant processing steps or back-end or tail-end dehulling.

4.5.2 Nutrient composition of CM air-classified fractions

Air classification reduced ADF and NDF content in the light-particle fraction while it enriched fiber content in the heavy-particle fraction. Canola hull fiber is rich in cellulose, lignin, and polyphenols while cell wall fiber from cotyledons is rich in hemicellulose and pectin (Mustafa et al., 1996; Bell, 1993; Slominski et al., 2012). The segregation of cotyledon from hull particles results in an enrichment of hemicellulose in the light-particle fraction (King and Dietz, 1987). Slominski et al. (2012) manually separated canola embryo and hull from each other and found greater lignin and polyphenols content in the hull. It should be emphasized that air-classification is an incomplete separation of cotyledon and hull, which could shift lighter hull particles into the light-particle fraction.

Purified canola cotyledon (oil-free) and hull contained 54 and 20% CP, respectively (Bell and Shires, 1982). However, CP content in this study only increased slightly (3%; DM basis) in

the light-particle fraction. Similar results were also found by studies that used sieving to dehull CM (de Lange et al., 1998; Clark et al., 2001; McCurdy and March, 1992) and air classification of rapeseed meal (Seth and Clandinin, 1973; Bayley and Hill, 1975). These findings may be attributed to the relatively high protein content (15-20%) in canola hull (Bell and Shires, 1982; Mustafa et al., 1996). The tight adherence between hull and cotyledons in canola seed, which are further strengthened by expeller-pressing (McCurrdy and March, 1992), also increases the difficulty of separation of these seed components. Hydrothermal treatments of CM before dehulling increased the efficiency of protein shifting (Thakor et al., 1995). However, additional processing procedures would increase fractionation cost.

Glucosinolates are the major anti-nutritional factor in CM that reduce animal performance by reducing feed intake and affecting thyroid and liver functions (Tripathi and Mishra, 2007). In contrast to pulse seed tannins that are located mostly in the seed hull and can be removed by dehulling or perling, glucosinolates are concentrated in the cotyledons of canola (Mińkowski, 2002; Matthäus, 1998). Thus, we thought that dehulling CM might enrich glucosinolates in the low-fiber fraction composed mostly of cotyledons. However, glucosinolate content and profile among parent CM and fractions were similar in the present study and other studies that dehulled CM by sieving (Clark et al., 2001; McCurdy and March, 1992), which could be mainly attributed to the breeding programs that have progressively reduced glucosinolates in canola seed over 3 decades (Newkirk, 2009).

4.5.3 Digestibility of Brassica napus and Brassica juncea CM

Brassica juncea has been labeled as the third canola species in Canada (Canadian Grain Commission, 2013). It is more thermo-tolerant and disease-resistant than *B. napus*. Therefore, it is better suited to grow on the marginal lands of the low precipitation northern Great Plains

(Miller et al., 2003). The greater ATTD of DM, GE and DE value for *B. juncea* over *B. napus* CM in the present experiment, which agrees with a previous study (Le et al., 2012), could be attributed to the thinner seed hull, less TDF, (Bell et al., 1998) and less proportion of lignin in *B. juncea* CM (Slominski et al., 2012). Feeding *B. juncea* CM may also increase digestion efficiency by decreasing digesta passage rate in the small intestine and increasing bacteria enzyme activity in the cecum (Jia et al., 2012). The increased ATTD of ADF and NDF in *B. juncea* over *B. napus* indicates greater fermentability of *B. juncea* CM. The 0.8 MJ/kg greater NE value of *B. juncea* CM over *B. napus* could be attributed to greater DE and lower ADF content in *B. juncea* CM, which agrees with the study of Le et al. (2012), but differs from Montoya and Leterme (2009) and Bell et al. (1998) who reported similar energy and nutrient utilization of *B. juncea* compared to *B. napus* CM in pigs.

On average, ATTD of DM and GE was 95.5 and 63.2% greater than their respective AID values, which indicate extensive fermentation and water absorption of CM in the large intestine. The SID of AA between *B. napus* and *B. juncea* CM showed no difference except for His, Ile, Val, Asp, and Pro that were greater for *B. juncea* CM. The same AA were also previously reported to have greater SID in *B. juncea* than in *B. napus* CM (Trindade Neto et al., 2011). It appears that the difference in fiber content and components between *B. napus* and *juncea* CM may not affect AA and CP digestibility as largely as it affected energy digestibility (Le et al., 2012).

4.5.4 Digestibility of parent CM and air-classified fractions

Feeding light-particle fractions increased ATTD of DM, GE and OM compared with feeding parent CM and heavy-particle fractions. Previous studies also reported increased energy and nutrient utilization for dehulled canola or rapeseed meal fractions in pigs (de Lange et al., 1998;

Bayley and Hill, 1975; Bourdon and Aumaitre, 1990; Kracht et al., 2004; Zhou et al., 2013). Increased ATTD of nutrients in the light-particle fraction could be explained by its reduced NDF content and lower proportion of cellulose and lignin that are indigestible in pigs and negatively affect the digestion of other nutrients (de Lange et al., 1998; Bell, 1993). The increased ATTD of ADF in the light-particle fraction in the present study may indicate greater fermentability of fiber in canola cotyledon. The similar ATTD of NDF among CM and air-classified fractions can be attributed to the presence of hemicellulose that could be better fermented by the gut micro-flora (Bell, 1993). Smaller particle size of the light-particle fraction may also contribute to its greater ATTD of nutrients by increasing surface area of feed particles for digestive enzyme hydrolysis (Wondra et al., 1995). The DE (14.8 MJ/kg) and NE (8.3 MJ/kg) value of parent CM in the present study are similar to 13.7 and 7.9 MJ/kg reported by NRC (2012). The 0.9 MJ/kg greater NE value of the light-particle fraction over parent CM may practically imply less dietary fat supplementation to meet the energy requirement of pigs, which could reduce feed cost (Clark et al., 2001).

Increased AID of DM and GE in the light-particle fraction over the parent CM and the heavy-particle fraction could be explained by its lower fiber content and smaller particle size. The SID of Lys, Met, and Thr of parent CM in the present study was 75, 81, 68% compared with 74, 85, and 70% reported by NRC (2012); 67, 84, and 72% by Woyengo et al. (2010); 68, 84, and 70% by González-Vega and Stein (2011); 74, 81, and 66% by Trindade Neto et al. (2011); and 84, 90 and 82% by Le et al. (2012). The remarkably lower SID of Lys reported by Woyengo et al. (2009) and González-Vega and Stein (2011) could be attributed to Maillard reactions mostly occurring during desolventizing and toasting after seed oil-expelling and solvent washing (Woyengo et al., 2010), which were closely monitored by the processor and avoided for the

meals fed in the present study. The SID values of other AA in the parent CM are in general agreement with previous studies (NRC, 2012; González-Vega and Stein, 2011; Trindade Neto et al., 2009; Eklund et al., 2012). Instead of feeding a corn starch-based basal diet, the present study fed a grain-based basal diet to simulate a conventional western-Canadian grower diet. Feeding ground cereals instead of semi-pure starch might lead to greater fiber content in the basal diet and trigger greater specific AA endogenous losses which would cause lower SID values (Stein et al., 2007). However, AA digestibility of parent CM in the present study did not differ much from studies that fed a starch-based diet. Cereals, pulse and wheat co-products fed in this study did not affect the digestion of CM.

The light-particle fraction had greater SID for all AA than the heavy-particle fraction, which could be attributed to its lower CF, ADF, and NDF content that are negatively correlated with the digestibility of AA (Fan et al., 1996; de Lange et al., 1998). Due to an enrichment of hull components, the heavy-particle fraction contains proteins that are tightly bound with cellulose and lignin (Finlayson, 1974; Bell and Shires, 1982), which results in poor digestion (Fan et al., 1996). Increased fiber content in the heavy-particle fraction may also trigger greater endogenous losses in pigs that reduces measured AA digestibility (Eklund et al., 2012). In the present study, only SID of Trp, Asp, Glu, and Tyr were greater in the light-particle fraction than the parent CM, indicating that some AA are contained mainly in storage proteins in the cotyledon of canola seed (Fan et al., 1996), associated less with the hull, and therefore are better digested by pigs.

Greater SID of AA in the light-particle fraction may support its inclusion in high nutrient density diets such as starter feeds for young monogastric animals and reduce the inclusion of synthetic AA in young pig diets to meet their requirements. The heavy-particle fraction could be directed to feeding gestating sows or broiler breeders as these would benefit from low-density

diets with higher fiber content that induce satiety and may reduce the incidence of stereotypies (de Leeuw et al., 2008; de Jong et al., 2005). The heavy-particle fraction could also be intended for ruminant feeding and thereby increase the whole value of CM (Clark et al., 2001).

4.5.5 Particle size

Particle size is an important factor affecting the efficiency of air classification. Fine grinding of CM breaks the bounding between hull and cotyledon so that seed components can be separated more efficiently (King and Dietz, 1987; Sosulski and Zadernowski, 1981). However, the partial confounding effect of particle size between fractions and parent CM was inevitable. Particle size is an intrinsic physical characteristic of fractions. The heavy-particle fraction had 88% reduced particle size but 9% increased NDF (DM basis) compared with parent CM, but also lower digestibility of energy, protein, and AA, which means the difference in fiber content between parent CM and fractions was the major cause of the difference in nutrient digestibility.

In conclusion, *B. juncea* CM had greater energy and AA (His, Ile, Val, Asp, Pro, and Tyr) digestibility than *B. napus* CM. Air classification of CM produced two fractions with distinctly different digestible nutrient profiles. The low-fiber, light-particle fraction had greater AA digestibility (Trp, Glu, Pro, and Tyr) and energy content than parent CM while the high-fiber, heavy-particle fraction had inferior energy and AA digestibility (SID of Arg and Lys) compared with the parent CM and the light-particle fraction (every AA and total AA).

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Table 4.1 Ingredient composition of experimental diets (as-fed basis).

Ingredient, %	Basal diet	Test diets	N-free diet
Test ingredient[1]	-	40.00	-
Wheat grain, ground	32.00	19.20	-
Barley grain, ground	32.00	19.20	-
Wheat distillers dried grains with solubles (DDGS)	10.00	6.00	-
Soybean meal	10.00	6.00	-
Field pea, ground	10.00	6.00	-
Limestone	2.00	1.20	0.50
Mono-di-calcium phosphate	0.80	0.48	1.90
Titanium dioxide	0.70	0.42	0.50
Salt	0.50	0.30	0.40
Vitamin premix[2]	0.50	0.30	0.50
Mineral premix[3]	0.50	0.30	0.50
Canola oil	1.00	0.60	3.00
Corn starch[4]	-	-	78.20
Cerelose[5]	-	-	10.00
Solka floc[6]	-	-	4.00
K_2CO_3	-	-	0.40
MgO	-	-	0.10

[1]Each of the 6 test ingredients (*B. napus* parent canola meal, *B. napus* light particle fraction, *B. napus* heavy particle fraction, *B. juncea* parent canola meal, *B. juncea* light particle fraction, and *B. juncea* heavy particle fraction) was mixed with the basal diet in a 4:6 ratio (wt/wt).

[2]Provided the following per kilogram of diet: vitamin A, 8,250 IU; vitamin D_3, 825 IU; vitamin E, 40 IU; niacin, 35 mg; D-pantotenic acid, 15 mg; riboflavin, 5 mg; menadione, 4 mg; folic acid, 2 mg; thiamine, 1 mg; D-biotin 0.2 mg; and vitamin B_{12}, 0.025 mg.

[3]Provided the following per kilogram of diet: Zn, 100 mg as $ZnSO_4$; Fe, 80 mg as $FeSO_4$; Cu, 50 mg as $CuSO_4$; Mn, 25 mg as $MnSO_4$; I, 0.5 mg as $Ca(IO_3)_2$; and Se, 0.1 mg as Na_2SeO_3.

[4]Melojel (National Starch and Chemical Co., Bridgewater, NJ).

[5]Corn Product U.S., Westchester, IN.

[6]International Fiber Corp., North Tonawanda, NY.

Table 4.2 Analyzed gross energy (GE) value and nutrient content of *Brassica (B) napus* and *B. juncea* parent canola meals and their air-classified fractions (as-is basis).

	B. napus			*B. juncea*		
Item	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Particle size, μm ± SD[a]	636 ± 2.14	21.60 ± 22.18	71.01 ± 40.16	640 ± 2.29	16.12 ± 17.29	81.14 ± 65.31
Density, g/1000 mL ± SD[a]	532 ± 16	381 ± 15	595 ± 21	555 ± 31	405 ± 49	625 ± 14
Moisture, %	10.5	7.7	8.8	9.7	7.7	8.2
CP (N × 6.25), %	38.1	41.0	37.7	39.0	40.7	37.6
GE, MJ/kg	18.1	18.9	18.2	17.8	18.6	17.9
Ether extract, %	2.70	4.77	2.37	2.20	3.35	1.95
ADF, %	19.8	13.8	23.0	12.4	8.7	15.0
NDF, %	27.4	19.3	30.1	19.9	14.8	22.3
Starch, %	1.28	1.62	1.01	3.08	4.14	3.63
Ash, %	7.61	7.84	7.64	7.38	7.18	7.54
P, %	1.06	1.15	1.05	1.19	1.23	1.12
Ca, %	0.60	0.55	0.66	0.66	0.58	0.73
Indispensable AA, %						
Arg	2.22	2.43	2.24	2.54	2.68	2.42
His	0.96	1.06	0.98	0.99	1.06	0.97
Ile	1.46	1.62	1.52	1.54	1.66	1.53
Leu	2.61	2.85	2.63	2.81	2.96	2.70
Lys	2.09	2.29	2.12	2.01	2.14	1.97
Met	0.71	0.77	0.72	0.70	0.75	0.67
Phe	1.42	1.55	1.44	1.51	1.59	1.46
Thr	1.55	1.67	1.52	1.64	1.68	1.55
Trp	0.48	0.52	0.47	0.43	0.45	0.44
Val	2.03	2.23	2.08	2.06	2.20	2.06
Dispensable AA, %						
Ala	1.58	1.73	1.60	1.71	1.80	1.67
Asp	2.60	2.81	2.62	2.92	3.07	2.82
Cys	0.87	0.93	0.89	0.79	0.82	0.78
Glu	5.75	6.22	5.79	5.91	6.16	5.72
Gly	1.81	1.99	1.83	1.92	2.03	1.90
Pro	2.23	2.42	2.22	2.10	2.16	2.03

Item	*B. napus*			*B. juncea*		
	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction
Ser	1.35	1.43	1.27	1.45	1.45	1.32
Tyr	1.02	1.11	0.98	1.09	1.12	1.04
Available lysine, %	1.98	2.15	2.01	1.91	2.02	1.80
Total glucosinolates μmol/g[b]	4.14	4.82	4.27	10.03	10.85	9.79

[a]The SD based on 5 replicates.

[b]*B. napus* parent canola meal contained the following glucosinolates (μmol/g as-is): 3-butenyl, 1.46; 4-pentenyl, 0.16; 2-OH-3-butenyl, 2.47; 2-OH-4-pentenyl, 0.05; Phenylethyl, 0.13; 3-CH3-indolyl, 0.21; 4-OH-3-CH3-indolyl, 1.07. *B. juncea* parent canola meal contained glucosinolates (μmol/g as-is): Allyl, 0.24; 3-butenyl, 8.96; 4-pentenyl, 0.36; 2-OH-3-butenyl, 0.71; Phenylethyl, 0.12; 3-CH3-indolyl, 0.06; 4-OH-3-CH3-indolyl, 0.19.

Table 4.3 Analyzed gross energy (GE) value and nutrient content of the experimental diets (as-fed basis).

		B. napus			*B. juncea*			
Item	Basal	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction	N-free
Moisture, %	8.66	8.62	8.01	8.68	8.35	8.22	8.56	8.56
CP (N × 6.25), %	21.37	30.02	30.19	28.67	30.38	28.33	28.92	0.92
GE, MJ/kg	16.63	17.22	17.39	17.18	17.18	17.20	17.04	14.97
Ether extract, %	2.10	2.34	3.29	2.08	2.18	2.53	1.84	3.20
ADF, %	5.29	12.35	9.39	13.69	8.90	7.24	9.87	3.87
NDF, %	16.78	23.52	18.67	24.91	19.64	17.07	21.70	4.39
Starch, %	37.41	18.22	19.76	17.87	18.36	23.97	19.76	78.18
Ash, %	7.87	7.96	7.99	7.99	7.92	7.47	7.93	4.34
P, %	0.69	0.89	0.89	0.83	0.94	0.91	0.91	0.30
Ca, %	1.33	1.12	0.89	1.05	1.15	1.03	1.08	0.46
Indispensable AA, %								
Arg	1.15	1.68	1.78	1.65	1.78	1.74	1.75	0.01
His	0.47	0.71	0.76	0.70	0.72	0.71	0.70	0.00
Ile	0.81	1.12	1.20	1.14	1.17	1.15	1.18	0.07
Leu	1.47	2.06	2.17	2.03	2.10	2.07	2.08	0.04
Lys	0.88	1.44	1.53	1.40	1.38	1.34	1.38	0.02
Met	0.29	0.49	0.51	0.48	0.47	0.47	0.48	0.00
Phe	1.04	1.30	1.36	1.28	1.30	1.30	1.29	0.02
Thr	0.62	1.02	1.07	0.98	1.02	0.99	0.98	0.01
Trp	0.22	0.32	0.32	0.31	0.28	0.28	0.28	0.00
Val	0.93	1.39	1.49	1.40	1.41	1.39	1.42	0.04
Dispensable AA, %								
Ala	0.80	1.20	1.27	1.18	1.22	1.20	1.20	0.02

		B. napus			*B. juncea*			
Item	Basal	Parent meal	Light fraction	Heavy fraction	Parent meal	Light fraction	Heavy fraction	N-free
Asp	1.43	1.88	2.04	1.82	2.01	2.01	2.00	0.02
Cys	0.36	0.59	0.60	0.58	0.53	0.52	0.55	0.01
Glu	4.59	5.39	5.52	5.29	5.30	5.34	5.32	0.09
Gly	0.54	1.12	1.16	1.09	1.13	1.03	1.09	0.00
Pro	1.59	1.78	1.90	1.71	1.76	1.80	1.72	0.02
Ser	0.84	1.13	1.16	1.06	1.13	1.09	1.08	0.01
Tyr	0.64	0.83	0.89	0.82	0.84	0.84	0.84	0.02

Table 4.4 Apparent total tract digestibility (ATTD) of gross energy (GE) and nutrients, and digestible energy (DE) values of experimental diets (DM basis).

	Species			Fractions				*P*-value		
Item	*B. napus*	*B. juncea*	SEM	Parent meal	Light fraction	Heavy fraction	SEM	Species	Fractions	Species × fractions
DM, %	78.4	80.9	0.4	80.0[a]	80.9[a]	78.3[b]	0.5	<0.001	<0.001	0.115
GE, %	77.9	80.3	0.5	78.9[b]	80.6[a]	77.7[b]	0.5	<0.001	<0.001	0.092
CP, %	79.0	79.2	0.6	80.8[b]	78.4[a]	78.1[a]	0.7	0.571	<0.001	0.546
Ether extract, %	80.0	76.4	1.7	74.2[b]	82.6[a]	77.8[b]	1.8	0.008	<0.001	0.053
ADF, %	39.6	55.1	1.0	46.4[b]	54.1[a]	41.5[c]	1.3	<0.001	<0.001	0.093
NDF, %	56.5	67.7	1.1	63.1	63.4	59.8	1.3	<0.001	0.071	0.250
Ash, %	48.6	51.1	1.1	53.0[b]	46.8[a]	49.7[a]	1.2	0.026	<0.001	0.676
OM, %	81.0	83.4	0.4	82.2[b]	83.8[a]	80.7[c]	0.4	<0.001	<0.001	0.042
DE, MJ/kg	14.7	15.0	0.1	14.8[b]	15.2[a]	14.5[c]	0.1	<0.001	<0.001	0.586

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

Table 4.5 Apparent total tract digestibility (ATTD) of gross energy (GE) and nutrients, and digestible energy (DE) and net energy (NE) values of parent *Brassica (B) napus* and *B. juncea* canola meals and their air-classified fractions (DM basis).

	Species			Fractions				*P*-value		
Item	*B. napus*	*B. juncea*	SEM	Parent meal	Light fraction	Heavy fraction	SEM	Species	Fractions	Species × fractions
DM, %	70.6	76.8	0.7	74.2[a]	76.7[a]	70.2[b]	0.8	<0.001	<0.001	0.097
GE, %	71.6	77.2	0.7	74.1[b]	78.0[a]	71.3[c]	0.9	<0.001	<0.001	0.092
CP, %	77.5	78.0	0.8	80.7[b]	76.6[a]	76.0[a]	0.9	0.576	<0.001	0.538
Ether extract, %	84.8	78.2	4.3	74.1[b]	88.4[a]	82.0[ab]	5.0	0.031	0.002	0.074
ADF, %	41.0	66.9	1.6	51.4[b]	66.5[a]	44.1[c]	1.9	<0.001	<0.001	0.493
NDF, %	52.3	76.1	2.6	65.6	67.5	59.6	2.9	<0.001	0.076	0.320
Ash, %	33.7	39.2	2.7	44.2[b]	28.9[a]	36.3[a]	3.0	0.047	<0.001	0.545
OM, %	73.8	80.0	0.6	76.8[b]	80.7[a]	73.1[c]	0.8	<0.001	<0.001	0.044
DE, MJ/kg	14.4	15.3	0.1	14.8[b]	15.7[a]	14.0[c]	0.2	<0.001	<0.001	0.287
NE, MJ/kg	8.0	8.8	0.1	8.3[b]	9.2[a]	7.7[c]	0.1	<0.001	<0.001	0.123

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

Table 4.6 Apparent ileal digestibility (AID) of gross energy (GE) and nutrients in experimental diets (DM basis).

	Species			Fractions				*P*-value		
Item, %	*B. napus*	*B. juncea*	SEM	Parent meal	Light fraction	Heavy fraction	SEM	Species	Fractions	Species × fractions
DM	52.5	55.7	1.2	53.1[b]	58.8[a]	50.3[b]	1.2	0.038	<0.001	0.637
GE	56.7	59.7	1.2	57.0[b]	63.0[a]	54.6[b]	1.4	0.038	<0.001	0.674
CP	68.0	70.1	1.0	69.5[a]	71.5[a]	66.2[b]	1.2	0.067	0.001	0.809
Indispensable AA										
Arg	80.8	82.2	1.0	81.6[a]	83.7[a]	79.2[b]	1.1	0.067	<0.001	0.554
His	78.6	80.5	0.9	79.5[ab]	81.3[a]	77.7[b]	0.1	0.023	0.003	0.848
Ile	70.2	72.6	1.2	71.3[ab]	73.9[a]	69.2[b]	1.3	0.034	0.007	0.752
Leu	73.1	74.3	1.2	73.7[ab]	75.9[a]	71.4[b]	1.3	0.266	0.005	0.867
Lys	71.9	72.8	1.2	72.8[ab]	74.5[a]	69.7[b]	1.3	0.392	0.003	0.797
Met	78.4	79.6	1.1	79.2[ab]	80.6[a]	77.3[b]	1.2	0.159	0.011	0.902
Phe	74.9	76.2	1.2	75.1[ab]	78.0[a]	73.4[b]	1.3	0.207	0.002	0.837
Thr	65.5	67.4	1.4	66.3[ab]	69.8[a]	63.3[b]	1.5	0.136	0.001	0.810
Trp	74.2	74.1	1.3	73.0[b]	76.8[a]	72.7[b]	1.4	0.914	0.004	0.737
Val	68.7	71.0	1.3	69.3[ab]	72.5[a]	67.6[b]	1.4	0.050	0.005	0.650
Dispensable AA										
Ala	80.8	82.2	1.0	81.6[ab]	83.7[a]	79.2[b]	1.1	0.250	0.004	0.818
Asp	78.6	80.5	0.9	79.5[ab]	81.3[a]	77.7[b]	0.1	0.030	0.001	0.676
Cys	70.2	72.6	1.2	71.3[ab]	73.9[a]	69.2[b]	1.3	0.479	0.014	0.520
Glu	73.1	74.3	1.2	73.7[b]	75.9[a]	71.4[b]	1.3	0.590	<0.001	0.764
Gly	71.9	72.8	1.2	72.8[ab]	74.5[a]	69.7[b]	1.3	0.973	0.001	0.828
Pro	78.4	79.6	1.1	79.2[b]	80.6[a]	77.3[b]	1.2	0.090	<0.001	0.292
Ser	74.9	76.2	1.2	75.1[ab]	78.0[a]	73.4[b]	1.3	0.235	0.004	0.684
Tyr	65.5	67.4	1.4	66.3[b]	69.8[a]	63.3[b]	1.5	0.062	0.001	0.695
Total AA	74.2	74.1	1.3	73.0[ab]	76.8[a]	72.7[b]	1.4	0.144	0.002	0.884

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

Table 4.7 Standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) in experimental diets (DM basis).

	Species			Fractions				*P*-value		
Item, %	*B. napus*	*B. juncea*	SEM	Parent meal	Light fraction	Heavy fraction	SEM	Species	Fractions	Species × fractions
CP	73.0	75.1	1.3	74.3^{ab}	76.5^{a}	71.3^{b}	1.3	0.052	0.001	0.789
Indispensable AA										
Arg	83.7	85.1	1.0	84.5^{ab}	86.5^{a}	82.1^{b}	1.0	0.086	<0.001	0.632
His	87.5	82.7	1.0	81.7^{ab}	83.5^{a}	80.0^{b}	1.0	0.019	0.004	0.891
Ile	72.9	75.3	1.4	73.9^{ab}	76.6^{a}	72.1^{b}	1.5	0.036	0.008	0.773
Leu	75.6	76.8	1.4	76.2^{ab}	78.4^{a}	74.0^{b}	1.4	0.254	0.005	0.891
Lys	75.0	76.1	1.4	76.0^{ab}	77.6^{a}	73.0^{b}	1.4	0.287	0.003	0.792
Met	80.2	81.5	1.2	81.0^{ab}	82.4^{a}	79.1^{b}	1.3	0.137	0.013	0.923
Phe	77.2	78.5	1.3	77.5^{ab}	80.3^{a}	75.8^{b}	1.4	0.201	0.003	0.852
Thr	70.1	72.2	1.7	70.5^{ab}	74.4^{a}	68.1^{b}	1.7	0.108	0.002	0.824
Trp	78.9	79.5	1.9	78.0^{b}	81.9^{a}	77.8^{b}	1.9	0.619	0.003	0.738
Val	72.1	74.5	1.5	72.8^{ab}	75.9^{a}	71.1^{b}	1.6	0.044	0.006	0.665
Dispensable AA										
Ala	73.5	74.9	1.4	74.1^{ab}	76.7^{a}	71.8^{b}	1.5	0.233	0.005	0.863
Asp	70.1	72.7	1.6	71.2^{ab}	74.6^{a}	68.3^{b}	1.7	0.035	0.001	0.754
Cys	70.0	71.3	1.7	70.2^{ab}	73.5^{a}	68.2^{b}	1.8	0.350	0.013	0.545
Glu	86.9	87.4	1.3	86.6^{b}	89.9^{a}	85.1^{b}	1.4	0.491	<0.001	0.687
Gly	74.8	74.8	2.6	74.5^{ab}	78.3^{a}	71.6^{b}	2.7	0.971	0.002	0.679
Pro	87.2	90.2	3.4	87.3^{ab}	92.0^{a}	86.8^{b}	3.4	0.012	0.001	0.187
Ser	74.5	76.0	1.5	74.8^{ab}	78.0^{a}	72.9^{b}	1.6	0.206	0.006	0.733
Tyr	78.8	80.6	1.1	78.9^{b}	82.2^{a}	77.9^{b}	1.1	0.059	0.001	0.680
Total AA	76.8	78.4	1.3	77.3^{ab}	80.1^{a}	75.4^{b}	1.4	0.122	0.002	0.873

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

Table 4.8 Apparent ileal digestibility (AID) of dry matter (DM) and gross energy (GE), and standardized ileal digestibility (SID) of amino acids (AA) in *Brassica (B) napus* and *B. juncea* parent canola meals (CM) and their air-classified fractions (DM basis).

	Species			Fractions				*P*-value		
Item, %	*B. napus*	*B. juncea*	SEM	Parent meal	Light fraction	Heavy fraction	SEM	Species	Fractions	Species × fractions
AID										
DM	34.7	40.7	2.2	35.7[b]	49.1[a]	28.3[b]	2.6	0.050	<0.001	0.433
GE	43.9	47.3	2.2	41.7[b]	57.2[a]	37.8[b]	2.5	0.194	<0.001	0.704
SID										
CP	72.8	75.6	2.2	73.7[ab]	78.8[a]	70.1[b]	2.2	0.126	0.001	0.875
Indispensable AA										
Arg	80.7	83.2	1.6	82.1[a]	85.6[a]	78.2[b]	1.8	0.057	<0.001	0.591
His	78.6	81.8	1.6	80.2[ab]	83.1[a]	77.3[b]	1.7	0.020	0.004	0.877
Ile	69.1	73.3	2.2	70.8[ab]	75.4[a]	67.5[b]	2.4	0.033	0.007	0.748
Leu	71.9	74.1	2.1	73.0[ab]	77.0[a]	69.0[b]	2.3	0.231	0.004	0.876
Lys	73.4	75.1	2.1	75.0[a]	77.5[a]	70.1[b]	2.3	0.315	0.003	0.765
Met	79.5	81.5	1.8	80.8[ab]	82.9[a]	77.8[b]	2.0	0.140	0.012	0.927
Phe	71.7	74.3	2.2	72.2[ab]	78.0[a]	68.8[b]	2.4	0.175	0.002	0.825
Thr	66.5	69.9	2.4	68.0[ab]	73.3[a]	63.2[b]	2.6	0.101	0.001	0.819
Trp	76.8	77.5	2.1	75.1[b]	81.6[a]	74.7[b]	2.2	0.715	0.003	0.706
Val	69.2	73.0	2.2	70.3[ab]	75.4[a]	67.6[b]	2.4	0.045	0.005	0.651
Dispensable AA										
Ala	72.4	74.7	2.2	73.4[ab]	77.7[a]	69.5[b]	2.4	0.224	0.005	0.856
Asp	66.5	71.3	2.3	68.7[ab]	74.5[a]	63.6[b]	2.6	0.027	<0.001	0.705
Cys	67.0	68.7	2.4	67.1[ab]	72.4[a]	64.0[b]	2.6	0.432	0.012	0.575
Glu	81.3	82.4	1.8	80.7[b]	87.6[a]	77.2[b]	1.9	0.507	<0.001	0.656
Gly	70.5	70.7	2.9	70.1[ab]	76.4[a]	65.4[b]	3.1	0.916	0.001	0.696
Pro	73.7	78.6	4.0	73.4[b]	83.2[a]	71.8[b]	3.9	0.038	<0.001	0.165
Ser	68.7	71.7	2.3	69.6[ab]	75.5[a]	65.6[b]	2.6	0.174	0.003	0.705
Tyr	75.1	78.5	1.7	75.5[b]	81.6[a]	73.5[b]	1.9	0.049	0.001	0.699
Total AA	71.9	74.8	2.1	72.8[a]	77.9[a]	69.2[b]	2.3	0.054	0.001	0.784

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

Chapter 5 Feeding increasing dietary inclusions of extruded Brassica juncea canola expeller-pressed cake on growth performance, carcass characteristics, and jowl fatty acids of growing-finishing pigs

5.1 Abstract

The energy value of canola meal is considered low because of its relatively greater fibre and depleted oil content. *Brassica (B) juncea* is a novel canola species with thinner seed coat and reduced fibre, but twice the glucosinolate content of *B. napus*. Remaining oil in canola cake provides greater dietary energy compared with solvent-extracted meal. Extrusion prior to expeller pressing may increase fat and protein digestibility and decrease the antinutritive effects of glucosinolates. A total of 880 pigs (38 kg), housed in 40 pens by sex, were fed 0, 5, 10, 15, or 20% extruded *B. juncea* expeller-pressed cake (EPC) to slaughter weight (120 kg) to evaluate the effects on growth performance, dressing, carcass traits, and jowl fatty acids. Diets provided 9.6 MJ net energy (NE) and 1.0, 0.9, 0.8, 0.7, and 0.7 g standardized ileal digestible Lys:MJ NE over 5 growth phases (d 0–14, 15–35, 36–56, 57–74, d 75 to slaughter weight). Each 5% EPC inclusion linearly decreased ($P < 0.05$) feed disappearance (ADFI) by 46 g and weight gain (ADG) by 8 g, but did not affect gain:feed. Each 5% EPC inclusion linearly decreased ($P < 0.01$) carcass weight by 440 g, loin depth by 0.6 mm, and increased days on test by 0.43, but did not affect dressing, backfat thickness, lean yield, or carcass index. Each 5% EPC inclusion linearly increased ($P < 0.001$) mono- and polyunsaturated fatty acid content and iodine value by 0.8, 1.0 and 1.4 g/100 g of jowl fat, respectively. In conclusion, increasing dietary EPC inclusions decreased ADFI, ADG, carcass weight, loin depth, and increased jowl fat unsaturation. We attributed much of the decrease in feed intake to greater 3-butenyl (9.7 μmol/g) content in

extruded *B. juncea* canola expeller-pressed cake, a glucosinolate more bitter than others in conventional canola.

5.2 Introduction

Soybean meal is the most common supplemental protein source fed to livestock worldwide (Newkirk 2009), but production is limited in temperate regions due to heat units. Replacing soybean meal with canola coproducts may reduce pig feed cost (Woyengo et al. 2014). However, the dietary energy value of canola meal (CM), mostly from *Brassica napus*, is considered low compared with soybean meal because of its relatively greater dietary fibre (Newkirk 2009).

Brassica juncea is a novel yellow-seeded canola species with a thinner seed coat and therefore reduced fibre content compared with *B. napus* (Khajali and Slominski 2012). The reduced fibre content may result in a greater dietary energy value for *B. juncea* allowing greater inclusions in pig diets vs. *B. napus* (Le et al. 2012). However, *B. juncea* generally has more than double the glucosinolate content of typically sourced *B. napus* (Landero et al. 2012a), which may decrease feed intake of animals and negatively affect thyroid, liver, and kidney functions (Tripathi and Mishra, 2007). Extrusion of canola seed prior to expeller pressing may decrease the negative effects of glucosinolates by inactivating myrosinase, the enzyme that hydrolyzes glucosinolates to harmful breakdown compounds (Liang et al. 2002; Huang et al. 1995). Extrusion may also improve the digestibility of seed protein and fat in animals (Oryschak et al. 2010). If seed is expeller-pressed rather than solvent-extracted, oil remains (8.5 - 20%; Spragg and Mailer, 2007; Grageola et al. 2013) in the cake, increasing its dietary energy value compared with meal (Seneviratne et al. 2010). Extruded *B. juncea* canola expeller-pressed cake might, therefore, be a cost attractive feedstuff for feeding pigs. However, remaining oil in canola cake is

rich in unsaturated fatty acids that may decrease fat firmness and compromise pork quality (Myer et al. 1992; Benz 2010).

To our knowledge, research on the effects of feeding extruded *B. juncea* canola expeller-pressed cake to growing-finishing pigs has not been published. The hypotheses of our study were that feeding increasing dietary inclusions of extruded *B. juncea* canola expeller-pressed cake to pigs would not affect growth performance and carcass traits, but pork fat firmness would decrease with increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake. The objective was therefore to compare the growth performance, dressing, carcass characteristics, and jowl fatty acid profile of growing-finishing pigs fed 0, 5, 10, 15 or 20% extruded *B. juncea* canola expeller-pressed cake housed in a pig commercial production facility.

5.3 Materials and methods

5.3.1 *Brassica juncea*, extrusion and expeller pressing

Brassica juncea canola seed was sourced from southern Saskatchewan, Canada. The seed was delivered to Apex Nutri-Solutions Inc. (Edgbert, AB) for extrusion (model X155, Wenger, Sabetha, KS; flow rate 1050 kg h^{-1}, extrudate temperature 90ºC) and expeller pressing (model ME-200, Anderson International Corp., Stow, OH; flow rate 600kg h^{-1} expeller-pressed cake temperature 110ºC). The ground cake (Table 5.1) was trucked to Sunhaven Feed Mill (Irma, AB) where the experimental diets were mixed.

5.3.2 Animals and Diets

Animal procedures were reviewed by the University of Alberta Animal Care and Use Committee: Livestock, and followed guidelines established by the Canadian Council on Animal Care (2009). The study was conducted at a commercial contract pig grower where one building was set up as a test barn (Lougheed, AB).

In total, 880 crossbred pigs [440 barrows and 440 gilts; Duroc (Line 380, PIC, Winnipeg, MB) × Large White/Landrace (Line 277; Fast Genetics; Saskatoon, SK)] with an initial age of 62 d at 30 kg body weight (BW) were housed in 40 pens, 22 pigs per pen.

Experimental diets (Table 5.2 and 5.3) were formulated to provide 9.6 MJ kg^{-1} net energy (NE) and 1.0, 0.9, 0.8, 0.7 and 0.7 g SID lysine MJ^{-1} NE for Grower 1 (days 0 – 14), Grower 2 (days 15 – 35), Grower 3 (days 36 – 56), Finisher 1 (days 57 – 74), and Finisher 2 (days 75 to market weight) phases, respectively. Grower 1 and 2 diets included 25% and Grower 3, Finisher 1 and 2 diets included 20% wheat distillers dried grain with solubles (DDGS). Increasing extruded *B. juncea* canola expeller-pressed cake (EPC) inclusions substituted lentil (Grower 1 only), barley, wheat, and soybean meal (Grower phases only) in diets on a least-cost basis. Within growth phase, diets were formulated to be isocaloric and isolysinic, with constant ratios of Thr, Met, Cys and Trp to Lys. Diets were fortified with premixes to exceed mineral and vitamin requirements (National Research Council, 1998).

5.3.3 Experimental Design and Measurements

The study was conducted as a randomized complete block design. The rectangular room was divided into 4 location area blocks of 10 pens each, five pens of barrows and five pens of gilts. The five dietary regimens were randomized within gender and block providing eight replicate pens per dietary EPC inclusion. Pen was the experimental unit for growth performance, dressing, carcass, and jowl lipid variables.

The flooring of each pen (6.15 × 2.39 m) was fully-slatted concrete, the sidewalls were concrete paneling with open slotting, and the front gate was made of polyvinyl chloride planking hinged at both ends. Pens were equipped with 1 wet/dry feeder (model F1-115; Crystal Spring Hog Equipment, St. Agathe, MB) providing 2 opposing feeding places (Gonyou and Lou, 2000) located halfway along a dividing sidewall between pens. An additional bowl drinker was located

on the opposite pen sidewall towards the back of the pen. The room ventilation was by negative pressure and was maintained within the thermo-neutral zone of the pigs. Fluorescent tube lamps provided a 12-h light (0700 to 1900 h), 12-h dark cycle. Pigs had free access to water and feed. Diets were provided in a mash form. Pigs were injected with porcine circovirus vaccine (CircoFLEX; Boehringer Ingelheim, Vetmedica, GmbH, Ingelheim, Germany) on the day of weaning.

Pigs were group-weighed at the initiation of feeding the experimental diets (day 0), days 14, 35, 56, 74, 85 and weekly thereafter. Feed was delivered to each pen, weighed and tracked using a robotic feed delivery system (Feed Logic Co., Willmar, MN). Feed remaining in each pen feeder on weigh days was estimated by levelling the feed, measuring to the top of the feeder hopper, and calculating the leftover feed weight using an equation that accounted for diet bulk density (Seneviratne et al. 2010).

Pigs reaching a target market weight of 120 kg were weighed, trucked and slaughtered at Maple Leaf (Brandon, MB) following commercial procedures. Individual warm carcasses were weighed including head, feet, omental fat, and kidneys. Carcass backfat and loin depth were measured between the caudal 3rd and 4th ribs, 7 cm off the midline using a light reflectance probe (Destron PG-100, Destron Technologies, Markham, ON; Pomar and Marcoux 2003). To establish pork lipid profile, 2 pigs per pen were shipped for slaughter at Sunterra Meats (Trochu, AB), where a piece of jowl from their carcasses was collected. Jowl fat samples were dissected free of skin, lean and connective tissue before grinding and homogenization at Agri-Food Discovery Place, University of Alberta (Edmonton, AB).

5.3.4 Chemical Analysis

Samples of *B. juncea* EPC and phase diets were ground in a centrifugal mill through a 1-mm screen (model ZM200, Retsch GMbH, Haan, Germany). Diets and *B. juncea* EPC were analysed

for moisture (method 934.01), CP (method 990.03), amino acids (AA) (method 982.30E a, b, c, Chp. 45.3.05; Otter 2012), ether extract (method 920.39 a), crude fibre (method 978.10), acid detergent fibre inclusive of residual ash (method 973.18 a, b, c, d), neutral detergent fibre (Holst, 1973), ash (method 942.05), calcium and phosphorus (method 985.01 a, b, d) using AOAC (2006) methods at the Agricultural Experiment Station Chemical Laboratories, University of Missouri, Columbia, MO. Samples of *B. juncea* EPC were also analysed for available Lys [reactive Lys with its free ε-amino group converted to homoarginine by guanidination; (method 975.44; Maga 1981)]. The glucosinolate profile of *B. juncea* EPC was determined by gas-liquid chromatography (Daun and McGregor 1981) at POS Bio-Sciences, Saskatoon, SK. The fatty acid profile of *B. juncea* EPC and jowl fat samples was determined by gas-liquid chromatography (method 996.06; Benz et al. 2010) at the University of Missouri and University of Alberta, respectively.

5.3.5 Calculations

Pig and feed weight data were used to calculate pen average daily feed disappearance (ADFI), daily weight gain (ADG), and gain:feed (G:F). Animals that were removed were accounted for by dividing the number of pigs × days to the date of removal plus number of pigs remaining in the pen × days to the date the growth phase ended. Carcass dressing was expressed as warm carcass weight divided by farm ship weight to slaughter. Carcass lean yield (%) was estimated using the equation $68.1863 - 0.7833 \times$ backfat, mm $+ 0.0689 \times$ loin, mm $+ 0.0080 \times \text{backfat}^2 - 0.0002 \times \text{loin}^2 + 0.0006 \times$ backfat × loin (Pomar and Marcoux 2003). Carcass index was determined using the packer's grid that interpolated warm carcass weight and estimated pork yield (Pomar and Marcoux 2003). The iodine value of jowl fat was calculated using the equation (AOCS, 1998) = C16:1 × 0.95 + C18:1 × 0.86 + C18:2 × 1.732 + C18:3 × 2.616 + C20:1 × 0.785 + C22:1 × 0.723.

5.3.6 Statistical Analysis

Data were analyzed using the MIXED procedure of SAS software (version 9.2, SAS Inst. Inc., Cary, NC, USA). The model included dietary inclusion of *B. juncea* EPC, sex, and interaction as fixed effects. Pen was considered the experimental unit. Block was the random term. Phase was the repeated term for analyses of overall growth performance variables. Contrasts tested linear and quadratic trends of the dietary inclusion of *B. juncea* EPC. The proportion of pigs dead or removed due to disease or injury and the proportion of pigs remaining in pens after shipping for slaughter each week were analyzed with a generalized linear model (GENMOD procedure of SAS) using a binomial distribution and the logit link function. To test the hypotheses, $P < 0.05$ was considered significant.

5.4 Results

The nutrient and glucosinolate content of *B. juncea* EPC is summarized in Table 5.1. Its NE value was estimated at 9.7 MJ kg^{-1} (Eq. 5, Noblet et al 1994). A single glucosinolate, 3-butenyl, represented 89% of total content.

During the study, 57 pigs were removed and excluded from analyses. Reasons were death or euthanasia (23), lame (20), poor growth (4), scours (3), tail biting (3), leg abcesses (2), and belly hernia (2). Increasing *B. juncea* EPC inclusion or sex had no effect on the proportion of pigs that died or were removed by growth phase or for the entire trial.

No interaction between increasing dietary EPC inclusion and sex was observed for any variable analyzed. The effect of sex is not reported, as typical sex differences were observed. Pigs were first shipped to slaughter on day 74. The proportion of pigs remaining in pens after the start of shipping for slaughter was not different until day 94, so performance variables are reported to day 85.

Average BW on day 0 was 38.2 ± 1.2 kg. Increasing dietary EPC inclusion linearly decreased ($P < 0.01$) pig BW at days 14, 35, 56, 74 and 85 (Table 5.4). Pigs fed 20% EPC were 2.7 kg lighter than controls at day 85. For the entire trial (d 0 to 85), increasing dietary EPC inclusion linearly decreased ($P < 0.001$) ADFI (Table 5.4). Increasing dietary EPC inclusion linearly decreased ($P < 0.05$) ADFI for days 0 to 14, days 15 to 35, days 36 to 56 and days 75 to 85, but did not affect ADFI for days 57 to 74. For the entire trial, increasing dietary EPC inclusion linearly decreased ($P < 0.005$) ADG. Increasing dietary EPC inclusion linearly decreased ($P \leq 0.01$) ADG for days 0 to 14, days 15 to 35, and days 57 to 74, but did not affect ADG for days 36 to 56 and days 75 to 85. For the entire trial, increasing dietary EPC inclusion had no effect on G:F. However, increasing dietary EPC inclusion linearly increased ($P < 0.05$) G:F for days 0 to 14 and days 15 to 35.

Increasing dietary EPC inclusion linearly decreased ($P < 0.05$) farm ship weight to slaughter, carcass weight, loin depth, and days on test (Table 5.5). Each 5% increase in dietary EPC inclusion, increased days on test by 0.43. Dressing, backfat thickness, lean yield, and index were not affected by increasing dietary EPC inclusion. Increasing dietary EPC inclusion linearly decreased ($P < 0.05$) C14:0, C16:0, C18:0, and saturated fatty acid (SFA) content and linearly increased ($P < 0.001$) C18:1, C18:2, C18:3, monounsaturated fatty acid (MUFA), polyunsaturated fatty acid (PUFA) content, and iodine value in the jowl fat (Table 5.6).

5.5 Discussion

5.5.1 Considerations for calculations and statistical analysis

For this experiment, calculations and statistical analysis reflected commercial scale pork production. On arrival to the barn, incidence of *Streptococcus suis* delayed the start of the trial until pigs averaged 38 kg (approximately 70 d of age). Removal rate (6.5%) during the trial was

nearly double that in the two experiments of Jha et al. (2013), yet mortality was only twice the barn historic rate (1.3%). Calculation of performance variables properly accounted for mortalities and animals removed. We confirmed that proportions of pigs removed by phase and over the entire trial were not confounded by increasing dietary EPC inclusion and sex (Proc Genmod).

Forty-eight feeders and corresponding water lines could not be practically detached from pen walls to be weighed at every weigh day. Measuring distance from the levelled feed to the top of the feeder hopper and diet bulk density were highly repeatable. The equation used resulted in a 0.1% error in the estimation of feed remaining in feeders on weigh days (Seneviratne et al. 2010). Considering the tonnage of phase feed consumed by group-housed pigs under commercial conditions, such error is small even compared with feed wastage (2%; Gonyou and Lou 2000).

Shipping pigs when they reach individual slaughter weight despite being over several weeks is the norm in Canada to attain a narrow carcass weight range stipulated by packers (Pomar and Marcoux 2003). To keep the statistical analysis of growth phase and overall performance variables reliable, we determined when the proportion of pigs remaining in pens started to differ (day 94; Proc Genmod) and conducted the analyses until a time point before that (day 85), which more closely matched the timing of the collection of carcass data. Furthermore, we confirmed that these results did not differ from those of the analysis conducted the last day pens were complete (day 74). Therefore, the statistical analysis of the data from this study reflected typical, commercial-scale, pork production and slaughter conditions.

5.5.2 Brassica juncea canola

Yellow-seeded *B. juncea* has recently been labelled the third canola species in Canada (Canadian Grain Commission 2011). *Brassica juncea* has agronomic advantages over conventional *B. napus* in terms of earlier maturation (Khajali and Slominski 2012), thermo-tolerance, and disease resistance. *Brassica napus* remains the species for cultivation in Black and

Dark Grey soils, but *B. juncea* yields better in the Brown and Dark Brown soils of the warmer, low-rainfall zones of the North American Great Plains (Miller et al. 2003), expanding canola production where *B. napus* yield is decreased.

5.5.3 Extrusion and expeller pressing

Extrusion compresses feedstocks using single or twin screws within a cylindrical barrel through a die nozzle. The decreasing channel between the screw and barrel combined with the reducing flight helix angle create shearing force, high pressure, and generate autogenous heat to cook feedstuffs (Lusas et al. 1988). Shearing may disrupt cell wall structures (fibre) and phytate that trap nutrients within their matrices increasing protein denaturation, fat solubility, and mineral availability, thus increasing AA, lipid and phosphorus digestibility, respectively (Camire 1991). Extrusion may also inactivate antinutritional factors (Lusas et al. 1988; Camire 1991). Extrusion processing thus alters the physical and chemical properties of feedstuffs (Fadel et al. 1988) and may improve the nutritional quality of coproducts (Oryschak et. al. 2010).

Oil content in canola seed is approximately 45% (Miller et al., 2003). Expeller pressing of seed without subsequent solvent extraction reduces the proportion of oil harvested. Yet oil remains in the cake resulting in greater dietary energy value. Seed maturity, moisture content, and ambient temperature at pressing affect oil content in cakes (Spragg and Mailer, 2007). Furthermore, torque, screw speed, flight angle and interruption that influence pressure exerted and pressing twice in tandem affect fat content in cakes that ranged from 8.5 to 20.0% (Grageola et al., 2013; Spragg and Mailer, 2007). The fat content in extruded *B. juncea* canola expeller-pressed cake was 16.8%, which was greater than 13.3, 13.8 and 12.0% reported by Seneviratne et al. (2010, 2011) and Woyengo et al. (2010), respectively. The high fat content of our extruded, expeller-pressed cake indicates that this plant could have achieved greater oil recovery, a processing step subsequent and independent of extrusion. Greater remaining oil content in cake

reduces producers' cost of fat supplementation to concentrate feed energy for young monogastric animals.

Oilseed extrusion prior to pressing may increase oil yield, due to increased oil liquidity (the seed is puréed) beyond that achieved by conventional seed pre-conditioning or flaking by steam-rolling (Mullan et al., 2000) that it replaces and precludes the need for twice-pressing. It may also increase cake nutrient availability (Oryschak et al., 2010) and decrease antinutritional factors (Huang et al., 1995) due to the additive effects of short-lived pressure exerted on the seedstock in tandem, first by the extruder (Liang et al., 2002), followed by the expeller press.

5.5.4 Growth performance and effects of glucosinolates

Increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake linearly decreased ADFI, ADG and BW. A similar decrease in growth performance was reported by Landero et al. (2013) feeding increasing levels of *B. juncea* canola meal to weaned pigs and Seneviratne et al. (2010) feeding increasing levels of *B. napus* expeller-pressed cake to growing-finishing pigs. Feed intake can be affected by certain nutrients (fat, fibre, AA), dietary energy level, and antinutritional factors (Nyachoti et al., 2004). We formulated phase diets to the same NE and SID AA/MJ NE, but dietary fat and fibre content increased with increasing inclusion of extruded *B. juncea* canola expeller-pressed cake. Either one or both additively could have decreased feed intake (Myer et al., 1992). Increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake from 0 to 20% only increased NDF by 1.3%-units without decreasing carcass dressing. The magnitude of this dietary fibre increment was only one-fifth of what we imposed on growing-finishing pigs housed in this barn before by feeding increasing coproduct inclusions from 2 to 50% without decreasing overall ADFI (Experiment 2, Jha et al. 2013). This increase in dietary fibre content was likely of lesser importance than the 2.9% increase in dietary fat content. Thacker (2009) reported that 6% liquid canola oil inclusion,

resulting in 9% fat in diets, did not decrease pig feed intake. In our study, fat content of diets was lower than 6%. Therefore, differences in energy and AA levels, the increase in dietary fibre or fat content were not likely the main cause of decreased ADFI. We instead attributed the decreased ADFI primarily to the effect of glucosinolates in *B. juncea*. The pattern of reduction in feed intake observed in response to increasing dietary inclusions of extruded *B. juncea* canola expeller-pressed cake closely match that observed by Landero et al. (2013) who fed pigs 0 to 24% *B. juncea* CM from 7 to 25 kg. The reduction in feed intake observed here was also consistent with the *B. juncea* meal diet being the least preferred by nursery age pigs in two preference trials reported by Landero et al. (2012a).

Glucosinolates are sulphur-containing secondary plant metabolites in *Brassica* spp. seeds (Tripathi and Mishra, 2007). Intact glucosinolates can be biologically inactive moleculae (Liang et al., 2002), but once hydrolysed, these release harmful breakdown products: Isothiocyanates are responsible for the meal bitterness (Mithen et al., 2000), thiocyanates disrupt thyroid function (Wallig et al., 2002), and nitriles cause methemoglobinemia (Cockburn et al., 2013). Growing-finishing pigs tolerate 2.5 μmol/g diet of glucosinolates without affecting growth performance (Newkirk, 2009). By increasing dietary inclusion of *B. napus* expeller-pressed cake, Landero et al. (2012b) increased total glucosinolate content to 2.2 μmol/g diet, yet did not observe a decrease in feed intake in weaned pigs. Including 20% extruded *B. juncea* canola expeller-pressed cake in our study diets also resulted in 2.2 μmol/g diet of total glucosinolates, but in contrast, it linearly decreased ADFI, ADG, and BW in older growing-finishing pigs. Each 5%-unit increase in dietary inclusion of extruded *B. juncea* canola expeller-pressed cake increased daily glucosinolate intake of pigs by 2.5 μmol. Each μmol/g increase of dietary glucosinolates decreased ADFI and ADG by 94 and 13 g, respectively. This discrepancy between studies is likely due to differences in glucosinolate profiles among canola species fed. More than 120 types of glucosinolates have

been identified (Chen and Andreasson, 2001). Unlike contemporary extruded *B. napus* expeller-pressed cake sourced from the same processor that tested relatively high in 3-butenyl (2.1 µmol/g), 2-OH-3-butenyl (3.3 µmol/g) and 4-OH-3-CH3-indolyl (2.3 µmol/g;), the extruded *B. juncea* canola expeller-pressed cake fed in our study was particularly high in 3-butenyl (9.66 µmol/g), a bitterer glucosinolate that causes greater reduction of feed intake. Breeding programs should therefore target decreasing 3-butenyl in novel *B. juncea* seed cultivars as this could be the most likely cue to feed aversion (Kyriazakis and Emmans, 1992).

Heat treatment can decrease the negative effects of glucosinolates on animals by inactivating myrosinase (Tripathi and Mishra, 2007). Heat generated by single-screw extrusion in tandem with expeller pressing did not appear to decrease the negative effect of glucosinolates on feed intake of pigs in our study. This finding contrasts that reported by Spragg and Mailer (2007), who found 50% degradation of glucosinolates with expeller pressing alone. Providing external heat and adding moisture (i.e., pre-conditioning, twin-screw extrusion) might be more effective ways of inactivating antinutritional factors (Friesen et al., 1993). However, the autogenous heat generated from shearing was sufficient to alter the colour, smell and texture of extrudates (Camire, 1991). Ammonia can be added during extrusion to decrease glucosinolates (Huang et al., 1995). The cost of extrusion nonetheless would increase with the provision of heat and addition of substances. Heat from extrusion has also been reported to decompose glucosinolates (Huang et al., 1995; Liang et al., 2002). Heat-degraded products of glucosinolates may be toxic, but their profile and effects on pigs have not been characterized.

Pigs in our study fed 20% extruded *B. juncea* canola expeller-pressed cake had overall ADG of 882 g, which was lower than 904 g observed by Mullan et al. (2000), who also fed 20% of canola cake to growing-finishing pigs. Seneviratne et al. (2010) fed 22.5 – 18.0% of canola expeller-pressed cake to growing-finishing pigs and reported overall ADG of 931 g. The linear

decrease in ADG with increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake to isocaloric and isolysinic phase diets can be explained by the decreased feed intake, which cancelled out the beneficial effects of increased dietary energy from remaining oil content in extruded *B. juncea* canola expeller-pressed cake. Increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake did not affect overall G:F of pigs. Similar results were reported by Landero et al. (2012b), who fed 0–20% *B. napus* expeller-pressed cake to weaned pigs. The increase in G:F for d 0-14 and d 15-35 with increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake in this trial might be attributed to increasing dietary fat that was likely highly digestible.

5.5.5 Dressing, carcass traits and jowl fatty acid profile

Increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake in isocaloric and isolysinic phase diets decreased farm ship weight to slaughter, carcass weight, and loin depth. The reduction in these traits may have been a consequence of decreased feed intake with increasing extruded *B. juncea* canola expeller-pressed cake inclusion, which may have reduced AA intake, decreased protein deposition, and affected loin depth. Increases in dietary fibre content with increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake did not decrease dressing beyond that attained by 20% DDGS inclusion (Beltranena and Zijlstra, 2010). Increasing dietary fat content could increase carcass backfat and decrease leanness (Miller et al., 1990). We did not observe differences in lean yield and backfat thickness probably because the range in dietary fat was not large enough to affect carcass fat content.

Modern pig genetic lines have increased lean growth. The fatty acid profile of pork thus primarily reflects dietary fatty acid intake (Miller et al., 1990; Wood et al. 2008). Feeding unsaturated fats to pigs decreases pork fat firmness and may influence backfat layer and fat-muscle separation (bacon, ham; Wood et al., 2003), which may increase the incidence of miscuts

during pork cutting. Feeding unsaturated fats to pigs also affects the quality of processed pork products (Averette Gatlin et al., 2002) increasing their oiliness and colour deterioration, reducing shelf life and sensory attributes (Miller et al., 1990; Myer et al., 1992; Wood et al., 2003). Feeding cereal-based diets to pigs favours deposition of linoleic acid (C18:2), whose incorporation into adipose and muscle tissue is greater than that of other dietary fatty acids (Wood et al., 2008). Canola oil is high in unsaturated fatty acids (93%) with a medium content of C18:2 (21 vs. 55% in corn or soy oil) and high content of linolenic acid (C18:3; 11 vs. <1% in other vegetable oils except 8% in soy oil), both with low melting points. Pork fat firmness must therefore be an important consideration when feeding canola cakes to finishing pigs. In our study, jowl instead of belly tissue was collected for fatty acid analysis to not reduce the value of carcasses. Benz et al. (2010) reported that the response of jowl fatty acid profile to dietary fatty acid changes is similar to belly and backfat. Increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake increased MUFA (C18:1), PUFA (C18:2, C18:3) and decreased SFA (C14:0, C16:0 and C18:0) content in jowl fat. Similar enrichment of unsaturated fatty acids in adipose tissue was found by Busboom et al. (1991) who fed 20% intact and ground canola seed to pigs, and Jørgensen et al. (1996) who fed 0-16% rapeseed oil to pigs. Seneviratne et al. (2010), who fed up to 22.5-18.0% canola expeller-pressed cake to pigs, did not report such a trend, which might be attributed to lower oil content in cake and shorter feeding duration. Whittington et al. (1986) found that the ratio of C18:0:C18:2 was the best predictor of backfat firmness. We observed a linear decrease of 0.11 in this ratio in jowl for every 5%-units increment in dietary extruded *B. juncea* canola expeller-pressed cake inclusion. Iodine value linearly increased with increasing dietary inclusion of extruded *B. juncea* canola expeller-pressed cake, but it did not exceed the 70-75 g/100 g fat considered acceptable (Benz et al., 2010). The maximum iodine value in the current trial (67) was lower than that observed for pigs housed in the same test barn

fed 30% wheat or corn DDGS (Beltranena and Zijlstra, 2010). Thus, increased unsaturation of jowl fat did not affect pork fat firmness beyond acceptable iodine values in the present study.

Feed is the single largest cost of pig production. With increasing prices of traditional energy and protein feedstuffs, including coproducts have become cost-effective in pig diets (Beltranena and Zijlstra, 2011). The risks of including coproducts into pig diets can be mitigated by formulating diets using NE and SID AA (Zijlstra and Payne, 2007). Formulating diets in such manner cannot eliminate the negative effects of antinutritional factors. However, feed processing opens new opportunities for both, improving digestible nutrient content and mitigating the effects of anti-nutritional factors in coproducts. Processing conditions should be fine-tuned to maximize the beneficial effects on feedstuffs like canola extrudates and screw- or expeller-pressed cakes.

5.6 Conclusion

In conclusion, increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake linearly decreased overall ADFI, ADG, BW, farm ship weight to slaughter, carcass weight and loin depth. We attributed much of the decrease in feed intake to greater 3-butenyl (9.7 μmol/g) content in extruded *B. juncea* canola expeller-pressed cake, a glucosinolate more bitter than others found in conventional *B. napus*. Increasing the dietary inclusion of extruded *B. juncea* canola expeller-pressed cake increased jowl fat unsaturation and decreased C18:0:C18:2 ratio, but it did not compromise jowl fat firmness beyond acceptable levels as assessed by iodine value.

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Table 5.1 Analysed nutrient and glucosinolate content (as-is) of extruded *Brassica* (*B.) juncea* canola expeller-pressed cake (EPC).

Item (%)	*B. juncea* canola EPC
Moisture	5.0
Crude protein	34.4
Ether extract	16.9
Crude fibre	6.00
Acid detergent fibre	12.7
Neutral detergent fibre	19.5
Starch	3.1
Ash	6.3
Calcium	0.6
Phosphorus	2.1
Indispensable amino acids[z]	
Arginine	2.1
Histidine	0.9
Isoleucine	1.4
Leucine	2.4
Lysine	1.7
Methionine	0.6
Phenylalanine	1.4
Threonine	1.4
Tryptophan	0.4
Valine	1.8
Total amino acids	31.1
Lysine/crude protein, %	0.5
Available lysine[y]	1.6
Total glucosinolates[x], µmol/g	10.9
Fatty acid composition (% of total fatty acids)	
C16:0	4.7
C16:1	0.2
C18:0	2.5
C18:1 n-9	60.2
C18:2 n-6	15.4
C18:3 n-3	8.6
C20:0	0.6

Item (%)	*B. juncea* canola EPC
C20:1 n-9	1.4
SFA[w]	7.8
MUFA[v]	61.8
PUFA[u]	24.0

[z] Extruded *B. juncea* canola expeller-pressed cake contained the following dispensable amino acid (% as-is): alanine, 1.46; aspartic acid, 2.35; cysteine, 0.70; glutamic acid, 5.92; glycine, 1.65; proline, 2.23; serine, 1.25; tyrosine, 1.03.
[y] Analyzed as reactive Lys (free ε-amino group converted to homoarginine by guanidination).
[x] Extruded *B. juncea* canola expeller-pressed cake contained the following glucosinolates (μmol/g as-is): allyl, 0.20; 3-butenyl, 9.66; 4-pentenyl, 0.39; 2-OH-3-butenyl, 0.83; 2-OH-4-pentenyl, 0.19; CH_3-thiobutenyl, 0.16; phenylethyl, 0.21; CH_3-thiopentenyl, 0.08; phenylethyl, 0.19; 4-OH-3-CH_3-indolyl, 1.69.
[w] $\sum$ saturated fatty acids.
[v] $\sum$ monounsaturated fatty acids.
[u] $\sum$ polyunsaturated fatty acids.

Table 5.2 Diet composition (as-fed) and analysed nutrient content (standardized to 11% moisture) of Grower 1, Grower 2 and Grower 3 diets including increasing dietary inclusion of extruded *Brassica* (*B.*) *juncea* canola expeller –pressed cake (EPC) fed from d 0 – 14, d 15 – 35 and d 36 – 56, respectively.

	Grower 1[z]					Grower 2[z]					Grower 3[z]				
	B. juncea EPC (%)					*B. juncea* EPC (%)					*B. juncea* EPC (%)				
	0	5	10	15	20	0	5	10	15	20	0	5	10	15	20
Ingredient (%)															
Wheat	50.2	49.8	48.7	49.6	50.7	45.2	40.4	35.8	35.3	34.8	47.9	42.9	41.8	40.8	40.3
Wheat DDGS	24.6	24.8	24.6	24.8	24.7	25.0	25.0	25.0	25.0	25.0	20.0	20.0	20.0	20.0	20.0
Barley	-	-	-	-	-	13.5	15.2	16.9	12.5	8.1	17.5	19.7	15.9	12.1	7.7
Lentil	19.1	15.7	14.1	8.0	2.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
B. juncea canola EPC	-	5.0	10.0	15.0	20.0	-	5.0	10.0	15.0	20.0	-	5.0	10.0	15.0	20.0
Soybean meal	3.24	2.00	-	-	-	3.85	2.00	-	-	-	2.00	-	-	-	-
Limestone	1.43	1.37	1.34	1.36	1.39	1.34	1.28	1.26	1.26	1.26	1.32	1.27	1.21	1.17	1.17
Mono-di-calcium phosphate	0.11	0.10	0.10	0.05	0.05	-	-	-	-	-	-	-	-	-	-
L-Lysine HCl	0.45	0.45	0.45	0.45	0.45	0.43	0.43	0.43	0.37	0.32	0.42	0.42	0.37	0.31	0.26
Salt	0.40	0.40	0.40	0.40	0.40	0.39	0.39	0.38	0.38	0.38	0.43	0.43	0.42	0.42	0.42
Vitamin/mineral premix[y]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
L-Threonine	0.13	0.12	0.11	0.10	0.09	0.09	0.08	0.08	0.05	0.01	0.12	0.12	0.08	0.05	0.02
$CuSO_4 \cdot 5H_2O$	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	-	-	-	-	-
DL-Methionine	0.10	0.08	0.07	0.06	0.04	0.06	0.05	0.04	0.02	-	0.06	0.05	0.03	0.01	-
Phytase[x]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Analysed content (%)															
Moisture	11.5	11.2	10.8	10.5	10.2	11.7	11.4	11.1	10.7	13.3	11.8	11.4	11.1	10.7	10.3
Crude protein	19.5	20.0	20.4	21.0	21.5	18.6	19.1	19.5	20.6	21.7	16.9	17.3	18.4	19.5	20.7
Ether extract	2.84	3.40	3.94	4.52	5.08	2.94	3.70	4.47	5.22	5.98	2.81	3.57	4.33	5.08	5.84
Crude fibre	3.94	4.13	4.31	4.47	4.62	4.00	4.12	4.24	4.33	4.41	3.78	3.91	4.00	4.09	4.17
Acid detergent fibre	5.92	6.49	7.03	7.60	8.13	6.03	6.43	6.83	7.21	7.59	5.55	5.96	6.35	6.74	7.12
Neutral detergent fibre	19.1	20.0	20.7	21.7	22.5	20.3	20.8	21.3	21.3	21.4	19.0	19.6	19.7	19.8	19.8
Ash	4.42	4.54	4.65	4.84	5.07	4.28	4.39	4.53	4.73	4.94	4.07	4.18	4.34	4.50	4.71
Calcium	0.70	0.70	0.71	0.73	0.76	0.65	0.65	0.66	0.68	0.70	0.62	0.62	0.62	0.62	0.64
Phosphorus	0.60	0.63	0.65	0.68	0.71	0.58	0.60	0.61	0.63	0.65	0.52	0.54	0.56	0.58	0.60

[z] Grower 1, Grower 2, and Grower 3 diets were formulated to provide 9.6 MJ/kg NE, 1.0, 0.9 and 0.8 g SID lysine/MJ NE, 2.5, 2.4 and 2.2 g/kg available (non-phytate) phosphorus, respectively.

[y] Provided the following per kilogram of diet: Zn, 125 mg as ZnO; Fe, 100 mg as $FeSO_4$; Cu, 14 mg as $CuSO_4$; Mn, 25 mg as MnO; I, 0.3 mg as $Ca(IO_3)_2$; and Se, 0.3 mg as Na_2SeO_3; vitamin A, 6000 IU; vitamin D, 1000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg and vitamin B_{12}, 0.02 mg.
[x] Phyzyme XP 5000G, Danisco Animal Nutrition, Marlborough, Wiltshire, United Kingdom.

Table 5.3 Diet composition (as-fed) and analysed nutrient content (standardized to 11% moisture) of the Finisher 1 and Finisher 2 diets including increasing dietary inclusion of extruded *Brassica* (*B.*) *juncea* canola expeller –pressed cake (EPC) fed from d 57 – 74 and d 75 – to market weight, respectively.

	Finisher 1[z] *B. juncea* EPC (%)					Finisher 2[z] *B. juncea* EPC (%)				
	0	5	10	15	20	0	5	10	15	20
Ingredient (%)										
Wheat	44.3	39.3	38.2	37.4	36.9	49.7	48.6	47.9	47.4	46.5
Wheat DDGS	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Barley	26.3	28.4	24.7	20.6	16.2	23.1	19.4	15.1	10.7	6.7
Lentil	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
B. juncea canola EPC	-	5.0	10.0	15.0	20.0	-	5.0	10.0	15.0	20.0
Limestone	1.28	1.22	1.16	1.15	1.16	1.21	1.15	1.14	1.15	1.13
L-Lysine HCl	0.39	0.39	0.34	0.29	0.23	0.38	0.33	0.27	0.22	0.17
Salt	0.43	0.43	0.42	0.42	0.42	0.43	0.43	0.42	0.42	0.42
Vitamin/mineral premix	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.06
L-Threonine	0.11	0.10	0.07	0.04	0.01	0.11	0.08	0.04	0.01	-
DL-Methionine	0.04	0.03	0.01	-	-	0.02	0.01	-	-	-
Phytasex	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Analysed content (%)										
Moisture	11.9	11.6	11.2	10.8	10.5	11.9	11.5	11.1	10.8	10.4
Crude protein	16.3	16.6	17.7	18.9	20.0	15.5	16.6	17.7	18.9	20.0
Ether extract	2.86	3.63	4.38	5.14	5.89	2.87	3.63	4.38	5.14	5.89
Crude fibre	3.81	3.94	4.03	4.11	4.19	3.75	3.84	3.92	4.00	4.09
Acid detergent fibre	5.60	6.01	6.40	6.78	7.16	5.46	5.85	6.23	6.61	6.99
Neutral detergent fibre	19.7	20.3	20.4	20.4	20.5	19.6	19.7	19.8	19.8	19.9
Calcium	0.58	0.58	0.58	0.60	0.63	0.54	0.54	0.57	0.60	0.60
Phosphorus	0.49	0.51	0.53	0.56	0.59	0.47	0.49	0.53	0.56	0.56

[z] Finisher 1 and Finisher 2 diets were formulated to provide 9.6 MJ/kg NE, 0.7 g SID Lys/MJ NE and 2.2 g/kg available (non-phytate) phosphorus for both growth phase diets.

[y] Provided the following per kilogram: Zn, 125 mg as ZnO; Fe, 100 mg as FeSO4; Cu, 14 mg as CuSO4; Mn, 25 mg as MnO; I, 0.3 mg as Ca(IO3)2; and Se, 0.3 mg as Na2SeO3; vitamin A, 6000 IU; vitamin D, 1000 IU; vitamin E, 25 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; folic acid, 0.5 mg; thiamine, 1 mg; D-biotin, 0.1 mg and vitamin B12, 0.02 mg.

[x] Phyzyme XP 5000G, Danisco Animal Nutrition, Marlborough, Wiltshire, United Kingdom.

Table 5.4 Effect of feeding increasing level of extruded *Brassica* (*B.*) *juncea* canola expeller-pressed cake (EPC) on growth performance of growing-finishing pigs[z].

	B. juncea canola EPC (% of diet)						P-values	
Varibles	0	5	10	15	20	SEM	Linear	Quadratic
BW (kg)								
d 0	38.7	38.2	38.0	38.0	38.5	0.4	0.667	0.099
d 14	53.2	53.1	53.1	52.5	52.4	0.3	0.035	0.500
d 35	75.3	74.9	74.4	73.8	73.8	0.4	<0.001	0.575
d 56	92.7	92.2	93.0	90.7	90.1	0.6	0.002	0.271
d 74	107.3	106.7	107.2	105.5	104.6	0.7	0.002	0.286
d 85	114.6	112.9	113.8	113.0	111.9	0.8	0.004	0.771
ADFI (g)								
d 0-14	2225	2156	2185	2092	2019	31	<0.001	0.253
d 15-35	2700	2632	2639	2498	2476	37	<0.001	0.647
d 36-56	2845	2730	2716	2634	2562	61	<0.001	0.939
d 57-74	2747	2572	2729	2698	2557	83	0.308	0.693
d 75-85	2801	2637	2739	2576	2640	74	0.032	0.367
d 0-85	2658	2547	2605	2504	2447	39	<0.001	0.688
ADG (g)								
d 0-14	1066	1056	1044	1008	1017	15	0.001	0.757
d 15-35	1040	1030	1018	996	1006	12	0.011	0.538
d 36-56	825	828	889	811	797	19	0.206	0.014
d 57-74	818	816	786	779	746	21	0.010	0.633
d 75-85	845	789	751	782	752	29	0.175	0.273
d 0-85	917	904	898	896	882	10	0.003	0.924
Feed efficiency (g:g)								
d 0-14	0.48	0.49	0.48	0.48	0.50	0.01	0.023	0.122
d 15-35	0.38	0.39	0.39	0.40	0.40	0.01	<0.001	0.633
d 36-56	0.29	0.30	0.33	0.31	0.31	0.01	0.158	0.022
d 57-74	0.30	0.31	0.29	0.29	0.29	0.01	0.129	0.914
d 75-85	0.30	0.30	0.27	0.30	0.30	0.01	0.177	0.058
d 0-85	0.35	0.36	0.35	0.36	0.37	0.01	0.101	0.373

[z] Least-squares means based on 8 pen observations per extruded *B. juncea* canola expeller inclusion level with 22 pigs per pen.

Table 5.5 Effect of feeding increasing levels of extruded *B. juncea* canola expeller-pressed cake (EPC) on farm ship live weight to slaughter, carcass characteristics, and days on test[z]

	B. juncea canola EPC (% of diet)						*P*-value	
	0	5	10	15	20	SEM	Linear	Quadratic
Ship weight, kg	123.7	122.1	122.8	122.3	121.9	0.6	0.022	0.555
Carcass weight, kg	96.3	94.0	94.8	94.2	94.0	0.9	0.038	0.252
Dressing	0.79	0.78	0.78	0.78	0.78	0.7	0.652	0.755
Backfat, mm	16.3	15.8	16.2	16.2	15.8	0.3	0.492	0.894
Loin depth, mm	60.5	60.9	60.3	58.6	58.8	0.6	0.002	0.467
Lean yield, g/kg	616	619	617	616	618	2	0.981	0.952
Index	109.5	109.7	109.0	109.0	110.2	0.5	0.690	0.132
Days on test	95.4	94.7	95.7	97.4	96.8	0.6	0.001	0.852

[z] Least-squares means based on 8 pen observations per extruded *B. juncea* canola expeller – pressed cake inclusion with 20 pigs per pen.

Table 5.6 Effect of feeding increasing level of extruded *B. juncea* canola expeller-pressed cake (EPC) on jowl fat fatty acid profile[z]

	B. juncea canola EPC (% of diet)						*P*-value	
g/100g of fat	0	5	10	15	20	SEM	Linear	Quadratic
C8:0	0.9	0.5	0.7	0.6	0.4	0.1	0.063	0.947
C10:0	0.6	0.4	0.4	0.5	0.4	0.1	0.069	0.121
C14:0	1.9	1.6	1.7	1.7	1.6	0.1	0.030	0.048
C16:0	25.9	23.7	23.9	22.8	22.1	0.4	<0.001	0.252
C16:1	1.2	1.5	1.4	0.9	1.6	0.2	0.758	0.707
C18:0	14.9	14.1	12.7	13.2	12.7	0.4	<0.001	0.103
C18:1 n-9	41.5	43.7	44.6	44.8	44.5	0.6	<0.001	0.038
C18:2 n-6	11.2	12.7	13.2	13.9	14.6	0.3	<0.001	0.304
C18:3	0.1	0.2	0.2	0.3	0.7	0.1	<0.001	0.132
C20:1	0.2	0.6	0.3	0.2	0.3	0.1	0.556	0.100
Other fatty acids	1.5	0.9	1.3	1.1	1.0	0.3	0.257	0.594
SFA[y]	44.2	40.4	39.4	38.8	37.3	0.7	<0.001	0.056
MUFA[x]	42.9	45.8	45.8	45.9	46.4	0.6	<0.001	0.035
PUFA[w]	11.3	12.9	13.5	14.1	15.3	0.4	<0.001	0.554
C18:0/C18:2	1.32	1.12	0.96	0.96	0.88	0.04	<0.001	0.023
Iodine value	56.8	62.0	63.1	64.3	67.1	0.7	<0.001	0.090

[z] Least-squares means based on 8 pen observations per extruded *B. juncea* canola expeller-pressed cake inclusion with 2 pigs sampled per pen.
[y] $\sum$ saturated fatty acids.
[x] $\sum$ monounsaturated fatty acids.
[w] $\sum$ polyunsaturated fatty acids.

Chapter 6 Effects of feeding canola press-cake on diet nutrient digestibility and growth performance of weaned pigs

6.1 Abstract

Canola press-cake (CPC) is a co-product of biodiesel production from small to medium-scale processing plants that mechanically press canola seed without pre-pressing conditioning, flaking, cooking and post-pressing solvent extraction. The CPC contains 370 g/kg CP and 204 g/kg remaining oil. Thus, CPC could be a source of AA and energy in pig diets. Growth responses to increasing dietary CPC inclusion have not been extensively evaluated in young pigs. In total, 240 pigs (7.5 ± 0.31 kg) starting 1 week after weaning at 19 d of age were fed five wheat-based diets containing 0, 50, 100, 150, or 200 g/kg CPC replacing soybean meal in two phases (Phase 1 and 2). Diets were formulated to contain 10.3 and 10.1 MJ NE/kg and 1.2 and 1.0 g standardised ileal digestible (SID) Lys/MJ NE, respectively, and were fed for 2 weeks as Phase 1 (day 0–14) and 3 weeks as Phase 2 (day 15–35). Feed added and remaining and individual pigs were weighed weekly to calculate average daily feed intake (ADFI), average daily weight gain (ADG) and feed efficiency (G:F) per pen (four pigs per pen). Freshly-voided faeces were collected on day 12 and 13 and day 33 and 34 for Phase 1 and 2, respectively, to determine diet apparent total tract digestibility coefficient (CATTD) of gross energy (GE), crude protein (CP) and digestible energy (DE) value. Increasing dietary inclusion of CPC linearly reduced ($P < 0.05$) the CATTD of GE, diet DE and calculated NE values for Phase 1 and 2. Increasing dietary inclusion of CPC did not

affect overall (d 0–35) ADFI and ADG of pigs, but quadratically reduced ($P < 0.05$) ADFI for day 29–35, linearly increased ($P < 0.05$) ADG for day 15–21 and linearly reduced ($P < 0.05$) ADG for day 29–35. Increasing CPC inclusion linearly increased ($P < 0.05$) G:F for the overall trial and day 15–21 and quadratically increased ($P < 0.05$) G:F for day 8–14. In conclusion, feeding up to 200 g/kg of CPC reduced CATTD of GE and CP, but did not affect overall growth performance of weaned pigs fed phase diets balanced for NE and SID Lys/NE ratio.

6.2 Introduction

Canola oil for human consumption is mostly extracted in large-scale crushing plants from conditioned, flaked and cooked canola seed using post-pressing solvent extraction follow by refining (Newkirk, 2009). Canola oil is also used to produce biodiesel (Koh, 2007). Demand for biodiesel is increasing worldwide due to policies supporting renewable bio-diesel content in fuels, e.g., in Canada from 2% in 2013 to 5% in 2020 (CRFA, 2013), as alternative to petroleum diesel to reduce green-house gas emissions. Consequently, canola seed crushing and oil production will increase further. Due to lower infrastructure cost and equipment requirements, small to medium-scale biodiesel producers extract canola oil by simply pressing seed without pre-conditioning, flaking, cooking and post-pressing solvent-extraction (Beshada et al., 2008; Newkirk, 2010). The resulting cake after oil removal has not been defined by AAFCO (2015). The term canola press-cake (CPC) is used for this co-product that can be used for animal feeding.

Mechanical pressing alone extracts oil less efficiently than post-pressing solvent extraction. As a result, CPC contains more ether extract (EE) than solvent-extracted canola meal (120–200 vs. 30 g/kg; Klein-Hessling, 2007, NRC, 2012). The greater EE content in CPC indicates a greater energy value for pigs. Due to exclusion of cooking and desolventizing, CPC can be subjected to lower temperature during processing that may avoid AA damage due to excessive heating (Woyengo et al., 2010). However, the lower pre-pressing temperature may be insufficiently high to inactivate the enzyme myrosinase that hydrolyses glucosinolates to produce harmful break-down compounds (Tripathi and Mishra, 2007). With increasing availability in North America (Seneviratne et al., 2011), CPC could be an attractive feedstuff for swine providing AA and energy. The growth response of weaned pigs to increasing dietary inclusion of CPC has not been researched extensively.

The present study tested the hypothesis that pigs fed diets with increasing inclusion up to 200 g CPC/kg would have similar diet nutrient digestibility and growth performance provided that diets were balanced for NE value and SID AA content. The objectives were to evaluate the apparent total tract digestibility coefficient (CATTD) of dietary gross energy (GE) and crude protein (CP), diet digestible energy (DE) and calculated NE value and growth performance of weaned pigs fed diets containing 0, 50, 100, 150 and 200 g CPC/kg.

6.3 Materials and methods

6.3.1 Canola press-cake preparation

Regular *Brassica* (*B.*) *napus* canola seed was sourced from Apex Nutri-Solutions Inc. (Edberg, AB, Canada) and processed at Agri-Food Discovery Place, University of Alberta (Edmonton, AB, Canada) to produce CPC (Table 6.1). The seed was cleaned using a seed cleaner (model ASC-3; Agriculex, Guelph, ON, Canada) to remove dockage. Seed was then expeller-pressed at a rate of 240 kg/hr using a single-screw press (model AP-12; Reinartz, Neuss, NRW, Germany) to produce CPC and canola oil. The temperature of the cake at the press outlet was 65.6 ± 2.1°C. The CPC was allowed to cool to room temperature and subsequently roller-milled (Commercial Single Mill; IFA, Stanley, IA, USA) to break the cake into mash.

6.3.2 Animals and diets

Animal use and experimental procedures were approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care (CCAC, 2009). The study was conducted at the Swine Research and Technology Centre, University of Alberta (Edmonton, AB, Canada). In total, 240 crossbred pigs (Duroc × Large white/Landrace F_1; Hypor, Regina, SK, Canada) were weaned at 19 ± 1 days of age. After weaning, pigs were fed a common commercial starter diet for 5 days. Pigs were then selected based on average daily weight gain (ADG) for the first 5 d post-weaning and body weight (BW; 7.5 ± 0.31 kg). Pigs were divided within gender into heavy and light. One heavy

and one light barrow and gilt were then randomly placed in one of 60 pens, four pigs per pen. Subsequently, pigs were fed experimental diets.

Five pelleted wheat-based diets including 0 (control), 50, 100, 150 and 200 g CPC/kg to replace soybean meal were formulated to provide 10.3 and 10.0 MJ net energy (NE)/kg and 1.2 and 1.0 g standardised ileal digestible (SID) lysine/MJ NE and were fed for 14 (Phase 1, Table 6.2) and 21 d (Phase 2; Table 6.2), respectively. The NE value and SID AA coefficients of CPC were adopted from Grageola et al. (2013). Other AA were formulated as ideal ratio to Lys (NRC, 2012). Acid-insoluble ash (Celite 281; World Minerals, Santa Barbara, CA, USA) was included as indigestible marker to determine CATTD of dry matter (DM), GE and CP. The Phase 1 diets were mixed (3061; Marion Process Solutions, Marion, IA, USA) and cold-pelleted (PM1230; Buskirk Engineering, Ossian, IN, USA) at the Metabolic Unit, University of Alberta (Edmonton, AB, Canada). The Phase 2 diets were mixed and steamed-pelleted (70 hp; California Pellet Mill, Crawfordsville, IN, USA) at the Feedmill of the University of Alberta (Edmonton, AB, Canada).

6.3.3 Experimental design and measurements

The study was conducted as a randomised complete block design with 60 pens divided over 3 nursery rooms filled 2 weeks apart. Each room had 4 blocks representing areas within room with 5 pens. Pens of pigs within block were randomly allocated to be fed one of 5 dietary regimens during the 35-day study for a total of 12 replicate pens per treatment. Pens (1.1 m × 1.5 m) were equipped with a 4-space dry feeder (model N4-424; Crystal Spring, MB, Canada), a nipple drinker, polyvinyl chloride partitions and plastic flooring. Rooms were ventilated using negative

pressure, maintained within the thermo-neutral zone for the pigs and provided a 12-h light (0600-1800 h), 12-h dark cycle. Pigs had continuous access to feed and water.

To calculate average daily feed intake (ADFI), average daily weight gain (ADG) and feed efficiency (G:F), individual pigs, pen feed added and feed remaining were weighed weekly. To calculate CATTD of DM, GE and CP, freshly-voided faeces were collected immediately upon defaecation from 0800 to 1600 h by grab sampling from pen floors on d 12 and 13 for phase 1 and d 33 and 34 for phase 2. To avoid contamination of collected faeces, pens were washed prior to the collection to remove old faeces and feed spills. Faeces were pooled by pen and stored frozen at –20°C for storage. Afterwards, faeces were thawed, homogenised, sub-sampled and freeze-dried.

6.3.4 Chemical analyses

Samples of CPC, experimental diets and lyophilized faeces were ground through a 1-mm screen in a centrifugal mill (model ZM200, Retsch GmbH, Haan, Germany). The CPC was analysed for GE using an adiabatic bomb calorimeter (model 5003; Ika-Werke GMBH & Co. KG, Staufen, Germany), DM (method 930.15), CP (method 984.13A-D), ether extract (EE, method 920.39A), ash (method 942.05), acid detergent fibre (ADF, method 973.18A-D), neutral detergent fibre (NDF, Van Soest et al., 1991), total dietary fibre (method 985.29), starch (assay kit STA-20; Sigma, St. Louis, MO, USA), calcium (method 968.08), phosphorus (method 946.06), AA (method 982.30E) and available lysine (method 975.44) as per AOAC (2006). Diets were analysed for DM, GE, CP, EE, ash, ADF, NDF and acid-insoluble ash (McCarthy et al.,

1974). Faeces were analysed for DM, CP, acid-insoluble ash and GE. Based on results of chemical analyses including for the indigestible marker, CATTD of DM, GE and CP were calculated using the indicator method (Adeola, 2001). Diet DE values were calculated by multiplying diet GE by CATTD. The NE value of diets was calculated based on the DE value and chemical composition (CP, EE, starch and ADF) using equation (5) developed by Noblet et al. (1994) and adopted by NRC (2012). NE = 0.7 DE + 1.61 ether extract + 0.48 starch − 0.91 CP − 0.87 ADF.

6.3.5 Statistical analyses

Digestibility coefficients and growth performance data were analysed using the MIXED procedure of SAS (version 9.3, SAS Inst. Inc., Cary, NC, USA) with pen as the experimental unit. Overall G:F for each pen was calculated by dividing overall pen weight gain by overall pen feed intake. Normality and homogeneity of variance for each variable were confirmed by UNIVARIATE procedure with 'Normal' option and GLM procedure with 'Hovtest = Levene' option, respectively. For diet CATTD and energy value and overall G:F data, the model included CPC inclusion level as fixed effect and block was included as random effect. Weekly and overall growth performance data (except overall G:F) were analysed as repeated measures. The model included CPC inclusion level; week and their interactions as fixed effects and block as random effect with week as the repeated term. Pen nested within dietary treatments (CPC inclusion level) was the subject of the repeated measures. The first-order ante-dependence [ANTE(1)] variance-covariance structure was used based on the Bayesian information criterion (BIC) fit statistics.

Initial BW was included as a covariate to analyse growth performance data and affected ($P < 0.05$) ADFI and ADG but not G:F ($P > 0.05$). Two single-degrees of freedom orthogonal polynomial contrasts were used to test linear and quadratic effects of dietary inclusion of CPC (Littell et al., 2006). To test the hypothesis, $P < 0.05$ was considered significant.

6.4 Results

On as-is basis, CP, EE and available lysine content in CPC was 370, 204 and 22.5 g/kg, respectively (Table 6.1). Total glucosinolate content was 11.1 μmol/g, with 57% 4-OH-3-CH_3-indolyl and 25% 2-OH-3-butenyl as major components. On DM basis, the NDF and EE content in the 200 g CPC/kg diet was 35 and 11% greater than in the control diet for phase 1 and 16 and 12% greater for phase 2, respectively (Table 6.2).

Increasing dietary inclusion of CPC linearly reduced ($P < 0.001$; Table 6.3) CATTD of DM, GE, CP and DE value for phase 1 and 2 diets, and linearly reduced calculated diet NE values for phase 1 but not for phase 2 diets.

Increasing dietary inclusion of CPC did not affect ($P > 0.05$; Table 6.4) overall ADFI, but quadratically reduced ($P < 0.05$) ADFI for day 29–35. Increasing inclusion of CPC did not affect overall ADG, but linearly increased ($P < 0.05$) ADG for day 15–21 and linearly reduced ($P < 0.05$) ADG for day 29–25. Increasing dietary CPC inclusion linearly increased G:F for the overall trial ($P < 0.05$) and day 15–21 ($P < 0.01$), but quadratically reduced ($P < 0.05$) G:F for day 8–14.

6.5 Discussion

6.5.1 Processing of CPC

Solvent extraction of canola oil includes steps such as pre-conditioning, flaking, seed cooking, pressing and desolventising that provide heat and friction (Newkirk, 2009) with canola meal as co-product. Production of canola expeller containing 80–150 g residual oil/kg also involves pre-conditioning, flaking and cooking (Newkirk, 2009; Newkirk, 2010; Landero et al., 2012). Flaking and cooking ruptures cell walls, reduces oil viscosity and coalesces oil droplets while maintaining oil quality (Unger, 2010) that together promote greater subsequent oil extraction. In contrast to canola meal and canola expeller, CPC is produced by simply pressing canola seed that leaves more remaining oil in the cake than in expeller.

6.5.2 Chemical composition of CPC

Compared with CPC in other studies, the EE content (as-is basis) of CPC in the present study was greater than the 178 and 153 g/kg reported previously (Leming and Lember, 2005; Seneviratne et al., 2011), similar to the 202 g/kg reported by our group (Grageola et al., 2013), but lower than the 275 g/kg reported by Thacker and Petri (2009). The EE content in CPC can vary due to seed quality, number of times seed passes through the press (Unger, 2010), processing temperature, screw speed and barrel size (Seneviratne et al., 2011). Consequently, the CPC had greater energy value than canola meal or canola expeller due to greater EE content.

The CPC in the present study contained 370 g CP/kg, similar to the 364–450 g/kg reported for CPC by Seneviratne et al. (2011). The CPC contained 22.7 g lysine/kg in the present study with 99% of lysine chemically-available, indicating no heat damage during processing. In solvent extraction, heat and roller-pressure may be applied during seed cooking and steam during desolventising increasing meal temperature to 105–120°C (Newkirk, 2009), which may cause Maillard reactions that reduce lysine digestibility and availability (Bell, 1993; Grageola et al., 2013). Previously, 80% or less of lysine in canola meal was chemically-available (Messerschmidt et al., 2013). However, the heat generated during pressing CPC was only 65.6 ± 2.1°C, a temperature that did not affect lysine availability in the present study, based on 99% of lysine being chemically available.

Glucosinolates are the major anti-nutritional factors in canola co-products. The CPC fed in the present study contained double the total glucosinolates than the 5.6 and 4.9 μmol/g reported for CPC previously (Seneviratne et al., 2011; Grageola et al., 2013), but similar to the 12.7 μmol/g measured in *B. napus* CPC (Thacker and Petri, 2009). Although harmless in intact form (Liang et al. 2002), glucosinolates can be hydrolysed by myrosinase in canola seed into compounds that affect liver function, inhibit thyroid hormone production and reduce feed intake of pigs due to their bitter taste (Bourdon and Aumaitre, 1990; Newkirk, 2009). Myrosinase can be inactivated by increasing seed temperature to 80–90°C during seed cooking (Newkirk, 2009). The relatively low pressing temperature in the present study may not have completely inactivated myrosinase activity in CPC. However, pig feed intake or growth was not reduced.

6.5.3 Nutrient digestibility

Increasing dietary inclusion of CPC linearly reduced CATTD of nutrients and diet DE and NE values similar to results for weaned pigs fed increasing dietary inclusion of canola expeller (Landero et al., 2012; Le et al., 2014). The reduced CATTD of nutrients can be attributed to increasing fibre content with increasing dietary CPC inclusion. The CPC in the present study contained 227 g total dietary fibre (TDF)/kg, a content greater than for SBM (175 g/kg, NRC, 2012) but lower than for canola meal (320 g/kg, Landero et al., 2011) and canola expeller (305 g/kg Landero et al., 2012). Fibre in canola co-products is poorly digested in pigs (0.43–0.61 CATTD of NDF; Maison et al., 2015) and reduces digestibility of other nutrients such as protein by dilution (Grieshop et al., 2001). Increasing dietary fibre may also increase endogenous protein excretion in faeces (Mroz et al., 2000), which leads to lower CATTD of nutrients. The EE in CPC could be highly digestible (0.78–0.92 CATTD of EE, Seneviratne et al., 2011). However, increasing dietary EE content with increasing CPC inclusion may not outweigh the reduction in nutrient digestibility caused by dietary fibre. Moreover, remaining oil encased in the canola seed matrix may be less digestible than added liquid oil (Summers et al., 1982; Thacker and Petri, 2009). Compared with canola meal and canola expeller, CPC has a greater GE value and CATTD of GE due to greater EE and reduced fibre content (Maison et al., 2015; Seneviratne et al., 2011) leading to greater DE and NE values.

Heat from toasting and steam application during desolventizing may increase the neutral detergent insoluble protein content in canola meal (Mustafa et al., 2000) that could reduce AA

digestibility and increase the NDF content in canola meal (Newkirk, 2002). The CPC may have greater AA digestibility than canola meal because desolventising is not applied. The AA digestibility in CPC was also greater than for canola expeller due to reduced fibre, increased EE content and reduced processing temperature (Grageola et al., 2013).

6.5.4 Growth performance

Feeding less heat-treated canola co-products may reduce pig feed intake and growth due to increasing dietary glucosinolate content (Seneviratne et al., 2010; Zhou et al., 2014). However, increasing CPC inclusion in the present study did not affect overall ADFI of pigs. Pigs may tolerate up to 2.5 μmol glucosinolates/g of diet without reducing feed intake (Bell, 1993; Schone et al., 1997). In the present study, the diet containing 200 g CPC/kg was calculated to contain 2.2 μmol total glucosinolates/g, which is below the recognized maximum tolerance. A recent study showed that 3-butenyl, a bitter glucosinolate (Kyriazakis and Emmans, 1992) accounting for 90% of total glucosinolates in *B. juncea* canola expeller, reduced feed intake even below 2.5 μmol/g of diet (Zhou et al., 2014). The CPC in the present study was produced from *B. napus* canola; thus, the CPC contained less 3-butenyl (11% of total glucosinolates) that will likely not reduce feed intake. The reason for reduced ADFI for day 29–35 was unclear. The reduction was likely not caused by increasing dietary EE (50.1–56.0 g/kg) and NDF (135–157 g/kg) content with increasing CPC inclusion. Increasing dietary EE content from 14.0 to 70.5 g/kg and NDF from 128 to 163 g/kg by canola oil and canola expeller inclusion did not affect pig feed intake (Thacker, 2009; Landero et al., 2012).

Increasing inclusion of CPC did not affect overall ADG of weaned pigs. Compared with DE, metabolisable energy, total AA content or apparent ileal digestible AA content, feed formulation based on NE value and SID AA content of feedstuffs more accurately reflects the available nutrient content that is useable for maintenance and growth and was thus the selected approach for diet formulation in the present study. Feed formulation based on NE system reduces detrimental effects of feeding co-products high in protein and fibre on pig performance (Zijlstra and Beltranena, 2013). Increasing CPC inclusion linearly increased ADG for day 15–21 that resulted in increased G:F. The reduction of ADG for day 29–35 can be attributed to reduced ADFI. Overall G:F of pigs increased with increasing CPC inclusion similar to previous studies feeding canola expeller to pigs (Seneviratne et al., 2010; Zhou et al., 2014). In the present study, SBM was replaced by CPC and synthetic AA causing reduced dietary CP content while still meeting AA requirements.

6.6 Conclusion

In conclusion, increasing inclusion of CPC reduced CATTD of GE and CP but did not reduce overall ADFI, ADG and G:F of weaned pigs feeding diets formulated to equal NE value and SID AA content. With increasing local availability, CPC may be used as alternative to soybean meal and vegetable oil inclusion in swine diets as source of AA and energy while maintaining growth performance of weaned pigs.

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Table 6.1 Analysed nutrient profile (g/kg as-is) of canola press-cake.

Item	Canola press-cake
Moisture	89.4
Crude protein	369.9
Crude fat	204.5
Total dietary fibre	227.0
Neutral detergent fibre	225.8
Acid detergent fibre	201.4
Starch	-
Ash	65.0
Phosphorus	11.4
Calcium	5.8
Indispensable amino acids[a]	
Arginine	23.7
Histidine	10.5
Isoleucine	15.0
Leucine	26.4
Lysine	22.7
Methionine	7.3
Phenylalanine	16.0
Threonine	16.5
Tryptophan	4.8
Valine	19.0
Total amino acids	352.7
Available lysine	22.5
Total glucosinolates, μmol/g[b]	11.1

[a] Dispensable amino acid (g/kg of canola press-cake): alanine, 16.3; aspartic acid, 28.2; cysteine, 9.1; glutamic acid, 64.6; glycine, 18.9; proline, 22.1; serine, 15.7; tyrosine, 10.9.

[b] Contained the following glucosinolates (μmol/g of canola press-cake): 3-butenyl, 1.21; 4-pentenyl, 0.09; 2-OH-3-butenyl, 2.75; CH_3-thiobutenyl, 0.08; phenylethyl, 0.19; CH_3-thiopentenyl, 0.08; 3-CH_3-indolyl, 0.40; 4-OH-3-CH_3-indolyl, 6.29.

Table 6.2 Ingredient composition and analysed nutrient content (g/kg diet as fed) of experimental diets.

	Canola press-cake (g/kg diet)									
	Phase 1 diets					Phase 2 diets				
	0	50	100	150	200	0	50	100	150	200
Ingredient composition										
Wheat, ground	519.2	538.1	556.9	575.7	594.5	637.2	656.0	674.9	693.7	712.2
Soybean meal (460 g CP/kg)	250.0	187.5	125.0	62.5	-	250.0	187.5	125.0	62.5	-
Canola press-cake (370 g CP/kg)	-	50.0	100.0	150.0	200.0	-	50.0	100.0	150.0	200.0
Lactose	50.0	50.0	50.0	50.0	50.0	-	-	-	-	-
Soy protein concentrate (560 g CP/kg)	50.0	50.0	50.0	50.0	50.0	22.0	22.0	22.0	22.0	22.0
Herring meal (700 g CP/kg)	50.0	50.0	50.0	50.0	50.0	22.0	22.0	22.0	22.0	22.0
Canola oil	43.7	35.5	27.3	19.1	10.9	32.5	24.3	16.1	7.9	-
Limestone	10.4	10.2	10.0	9.8	9.6	11.2	11.0	10.8	10.6	10.4
Mono/di-calcium phosphate	2.5	2.6	2.7	2.8	2.9	1.8	1.9	2.0	2.1	2.2
Salt	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
L-Lysine HCl	0.9	2.1	3.3	4.5	5.7	-	1.2	2.4	3.6	4.8
L-Threonine	-	0.4	0.9	1.4	1.9	-	0.5	1.0	1.5	2.0
DL-Methionine	-	0.1	0.2	0.3	0.4	-	0.1	0.2	0.3	0.4
L-Tryptophan	-	0.2	0.4	0.6	0.8	-	0.2	0.4	0.6	0.8
Vitamin premix[a]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Mineral premix[b]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Choline chloride (600 g/kg)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Acid-insoluble ash[c]	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Analysed nutrients										
Moisture	93.1	98.9	88.9	90.8	99.7	109.7	115.1	107.5	107.0	110.7
Crude protein	277.2	272.1	263.8	258.5	245.5	257.9	243.6	244.4	231.1	217.4
Ash	70.2	71.3	68.3	68.0	69.8	61.4	59.9	62.5	60.9	59.0
Ether extract	63.4	67.1	69.6	71.9	70.2	50.1	50.7	57.3	56.0	56.0
Neutral detergent fibre	96.6	89.7	116.9	129.2	129.8	135.5	104.4	148.0	129.7	157.1
Acid detergent fibre	43.4	41.4	56.5	67.9	63.7	44.4	47.7	57.9	60.1	56.9
Gross energy (MJ/kg)	17.8	17.7	17.9	17.7	17.6	16.9	16.8	17.0	16.9	16.9

[a] Supplied per kilogram of diet: 7500 IU of vitamin A, 750 IU of vitamin D, 50 IU of vitamin E, 37.5 mg of niacin, 15 mg of pantothenic acid, 2.5 mg of folacin, 5 mg of riboflavin, 1.5 mg of pyridoxine, 2.5 mg of thiamine, 2000 mg of choline, 4 mg of vitamin K, 0.25 mg of biotin and 0.02 mg of vitamin B_{12}.

[b] Supplied per kilogram of diet: 125 mg of Zn, 50 mg of Cu, 75 mg of Fe, 25 mg of Mn, 0.5 mg of I and 0.3 mg of Se.

[c] Celite 281 (World Minerals Inc., Santa Barbara, CA, USA).

Table 6.3 Apparent total tract digestibility coefficients (CATTD) of dry matter, gross energy and crude protein (DM basis) and digestible energy (DE) and net energy (NE) values (as-fed basis) of Phase 1 and 2 diets of pigs fed increasing level of canola press-cake (CPC)[a].

	Canola press-cake (g/kg of diet)						*P*-values	
Variables	0	50	100	150	200	SEM[b]	Linear	Quadratic
CATTD								
DM								
Phase 1 diets	0.858	0.857	0.849	0.843	0.838	0.002	<0.001	0.143
Phase 2 diets	0.852	0.843	0.849	0.843	0.838	0.002	<0.001	0.543
Gross energy								
Phase 1 diets	0.860	0.863	0.857	0.852	0.848	0.003	<0.001	0.101
Phase 2 diets	0.860	0.850	0.857	0.851	0.847	0.002	<0.001	0.304
Crude protein								
Phase 1 diets	0.860	0.863	0.852	0.839	0.835	0.003	<0.001	0.167
Phase 2 diets	0.857	0.852	0.853	0.840	0.836	0.003	<0.001	0.240
Diet DE, MJ/kg								
Phase 1 diets	15.0	15.0	15.0	14.8	14.8	0.04	<0.001	0.056
Phase 2 diets	14.5	14.3	14.5	14.4	14.3	0.04	<0.001	0.091
Predicted diet NE, MJ/kg								
Phase 1 diets	10.5	10.5	10.5	10.4	10.3	0.03	<0.001	0.053
Phase 2 diets	10.1	10.0	10.2	10.1	10.0	0.02	0.0744	0.113

[a] Least-squares means based on 12 pen observations of 4 pigs per diet.
[b] Standard error of the mean.

Table 6.4 Average daily feed intake (ADFI), average daily gain (ADG) and feed efficiency (ADG/ADFI) of weaned pigs fed increasing level of canola press-cake (CPC)[a].

	Canola press-cake (g/kg of diet)						*P*-values[c]	
Variables	0	50	100	150	200	SEM[b]	Linear	Quadratic
ADFI (g/d)								
Day 0–7	267	283	271	256	275	9	0.730	0.999
Day 8–14	489	523	484	489	505	23	0.958	0.935
Day 15–21	716	714	718	724	753	27	0.310	0.533
Day 22–28	1029	996	1004	1002	1019	25	0.848	0.343
Day 29–35	1287	1220	1150	1142	1180	33	0.006	0.028
Day 0–35	758	747	726	723	746	16	0.350	0.149
ADG (g/d)								
Day 0–7	221	229	212	190	219	12	0.200	0.331
Day 8–14	330	404	358	381	381	22	0.249	0.331
Day 15–21	474	423	467	507	512	22	0.022	0.186
Day 22–28	622	593	621	621	637	21	0.401	0.440
Day 29–35	800	766	769	731	760	18	0.039	0.196
Day 0–35	490	483	485	486	502	11	0.404	0.280
Feed efficiency (g:g)								
Day 0–7	0.834	0.815	0.773	0.739	0.799	0.03	0.142	0.155
Day 8–14	0.667	0.771	0.734	0.776	0.753	0.02	0.017	0.047
Day 15–21	0.661	0.592	0.648	0.700	0.680	0.02	0.005	0.130
Day 22–28	0.604	0.594	0.619	0.619	0.625	0.01	0.133	0.903
Day 29–35	0.625	0.629	0.675	0.641	0.646	0.02	0.299	0.198
Day 0–35	0.647	0.642	0.665	0.670	0.669	0.01	0.002	0.687

[a] Least-squares means based on 12 pen observations of 4 pigs per diet.
[b] Standard error of the mean.
[c] A week effect was observed ($P<0.001$) for ADFI, ADG and feed efficiency. Two-way interactions between CPC inclusion level and week were observed ($P<0.05$) for ADG and feed efficiency, but not ($P>0.05$) for ADFI.

Chapter 7 Apparent and true ileal and total tract digestibility of fat in canola press-cake or canola oil, endogenous fat loss, and effects of increasing dietary fat on amino acid and energy digestibility in growing pigs

7.1 Abstract

The digestibility of remaining oil in canola press-cake (CPC) may be lower than that of extracted, liquid canola oil (CO) because oil may be partly entrapped in the matrix of CPC. To determine true digestibility of fat in ingredients, endogenous fat losses should be estimated. Dietary fat may interact with digestion of other dietary components. To test these hypotheses, 8 ileal-cannulated pigs (initial BW, 25.4 kg) were fed 10 diets in a 10 × 8 Youden square design. A basal diet was formulated based on wheat grain, barley grain, and canola meal. The 4 CPC and 4 CO test diets were prepared by replacing identical portion of basal diet with 10, 20, 30, or 40% CPC, or 1.5, 3.0, 4.5, or 6.0% CO, respectively, to match the fat content of CPC diet with CO diet at each fat level. An N-free diet based on corn starch was prepared to measure basal endogenous losses of AA. Apparent total tract digestibility (ATTD) and apparent ileal digestibility (AID) of acid-hydrolyzed ether extract (AEE) were calculated for each diet. True ileal digestibility (TID) and true total tract (TTTD) digestibility of AEE in CPC and CO, and total endogenous losses of AEE were estimated by regressing apparent digestible AEE (g/kg of DMI) against dietary AEE intake (g/kg of DM) at the total tract and distal ileum, respectively. The AID and ATTD of AEE in CPC diets were 78.9 and 61.5%, which were lower ($P < 0.01$) than 81.9 and 63.4% in CO diets. Apparent ileal and total tract digestible AEE content in CPC and CO diets increased linearly ($P < 0.01$) with increasing AEE intake. Endogenous losses of AEE were greater ($P < 0.05$) for the total tract than for the ileum (23.4 vs. 9.4 g/kg of DMI). Dietary fat source did not affect ($P > 0.05$) total tract or ileal endogenous losses of AEE. The TID and TTTD of AEE in CPC were

92.3 and 94.5%, respectively, lower ($P < 0.01$) than 96.5 and 100% in CO. Increasing dietary inclusion of CO linearly increased ($P < 0.001$) standardized ileal digestibility (SID) of CP, Lys, Met, Thr, and Trp, and quadratically increased ($P < 0.001$) the AID and ATTD of energy in the basal part of the test diets. In conclusion, CPC had lower TID and TTTD of AEE than CO. Dietary fat source did not affect endogenous losses of AEE. The lower AEE digestibility in CPC than CO indicates that fat digestibility of CPC should be considered to predict its nutritional value accurately. Dietary inclusion of CO may increase digestibility of CP and energy originating from the rest of the diet.

7.2 Introduction

Canola press cake (CPC) is a co-product of biodiesel production from mechanically pressing canola seed without conditioning, flaking, cooking, and solvent extraction. The CPC contains 12–20% remaining fat and can be fed to pigs as source of energy and fatty acids (Klein-Hessling, 2007). The remaining fat in CPC, which is mostly oil, may be entrapped in the seed matrix and thus be less digestible than extracted liquid canola oil (CO), which may cause over-estimation of the predicted NE value of CPC (Thacker and Petri, 2009) because total, but not digestible fat is included in the equation (NRC, 2012). To our knowledge, studies comparing fat digestibility between CPC and CO have not been published. Endogenous fat losses influence apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of fat (Jørgensen et al., 1993). These losses require quantification to determine true ileal digestibility (TID) and true total tract digestibility (TTTD) of fat that may better reflect fat bioavailability in pigs (Kim et al., 2013).

For diet formulation, digestible nutrient content and energy value in feedstuffs are assumed to be additive without interactions. However, dietary fat may affect digestibility of AA and energy in other dietary components by delaying gastrointestinal emptying (Bakker et al., 1995;

Jørgensen et al., 1996; Li and Sauer, 1994). Whether fat in CPC or CO affects digestibility of AA and energy is unknown.

The hypotheses of the present study were that: 1) AID and ATTD of acid-hydrolyzed ether extract (AEE) in CPC would be lower than that in CO; 2) endogenous AEE losses would be greater for the total tract than ileum; 3) increasing dietary CO inclusion would increase AA and energy digestibility in other feed components; and 4) increasing CPC inclusion would increase AA digestibility in CPC. The objectives were thus to measure the TID and TTTD of AEE in CPC and CO and energy digestibility and standardized ileal digestibility (SID) of AA in diets or CPC with increasing dietary inclusion of CO or CPC.

7.3 Materials and methods

7.3.1 Test ingredient and processing

Brassica (*B.*) *napus* canola seed (Camrose, AB, Canada) was processed at the Agri-Food Discovery Place, University of Alberta (Edmonton, AB, Canada) to produce CPC and CO. Briefly, seed was cleaned using a seed cleaner (model ASC-3; Agriculex, Guelph, ON, Canada) to remove chaff and dockage. Subsequently, seed was single-pressed at a rate of 240 kg/h with a single-screw press (model AP-12; Reinartz, Neuss, NRW, Germany) to produce CPC and CO. The temperature of CPC at the press outlet was 65.6 ± 2.1°C. The CPC was cooled to room temperature and subsequently roller-milled (Commercial Single Mill; IFA, Stanley, IA) to break the cake into mash. Pressed canola seed material remaining in CO was removed by sedimentation.

7.3.2 Experimental diets and design

A basal diet of wheat and barley grain, canola meal, and soybean meal was formulated to provide 2.9% acid-hydrolyzed ether extract (AEE) and exceeded NRC (2012) requirements for

most nutrients. The 4 CPC and 4 CO diets were formulated to have similar AEE content at each of 4 levels by mixing 4 levels of CPC (10, 20, 30, and 40%) and 4 levels of CO (1.5, 3.0, 4.5, and 6.0%) with the basal diet, respectively. An N-free diet was formulated (Stein et al., 2007) and fed exclusively to correct for basal endogenous losses of AA (Table 7.1). The 10 diets were fed to 10 pigs over 8 periods in a 10 × 8 Youden square to achieve 8 observations per treatment. Titanium dioxide (TiO_2) was included as an indigestible marker. Mash diets were mixed in a horizontal paddle mixer (model 3061; Marion Process Solutions, Marion, IA).

7.3.3 Experimental procedures

Animal procedures were approved by the University of Alberta Animal Care and Use Committee for Livestock, and followed principles established by the Canadian Council on Animal Care (CCAC, 2009). The animal study was conducted at the Swine Research and Technology Centre, University of Alberta (Edmonton, AB, Canada).

Ten crossbred barrows (initial BW 25.4 ± 1.9 kg; Duroc × Large White/Landrace F_1; Genex Hybrid; Hypor, Regina, SK, Canada) were housed in individual metabolism pens (1.2 m wide, 1.2 m long, and 0.9 m high) that allowed freedom of movement. Pens were equipped with a stainless-steel feeder attached to the front of the pen, cup drinker next to the feeder, polyvinyl chloride walls with windows, and slatted flooring in a temperature-controlled room (22.0 ± 2.5ºC). During a 10-d adaptation to pens, barrows had free access to an 18%-CP pre-grower diet. Pigs were then surgically fitted with a simple T-cannula at the distal ileum, approximately 5 cm prior to the ileocecal sphincter. Cannula dimensions, surgical procedure, and modifications were described previously (Sauer et al., 1983; de Lange et al., 1989). Pre-and post-operative care was also described previously (Li et al., 1993). After surgery, barrows recovered for 7 d with a gradual increase in feed allowance, and were then switched to the first assigned experimental diet. Daily feed allowance was adjusted to 2.7 times the maintenance requirement for DE (2.7 ×

110 kcal of DE/kg of $BW^{0.75}$; NRC, 1998), which was fed in 2 equal meals at approximately 0800 and 1500 h. Each 9-d experimental period consisted of a 5-d acclimation to the experimental diet, followed by a 2-d collection of feces and a 2-d collection of ileal digesta. Pigs had free access to water throughout the experiment.

Feces were collected using plastic bags attached to the skin around the anus (Van Kleef et al., 1994) continuously for 48 h. Digesta samples were collected for 2 d from 0800 to 2000 h using plastic bags (length, 20 cm; i.d., 4 cm) containing 15 mL of 5% formic acid that were attached to the opened barrel of the cannula with a rubber band. Bags were replaced as soon as filled or after every 20 min (Li et al., 1993). Collected feces and digesta were pooled for each pig within experimental period and frozen at -20ºC. Prior to analyses, feces and digesta were thawed, homogenized, sub-sampled, and freeze-dried.

7.3.4 Chemical analyses

The CPC, test diets, lyophilized feces, and digesta were ground through a 1-mm screen in a centrifugal mill (model ZM200; Retsch GmbH, Haan, Germany). The CPC was analyzed for GE using an adiabatic bomb calorimeter (model 5003; Ika-Werke GMBH & Co. KG, Staufen, Germany), DM (method 934.01), CP (method 984.13A-D), ether extract (EE, method 920.39A), acid hydrolyzed ether extract (AEE, method 954.02), crude fiber (CF, method 978.10), ash (method 942.05), ADF (method 973.18A-D), NDF (Van Soest et al., 1991), total dietary fiber (TDF, method 985.29), calcium (method 968.08), phosphorus (method 946.06), AA (method 982.30E), and chemically-available lysine (method 975.44) as per AOAC (2006). Glucosinolate profile of CPC was determined by GLC (Daun and McGregor, 1981) at the POS Bio-Sciences, Saskatoon, SK, Canada. The CO was analyzed for DM, GE, EE, and AEE. Experimental diets were analyzed for DM, GE, CP, EE, AEE, ash, CF, ADF, AA, and TiO_2 (Myers et al., 2004).

Feces were analyzed for DM, GE, CP, EE, AEE, ash, CF, ADF, and TiO_2. Digesta were analyzed for DM, GE, CP, EE, AEE, AA, and TiO_2.

7.3.5 Calculations

The apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of components (AEE, AA, and energy) of each diet were calculated using the indicator method (Adeola, 2001): AID or ATTD, % = 100 – [100 × (concentration of TiO_2 in diet × concentration of component in feces or digesta / concentration of TiO_2 in feces or digesta × concentration of component in diet)].

The AEE values of test ingredients, test diets, feces and digesta were used in all fat digestibility calculations. The true ileal digestibility (TID) of AEE, true total tract digestibility (TTTD) of AEE, total endogenous losses of AEE at the ileum (TEL_i) and total tract (TEL_t) were estimated using the regression method (Kil et al., 2010). The digestible AEE content at the ileum ($DAEE_i$, g/kg of DMI) and total tract level ($DAEE_t$, g/kg of DMI) were calculated and regressed against dietary AEE intake (g/kg of DM) for each ingredient. The Y-intercept of the regression equation was considered the total endogenous losses of AEE (TEL_i or TEL_t g/kg of DMI), and the slope of the equation was considered the true digestibility of AEE (TID or TTTD) in CPC or CO. The TID and TTTD of AEE in each experimental diet were also calculated by correcting the AID and ATTD of AEE in each diet for TEL_i and TEL_t, respectively (Eq. 7, Stein et al., 2007).

The AID of AA was calculated for each diet. The basal ileal endogenous losses (I_{end}) of AA or CP (g/kg of DMI) was calculated by the equation for the N-free diet (Eq. 3, Stein et al., 2007): I_{end} = [AA or CP in digesta × (TiO_2 in diet / TiO_2 in digesta)]. Standardized ileal digestibility (SID) for AA was then calculated by correcting the AID for basal ileal endogenous losses using the equation (Eq. 7, Stein et al., 2007): SID = [AID + (I_{end} / AA in diet)].

The AA digestibility in CPC was calculated according to the difference method (Eq. 2, Bureau et al., 1999): $D_{CPC} = D_{test\ diet} + [(D_{test\ diet} - D_{basal}) \times (P_{basal} \times N_{basal} / P_{CPC} \times N_{CPC})]$, where D_{CPC} = % digestibility of CPC; $D_{test\ diet}$ = % digestibility of test diet; D_{basal} = % digestibility of basal diet, P_{basal} = % of basal diet in test diet, P_{CPC} = % of CPC in test diet; N_{basal} = % nutrient of basal diet (DM-basis), and N_{CPC} = % nutrient of test ingredient (DM-basis).

The TID and TTTD of energy in CO should be similar as the determined TID and TTTD of fat. To evaluate the effect of CO inclusion on energy digestibility of other dietary components in test diets, the AID and ATTD of energy in CO were assumed to be the greatest value possible, equal to the 96.5% TID and 100% TTTD of energy. Then, the AID and ATTD of the basal part of test diets were calculated by difference (Eq. 2; Bureau et al., 1999).

7.3.6 Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (ver. 9.3, SAS Inst. Inc., Cary, NC). Normality (PROC UNIVARIATE) and homogeneity of variance (PROC GLM, Hovtest = Levene) of the residual were examined prior to the ANOVA. For AID and ATTD of AEE, $DAEE_i$, and $DAEE_t$ in CPC and CO diets, diet was the fixed effect, and period and pig were random terms. Diet means for each variable were reported as least-squares means. Diet fed in the previous period was used as covariate to test for carry-over effects. Orthogonal polynomial contrasts were used to test the linear and quadratic effects of these variables to increasing dietary inclusion of CPC or CO. The REG procedure was used to generate linear regression equations. The Y-intercept and slope of regression equations were compared between the 2 fat sources and the 2 collection sites by the GLM procedure (UCLA Statistical Consulting Group, 2015). The AID, ATTD, TID, and TTTD of AEE in each diet were then analyzed as a 4 × 2 factorial arrangement. The model included fat source, fat level, and their interaction as fixed effect, with period and pig as random terms. If interactions were not significant, only the main effects were

reported. Multiple means were compared using the PDIFF statement with the TUKEY adjustment.

For SID of AA and AID and ATTD of energy, orthogonal contrasts were used to test their linear and quadratic response to increasing dietary inclusion of CPC or CO. To test the hypotheses, $P < 0.05$ was considered significant.

7.4 Results

Pigs remained healthy during the experiment. Pigs consumed their entire daily feed allowance for all diets throughout the experiment.

On as-is basis, the CPC contained 36.7% CP, 25.4% TDF, 15.6% AEE, and 2.37% lysine, 15.2 μmol/g total glucosinolates, and 5.4 Mcal/kg GE (Table 7.2). The CO contained on as-is basis 0.24% moisture, 99.7% AEE, and 9.4 Mcal/kg of GE. Dietary AEE content ranged from 3.80 to 9.92% in CPC diets, and 3.91 to 8.81% in CO diets. The ADF content was 11.3% in the basal diet, and ranged from 13.5 to 14.0% in CPC diets and 11.4 to 10.8% in CO diets (Table 7.3).

Carry-over effects were not identified ($P > 0.05$) among periods for digestibility variables. The AID and ATTD of AEE increased quadratically ($P < 0.05$) whereas the $DAEE_i$ and $DAEE_t$ increased linearly ($P < 0.001$) with increasing dietary AEE intake achieved by inclusion of either CPC or CO (Table 7.4). The $DAEE_i$ and $DAEE_t$ were strongly related ($P < 0.001$, $R^2 > 0.98$) to dietary AEE intake for both CPC and CO diets. The TID and TTTD of AEE in CPC were 92.3 and 94.5% and were lower ($P < 0.05$) than 96.5 and 100% for CO, respectively. The TID and TTTD of AEE did not differ for either CPC or CO. The TEL_t for CPC and CO were 23.9 and 23.0 (g/kg DMI), which were greater ($P < 0.001$) than the TEL_i at 9.5 and 9.3 (g/kg DMI), respectively. For both ileal and total tract, endogenous losses of AEE did not differ between CPC

and CO (Table 7.5). The TTTD and TID of AEE in either CPC or CO diets were not affected by increasing dietary fat content (Table 7.6).

The SID of CP, Arg, Ala, Gly, Pro, and Ser in the basal diet increased quadratically ($P < 0.05$) with increasing dietary inclusion of CO to the basal diet. The SID of other AA and total AA in the basal diet increased linearly with increasing CO inclusion ($P < 0.001$, Table 7.7). Dietary inclusion of 10 to 40% CPC did not affect the SID of CP and AA in CPC, except for SID of Met and Phe that were increased linearly ($P < 0.05$, Table 7.8).

The AID and ATTD of energy in diets increased quadratically ($P < 0.001$) with increasing inclusion of CO. Assuming 96.5 of AID and 100% of ATTD of energy in CO, the ATTD and AID of energy in the basal part of the test diets increased quadratically ($P < 0.001$) with increasing CO inclusion (Table 7.9).

7.5 Discussion

7.5.1 Canola press-cake

Canola oil is widely used for human food consumption and animal feeding. It is also the major feedstock for producing biodiesel due to superior flow in cold weather and oxidative stability (Hoekman et al., 2012). In large-scale processing plants, canola oil extraction includes seed cleaning, pre-conditioning, flaking, seed cooking, screw-pressing, solvent extraction, and desolventising with canola meal (CM) as final co-product (Newkirk, 2009). Due to lower infrastructure cost and equipment requirements, small to medium-scale biodiesel producers extract canola oil merely by mechanically pressing cleaned seed (Newkirk, 2010). Mechanical pressing alone extracts oil less efficiently than post-pressing solvent extraction. Therefore, CPC contains more EE than canola meal (3.0%; NRC, 2012). The availability of CPC in Canada is expected to increase due to increased seed production and demand for biodiesel (CRFA, 2013).

7.5.2 Apparent digestibility of AEE and regression method

Free fatty acids can bind with Ca or Mg in the pig digestive tract to form insoluble soaps that cannot be absorbed (Jørgensen, et al., 1992). Soaps in feces and digesta cannot be extracted using ether extraction (Atteh and Leeson, 1985). Because little soap is presented in diet, measuring fat digestibility based on ether extract would under-estimate the fat excretion in feces and digesta thus over-estimate fat digestibility (Ji et al., 2008). Ether extraction with acid-hydrolysis could release fatty acids in soap form, thus, more accurately measures fat digestibility. Therefore, the AEE value in all experimental articles was used for fat digestibility calculations.

The AID and ATTD of AEE in diets increased quadratically with increasing CPC or CO inclusion in the present study, similar to the observations in corn and soybean products and animal fat (Jørgensen and Fernandez, 2000; Kil et al., 2010; Kim et al., 2013). The low AID (65.2%) and ATTD (24.4%) of AEE in the basal diet and the digestibility plateau reached at greater level of fat inclusion indicated greater contribution of endogenous fat to total fat excretion when dietary fat content was low (Jørgensen and Fernandez, 2000; Kil et al., 2010). The regression method was used in the present study to estimate total endogenous losses and true digestibility of fat. The prerequisite of using the regression method is the linear response of apparent digestible fat content to dietary fat intake (Jørgensen et al., 1993; Kil et al., 2010), which was met in the present study. Dietary fiber limits the digestion of fat (Dégen et al., 2009), therefore, fiber content among diets needs to be similar for accurate estimation of fat digestibility and endogenous losses using regression method (Kim et al., 2013). Due to the need to use the difference method to calculate nutrient digestibility in the test ingredients, CPC and CO were directly added to replace the basal diet without balancing for fiber content using additional fiber sources. However, the ADF content among CPC and CO diets was within a narrow range (< 2%-units) that may not strongly affect fat digestion. The fat in CPC and CO was from the same batch

of canola seed in the present study, which would make more unbiased comparison in terms of fat digestibility.

7.5.3 Total endogenous loss of fat

Total endogenous losses of fat for CPC and CO were 23.0 and 23.9 g/kg of DMI for the total tract and 9.34 and 9.52 g/kg DMI for the ileum, respectively. These values were greater than 3.77–12.08 g/kg DMI reported by Kil et al. (2010), 2.62–6.51 g/kg DMI by Kim et al. (2013), and 4.4–22.4 g/kg by Adams and Jensen (1984) that studied corn, soybean, and sunflower products. This difference could be due to the greater fiber content in diets fed in the present study. Instead of feeding diets based on low-fiber ingredients (corn or starch), the basal diet in the present study was formulated to include wheat, barley, and CM that contained more fiber to simulate typical western-Canada grower rations. Greater dietary fiber may increase epithelial cell sloughing and fecal microbial output (Le Goff and Noblet, 2001; Sauer et al., 1991), and reduce reabsorption of endogenous fat from bile (Bach Knudsen and Hansen, 1991), thus increasing endogenous fat excretion.

The TEL_t in the present study was greater than the TEL_i for pig fed CPC and CO. This difference could be attributed to the greater excretion of microbial lipid (on cell membrane) in feces than ileal digesta (Jørgensen et al., 1992). However, such a difference was not reported by Jørgensen et al. (1993) that may be explained by the relatively low dietary fiber content in their diets. Endogenous fat losses were greater in pigs fed inherent fat source over extracted fat (Kil et al., 2010), which was not observed in the present study. Fiber content and source were similar between CPC and CO diets in the present study, providing an explanation for the lack of difference in endogenous excretion of fat.

7.5.4 True digestibility of fat

The TID and TTTD of fat in CO was 96.5 and 100% in the present study, respectively. These values were greater than those reported for corn oil (94.2–95.4% TID; 84.7–94.3% TTTD, Adams and Jensen, 1984; Kil et al., 2010; Kim et al., 2013), soybean oil (91.0–97.7% TTTD, Adams and Jensen, 1984; Jørgensen et al., 1993; Jørgensen and Fernandez, 2000), sunflower oil (88.9% TTTD, Adam and Jensen, 1984), rapeseed oil (92.7% TTTD, Jørgensen et al., 1996), and animal fat (88.9 – 91.2% TTTD, Jørgensen and Fernandez, 2000). Greater fat digestibility in the present study could be related to the presence of canola meal in the basal diet. Canola protein has greater emulsifying property than soy protein (Khattab and Arntfield, 2009), which may contribute to the formation and stabilization of micelles during fat digestion thus increasing the digestibility of fat (Myer et al., 1976; LaRusso, 1984). Heat-treated oils may be subjected to fatty acid oxidation that reduces fat digestibility in pigs (Liu et al., 2014). The CO in the present study was mechanically cold-pressed (barrel temperature < 65.6 ± 2.1°C) thus was not exposed to high heat (from seed cooking, extrusion, or distillation). Cold-pressed oil has lower peroxide value and saturated fatty acid content than solvent-extracted and hot-pressed oil (Ghazani et al., 2014), which may also contribute to greater digestibility of fat in CO in the present study.

To our knowledge, this is the first study that measured the TID and TTTD of inherent fat in CPC, which was 92.3 and 94.5%, respectively. These values were greater than those reported for other inherent fat sources, such as corn germ meal (50.1–78.6% TID; 43.9–84.1% TTTD, Kil et al., 2010; Kim et al., 2013), corn distillers dried grains with solubles (cDDGS, 62.1% TID; 51.9% TTTD, Kim et al., 2013), full-fat soybean (85.2% TID; 74.9–79.7% TTTD, Adams and Jensen, 1984; Kim et al., 2013), and sunflower seed (75.0% TTTD, Adams and Jensen, 1984). Fat stored in different manners within grain matrixes would be digested differently (Adeola and Bajjalieh,

1997; Kim et al., 2013). The encapsulation of fat by the seed matrixes in CPC might be looser than that in corn, soybean, and sunflower, which may explain the greater fat digestibility.

The TTTD and TID of fat in CPC was lower than that in extracted CO. Similar difference were also found for corn, soybean and sunflower (Adams and Jensen, 1984; Kil et al., 2010; Kim et al., 2013). The fat in CPC may be bound to or encased in the fiber-containing seed matrixes that physically prevent the access of digestive enzymes (Adams and Jensen, 1984; Thacker, 1998). About 4% of fat in canola seed is presented in the fibrous canola hull and was poorly digested (Bell and Shires, 1982). Therefore, the true digestibility of fat in CPC should be considered when predicting the energy value of CPC using its nutrient composition.

The TID of fat was not different from TTTD of fat for CPC or CO in the present study, which agrees with Kil et al. (2010). These results indicate complete fat digestion and absorption by the terminal ileum. In contrast to AID and ATTD of fat, TID and TTTD of fat in experimental diets were not affected by the dietary fat content. Therefore, the TID or TTTD value of fat would have better additivity and should be preferred over AID and ATTD for diet formulation.

7.5.5 Dietary fat and amino acid digestibility

Dietary fat might increase digesta viscosity, reduced gastric emptying and digesta passage rate (Danicke et al., 2000; Hunt and Knox, 1968; Valaja and Siljander-Rasi, 2001), thus provides more time for protein digestion and AA absorption (Li and Sauer, 1994). Dietary fat may increase endogenous secretion of cholecystokinin (CCK) that could slow down gastric emptying (Moran et al., 1982). With 6%-units of increase of CO inclusion, the SID of CP, Lys, Met, Thr, and Trp in the basal diet increased by 10.1, 6.9, 6.0, 9.1, and 4.2% in the present study, respectively. The increase of CO inclusion by 9%-units in starch and soybean meal-based basal diet increased the AID of CP, Lys, and Thr by only 3.2, 3.7, and 4.6%, respectively (Li and Sauer, 1994). The increase of CO inclusion by 8%-units in starch and canola meal-based diet

increased AID of Lys and Thr by 2.5 and 3.4% (Imbeah and Sauer, 1991). In contrast, 5% inclusion of soybean oil or choice white grease in diets based on corn, soybean meal, and cDDGS did not increase AID of CP, Lys, Met, Thr, or Trp (Kil and Stein, 2011). The greater response of AA digestibility to dietary fat inclusion in the present study may be due to the low AA digestibility in the basal diet. Basal diet in the present study contained wheat (30%), barley (25%), and canola meal (30%) that had greater fiber content than diets based on starch, corn grain, and soybean meal. Dietary fiber in canola meal was 90% insoluble (Bell, 1993; Slominski et al., 2012) that may increase digesta passage rate (Chesson, 2006) and thereby limits protein digestion. Therefore, adding CO into such diet could increase AA digestibility more effectively.

Using the difference method, the SID of CP and AA within CPC was similar at different inclusion levels (10 to 40%), except for Met and Phe that had linearly increased SID. Le et al. (2012) included 2 levels (25 and 50%) of canola meal into the same basal diet and did not observe difference of SID of AA in canola meal. The inherent fat in CPC did not seem to interact with the protein digestion as much as extracted CO. The SID of Ile and Val in CPC was lower than expected relative to other AA (Grageola et al., 2013; NRC, 2012). The lower digestibility was caused by greater output of these AA in ileal digesta indicating poorer Ile and Val digestion of this particular CPC sample. However, the exact reason for the low digestibility is unknown.

7.5.6 Dietary fat and energy digestibility

Increasing dietary CO inclusion increased the AID and ATTD of energy in the diets. Similar increase was also found by Jørgensen et al. (1996) that fed 0–16% of rapeseed oil to pigs. However, assuming constant energy digestibility of the basal diet with increasing level of CO inclusion, the AID and ATTD of energy in CO calculated by the different method was over 139%, which is not realistic. This overestimation means energy digestibility in the basal diet was not equal with different CO inclusion levels. The CO may increase energy digestibility of other

dietary components in the basal diet. By assuming maximum AID and ATTD of energy (96.5 and 100%) in CO and using the difference method to subtract the energy contribution of CO from test diets, it was found that the AID and ATTD of energy in the basal part of test diets increased quadratically with increasing CO inclusion. The increment in energy digestibility could not be fully accounted for by the increase of SID of CP, therefore, CO inclusion affected the digestibility of other energy-yielding nutrients in the basal diet such as starch, fat, or fiber. The ATTD of crude fiber increased when 5–10% vegetable and animal fat mixture was added into basal diets of wheat, soybean, and wheat bran but it did not affect energy digestibility (Dégen et al., 2009). The ATTD of crude fiber and N-free extracts did not increase when increasing amount of animal fat was added to diet (Bakker et al., 1995). Inclusion of CO may have increased digestibility of protein and starch in the small intestine in the present study, and increased hindgut fermentation of fiber due to reduced flow of undigested protein in the hindgut (Jha and Leterme, 2012). As a result, the energy contribution of the basal diet and oil was not independent when blended together (Wiseman and Cole, 1987).

In conclusion, the AID and ATTD of fat was reduced in diets with CPC as fat source instead of CO. The TID and TTTD of fat in CPC was lower than that in CO. Total endogenous losses of fat was greater at the total tract than ileal level, but was not affected by fat source. Increasing dietary fat content by CO inclusion increased SID of CP and AA in the basal diet. Dietary CO inclusion could have interacted with the energy digestibility in the basal part of test diets.

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Table 7.1 Ingredient composition of experimental diets.

		Canola press-cake, %				Canola oil, %				
Item, %	Basal diet	10	20	30	40	1.5	3.0	4.5	6.0	N-free
Wheat grain, ground	30.25	27.21	24.17	21.13	18.09	29.80	29.34	28.89	28.44	–
Barley grain, ground	25.00	22.49	19.98	17.46	14.95	24.63	24.25	23.88	23.50	–
Canola press-cake	–	10.05	20.10	30.15	40.20	–	–	–	–	–
Canola meal	30.00	26.99	23.97	20.96	17.94	29.55	29.10	28.65	28.20	–
Soybean meal	10.00	9.00	7.99	6.99	5.98	9.85	9.70	9.55	9.40	–
Canola oil	–	–	–	–	–	1.50	3.00	4.50	6.00	3.00
Limestone	1.50	1.35	1.20	1.05	0.90	1.48	1.46	1.43	1.41	0.50
Monodicalcium phosphate	1.00	0.90	0.80	0.70	0.60	0.98	0.97	0.95	0.94	1.90
Salt	0.50	0.45	0.40	0.35	0.30	0.49	0.48	0.48	0.47	0.40
Vitamin premix[1]	0.50	0.45	0.40	0.35	0.30	0.49	0.48	0.48	0.47	0.50
Mineral premix[2]	0.50	0.45	0.40	0.35	0.30	0.49	0.48	0.48	0.47	0.50
Corn starch[3]	–	–	–	–	–	–	–	–	–	78.20
Cerelose[4]	–	–	–	–	–	–	–	–	–	10.00
Solka floc[5]	–	–	–	–	–	–	–	–	–	4.00
K_2CO_3	–	–	–	–	–	–	–	–	–	0.40
MgO	–	–	–	–	–	–	–	–	–	0.10
Titanium dioxide	0.75	0.67	0.60	0.52	0.45	0.74	0.73	0.72	0.70	0.50

[1]Provided the following per kilogram of diet: vitamin A, 8,250 IU; vitamin D_3, 825 IU; vitamin E, 40 IU; niacin, 35 mg; D-pantothenic acid, 15 mg; riboflavin, 5 mg; menadione, 4 mg; folic acid, 2 mg; thiamine, 1 mg; D-biotin 0.2 mg; and vitamin B_{12}, 0.025 mg.

[2]Provided the following per kilogram of diet: Zn, 100 mg as $ZnSO_4$; Fe, 80 mg as $FeSO_4$; Cu, 50 mg as $CuSO_4$; Mn, 25 mg as $MnSO_4$; I, 0.5 mg as $Ca(IO_3)_2$; and Se, 0.1 mg as Na_2SeO_3.

[3]Melojel (National Starch and Chemical Co., Bridgewater, NJ).

[4]Corn Product U.S., Westchester, IN.

[5]International Fiber Corp., North Tonawanda, NY.

Table 7.2 Analyzed nutrient profile (as-is basis) of canola press-cake.

Item	Canola press-cake
Moisture, %	7.73
CP (N × 6.25), %	36.7
GE, Mcal/kg	5.40
Ether extract, %	14.9
Acid-hydrolyzed ether extract, %	15.6
Crude fiber, %	9.70
ADF, %	15.8
NDF, %	24.9
Total dietary fiber, %	25.4
Insoluble fiber, %	23.3
Soluble fiber, %	2.03
Ash, %	5.76
Ca, %	0.46
P, %	0.88
Indispensable AA[1], %	
Arg	2.24
His	1.01
Ile	1.49
Leu	2.58
Lys	2.37
Met	0.73
Phe	1.50
Thr	1.55
Trp	0.44
Val	1.91
Total AA	34.3
Chemically-available Lys	2.36
Total glucosinolates[2], μmol/g	15.2

[1]Dispensable AA (% of canola press-cake): Ala, 1.58; Asp, 2.49; Cys, 0.93; Glu, 6.30; Gly, 1.85; Pro, 2.44; Ser, 1.35; and Tyr, 1.09.

[2]Contained the following glucosinolates (μmol/g of canola press-cake): 3-butenyl, 2.28; 4-pentenyl, 0.34; 2-OH-3-butenyl, 5.91; 2-OH-4-pentenyl, 0.13; CH_3-thiobutenyl, 0.09; phenylethyl, 0.12; CH_3-thiopentenyl, 0.07; 3-CH_3-indolyl, 0.26; and 4-OH-3-CH_3-indolyl, 5.97.

Table 7.3 Analyzed nutrient profile of experimental diets (as-fed basis).

		Canola press-cake, %				Canola oil, %				
Item, %	Basal diet	10	20	30	40	1.5	3.0	4.5	6.0	N-free
Moisture, %	10.8	10.3	10.1	9.9	9.6	10.6	10.3	10.2	10.1	8.65
CP (N × 6.25), %	23.8	24.9	26.1	27.5	28.8	23.4	22.8	22.6	22.3	0.82
GE, Mcal/kg	3.89	4.04	4.13	4.23	4.35	3.99	4.09	4.18	4.23	3.70
Starch, %	30.1	26.8	24.3	18.8	18.4	27.8	30.7	28.1	27.1	69.3
Ether extract, %	1.60	3.22	4.53	5.83	7.34	2.57	3.35	4.43	5.62	0.65
Acid-hydrolyzed ether extract %	2.92	3.80	6.27	8.15	9.92	3.91	5.49	7.35	8.81	1.30
Crude fiber, %	6.70	6.55	6.83	7.38	7.31	6.53	6.57	6.44	5.71	2.13
ADF, %	11.3	13.5	13.2	13.3	14.0	11.4	11.1	11.7	10.8	3.43
Ca, %	1.27	1.11	1.07	0.88	0.89	1.11	1.10	1.06	1.07	0.36
P, %	0.84	0.83	0.89	0.85	0.95	0.80	0.79	0.76	0.77	0.26
Indispensable AA, %										
Arg	1.35	1.37	1.43	1.55	1.67	1.22	1.25	1.24	1.27	0.01
His	0.60	0.62	0.65	0.69	0.76	0.54	0.55	0.54	0.56	0.00
Ile	0.95	0.93	0.98	1.05	1.14	0.87	0.86	0.85	0.89	0.01
Leu	1.74	1.74	1.81	1.93	2.06	1.60	1.59	1.57	1.63	0.03
Lys	1.11	1.17	1.25	1.38	1.53	1.02	1.03	1.01	1.05	0.01
Met	0.40	0.41	0.46	0.50	0.53	0.36	0.38	0.39	0.40	0.01
Phe	1.08	1.05	1.10	1.14	1.21	0.99	1.00	1.00	1.02	0.01
Thr	0.92	0.94	1.00	1.07	1.17	0.84	0.84	0.84	0.85	0.01
Trp	0.27	0.27	0.28	0.26	0.30	0.22	0.23	0.23	0.22	0.08
Val	1.14	1.15	1.20	1.31	1.43	1.05	1.05	1.02	1.05	0.01
Dispensable AA, %										
Ala	0.97	1.00	1.04	1.12	1.20	0.89	0.91	0.90	0.92	0.02
Asp	1.75	1.75	1.80	1.93	2.03	1.57	1.61	1.61	1.65	0.03
Cys	0.47	0.48	0.55	0.60	0.64	0.43	0.44	0.43	0.47	0.01
Glu	4.73	4.73	4.91	5.04	5.29	4.40	4.41	4.46	4.49	0.07
Gly	1.07	1.10	1.17	1.25	1.36	0.97	1.00	0.98	1.00	0.01
Pro	1.70	1.70	1.78	1.83	1.92	1.62	1.60	1.64	1.64	0.01
Ser	0.96	0.98	1.02	1.07	1.12	0.88	0.91	0.90	0.92	0.01
Tyr	0.63	0.63	0.64	0.68	0.73	0.59	0.59	0.59	0.62	0.02

Table 7.4 Apparent ileal digestibility (AID) of acid hydrolyzed ether extract (AEE), apparent total tract digestibility (ATTD) of AEE, apparent ileal digestible AEE ($DAEE_i$), and apparent total tract digestible AEE ($DAEE_t$) content of diets including increasing canola press-cake or canola oil[1].

		Canola press-cake, %					*P*-value		Canola oil, %					*P*-value	
Item	Basal	10	20	30	40	SEM	Linear	Quadratic	1.5	3.0	4.5	6.0	SEM	Linear	Quadratic
AID of AEE, %	65.2	70.7	78.0	82.9	83.9	1.7	<0.001	0.012	74.4	81.1	85.0	86.9	1.2	<0.001	0.003
$DAEE_i$, g/kg of DMI	21.4	30.0	54.4	75.0	96.1	1.2	<0.001	0.425	32.6	49.7	69.7	87.5	0.9	<0.001	0.411
ATTD of AEE, %	24.4	41.8	59.8	69.7	74.6	1.3	<0.001	<0.001	45.2	61.0	71.5	76.3	1.1	<0.001	<0.001
$DAEE_t$, g/kg of DMI	8.0	17.6	41.6	62.9	85.5	0.9	<0.001	0.344	19.5	37.1	58.4	76.9	0.7	<0.001	0.282

[1]Least-squares means based on 8 observations per diet.

Table 7.5 Regression of apparent ileal and total tract digested acid-hydrolyzed ether extract (AEE) (Y, g/kg of DMI) on dietary AEE intake (X, g/kg of DM), estimated total endogenous loss (TEL) of AEE and true digestibility of AEE in canola press-cake and canola oil[1].

	Ileal		Total tract	
	CPC	CO	CPC	CO
Regression equation	Y = 0.923 X – 9.34	Y = 0.965 X – 9.52	Y = 0.945 X – 23.0	Y = 1.000 X – 23.9
SE of the slope	0.022	0.019	0.019	0.018
SE of the intercept	1.871	1.444	1.557	1.361
R^2	0.982	0.988	0.988	0.990
Estimated TEL, g/kg of DMI	9.34[b]	9.52[b]	23.0[a]	23.9[a]
Estimated true digestibility of AEE, %	92.3[c]	96.5[ab]	94.5[bc]	100.0[a]

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

[1]Each regression equation was developed using 32 pig observations for diets containing 10 to 40% canola press-cake or containing 1.5 to 6.0% canola oil.

Table 7.6 Apparent ileal digestibility (AID), true ileal digestibility (TID), apparent total tract digestibility (ATTD), and true total tract digestibility (TTTD) of acid-hydrolyzed ether extract in diets with canola press-cake (CPC) or canola oil (CO) at 4 inclusion levels[1].

	Basal	Fat source		SEM[1]	Dietary fat level[3]				SEM[2]	*P*-value		
		CPC	CO		1	2	3	4		Source	Level	Source × Level
AID, %	65.2	78.9	81.9	1.2	72.5[a]	79.5[b]	84.0[c]	85.4[c]	1.3	<0.001	<0.001	0.820
TID, %	93.9	92.6	96.2	0.1	94.4	94.0	94.9	94.2	0.1	<0.001	0.756	0.630
ATTD, %	24.4	61.5	63.4	1.0	43.6[a]	60.4[b]	70.5[c]	75.2[d]	1.1	0.003	<0.001	0.573
TTTD, %	95.9	94.7	99.9	0.1	98.0	96.4	97.9	97.1	0.1	<0.001	0.178	0.166

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

[1]Least-squares means based on 32 observations for each fat source.

[2]Least-squares means based on 16 observations for each level.

[3]Dietary fat level: 1 = diets including 10% of CPC and 1.5% of CO; 2 = diets including 20% of CPC and 3.0% of CO; 3 = diets including 30% of CPC and 4.5% of CO; and 4 = diets including 40% of CPC and 6.0% of CO.

Table 7.7 Standardized ileal digestibility (SID) of CP and AA of experimental diets with increasing inclusion of canola oil (DM basis)[1]

	Canola oil, %						*P*-value	
Item, %	0 (Basal)	1.5	3.0	4.5	6.0	SEM	Linear	Quadratic
CP	69.1	73.8	75.8	76.3	76.1	0.75	<0.001	<0.001
Indispensable AA								
Arg	81.7	84.1	85.7	86.7	87.5	0.80	<0.001	0.049
His	80.7	82.1	83.7	84.8	85.8	0.64	<0.001	0.490
Ile	75.0	76.9	78.5	79.9	81.0	0.70	<0.001	0.387
Leu	76.6	78.7	80.2	81.5	82.5	0.72	<0.001	0.251
Lys	72.7	74.4	76.1	77.1	77.4	0.64	<0.001	0.122
Met	82.3	83.1	85.0	86.3	87.2	0.64	<0.001	0.907
Phe	77.0	79.1	80.8	82.2	83.1	0.74	<0.001	0.229
Thr	68.3	70.4	72.4	73.7	74.5	0.90	<0.001	0.211
Trp	85.3	85.2	86.6	89.0	88.9	0.88	<0.001	0.722
Val	71.3	73.5	75.5	76.4	77.3	0.82	<0.001	0.121
Dispensable AA								
Ala	71.2	73.7	75.9	76.9	77.2	0.82	<0.001	0.028
Asp	70.1	72.2	74.9	76.6	77.7	0.88	<0.001	0.235
Cys	72.3	73.9	76.4	77.3	79.7	0.87	<0.001	0.978
Glu	82.6	84.7	87.3	88.0	88.8	0.79	<0.001	0.117
Gly	65.1	69.0	73.1	73.8	74.0	1.25	<0.001	0.005
Pro	65.2	73.9	78.7	79.3	78.7	3.18	<0.001	0.008
Ser	72.8	74.6	77.5	78.4	77.7	0.86	<0.001	0.003
Tyr	76.7	78.8	80.2	81.5	82.5	0.69	<0.001	0.257
Total AA	76.5	78.3	81.2	82.0	82.5	0.94	<0.001	0.060

[1]Least-squares means based on 8 observations per diet.

Table 7.8 Standardized ileal digestibility (SID) of CP and AA in canola press-cake at increasing inclusion level (DM basis)[1]

	Canola press-cake, %					*P*-value	
Item, %	10	20	30	40	SEM	Linear	Quadratic
CP	73.4	74.6	77.3	76.7	3.8	0.466	0.783
Indispensable AA							
Arg	80.5	79.5	82.3	84.9	2.6	0.126	0.428
His	80.9	80.2	82.2	84.5	2.0	0.100	0.082
Ile	63.9	64.2	64.3	65.3	2.2	0.629	0.867
Leu	70.5	69.7	73.1	73.8	2.4	0.080	0.614
Lys	72.2	70.0	69.3	70.3	2.5	0.457	0.397
Met	78.3	80.6	81.4	83.7	1.6	0.033	0.978
Phe	65.4	67.7	68.7	70.8	1.7	0.019	0.942
Thr	72.3	69.7	70.3	69.1	2.1	0.176	0.607
Trp	69.8	70.0	67.9	70.5	2.9	0.950	0.203
Val	65.4	65.3	66.3	68.3	2.3	0.254	0.563
Dispensable AA							
Ala	77.5	74.3	74.9	74.7	2.7	0.455	0.506
Asp	76.7	74.5	74.9	74.0	3.0	0.355	0.696
Cys	68.2	70.5	72.6	71.4	1.8	0.185	0.353
Glu	82.1	85.8	81.2	84.9	3.7	0.769	0.992
Gly	75.7	77.0	77.8	75.4	2.5	0.997	0.402
Pro	85.9	80.0	92.5	90.2	4.0	0.195	0.628
Ser	65.6	67.1	67.2	67.5	2.1	0.563	0.790
Tyr	66.0	67.2	69.2	70.8	2.1	0.110	0.912
Total AA	71.8	75.0	74.6	77.3	3.2	0.109	0.894

[1]Least-squares means based on 8 observations per diet.

Table 7.9 Apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of energy in experimental diets including canola oil and basal part of the experimental diets (DM basis)[1]

	Canola oil inclusion, %						*P*-value	
Item, %	0 (Basal)	1.5	3.0	4.5	6.0	SEM	Linear	Quadratic
Energy digestibility of experimental diets								
AID	58.2	64.7	67.6	69.7	70.4	0.86	<0.001	<0.001
ATTD	70.0	75.9	77.3	79.0	79.4	0.54	<0.001	<0.001
Energy digestibility in basal part of the experimental diets[2]								
AID	58.2	64.2	66.7	68.0	68.0	0.70	<0.001	0.002
ATTD	70.0	75.6	76.1	77.8	77.3	0.55	<0.001	<0.001

[1]Least-squares means based on 8 observations per diet.

[2]If AID and ATTD of energy in the basal part of each experimental diet was assumed to be equal among diets with increasing canola oil inclusion, AID and ATTD of canola oil calculated using the difference method would be greater than 100% (data not shown). Thus, AID and ATTD of energy in the basal part of experimental diets were calculated using the difference method assuming 96.5% AID and 100% ATTD of energy (the highest values possible) in canola oil to show the minimum effect of canola oil inclusion on the energy digestibility in the basal diet.

Chapter 8 General discussion

8.1 Low-fibre canola co-products

Soybean meal (SBM) is the most widely fed supplemental protein feedstuff to animals worldwide but its price has doubled in the last 2 decades (World Bank, 2015). Cost-effective alternatives to inclusion of SBM in swine diets are therefore needed to reduce the feed cost and increase profit. Solvent-extracted canola meal (CM) can be a SBM alternative due to its relatively high protein content, complementing AA profile, and increased production (Arntfield and Hickling, 2011). However, dietary inclusion of CM is limited by its relatively high fibre content that reduces its energy value and AA digestibility (Bell, 1993). Breeding low-fibre canola species (such as *B. juncea*) and fractionation methods such as air-classification may reduce fibre content in CM and promote its greater dietary inclusion.

In Chapter 3 and 4, conventional dark-seeded *B. napus* and novel yellow-seeded *B. juncea* CM were air-classified to produce low-fibre, light-particle fractions and high-fibre, heavy-particle fractions. For growth performance and nutrient digestibility, an interaction between canola species and air-classified fractions was not observed. *Brassica juncea* CM had greater energy digestibility and NE value than *B. napus* CM. This increase in energy digestibility could be due to the thinner seed hull in *B. juncea* that reduced total dietary fibre, cellulose, and lignin content compared with *B. napus*. Greater apparent total tract digestibility (ATTD) of acid detergent fibre (ADF) and neutral detergent fibre (NDF) in *B. juncea* CM indicated its greater fibre fermentability in the hindgut. The standardised ileal digestibility (SID) of His, Ile, Val, Asp, Pro, and Tyr in *B. juncea* CM was greater than *B. napus* CM, but

it did not differ for other amino acids (AA). Due to the increased nutrient digestibility, feeding *B. juncea* CM resulted in greater feed efficiency (G:F) in weaned pigs than *B. napus*. However, *B. juncea* CM had double the glucosinolate content than *B. napus* CM that reduced average daily feed intake (ADFI) in weaned pigs. The reduced ADFI cancelled out the beneficial effect of increased G:F. Consequently, the average daily gain (ADG) of weaned pigs fed *B. napus* and *juncea* CM did not differ.

On the other hand, air-classification produced a light-particle, low-fibre fraction and a heavy-particle, high-fibre fraction. The light-particle fraction is a concentrate of mostly cotyledons that are less fibrous, cellulosic, and lignified; whereas the heavy-particle fraction is a concentrate of mostly the hulls that are more fibrous and contains more cellulose and lignin. As a result, the light-particle fraction had greater and the heavy-particle fraction had lower energy digestibility and energy value compared with parent CM fed to ileal-cannulated grower pigs. The ATTD of ADF in the light-particle fraction was also greater than that in the parent CM and heavy-particle fraction, suggesting greater fibre fermentation of the light-particle fraction. The light-particle fraction also had greater SID for all AA compared with the heavy-particle fraction. However, only the SID of Trp, Glu, Pro, and Tyr was greater in the light-particle fraction compared with the parent CM. Interestingly, the increased nutrient digestibility in the light-particle fraction over the parent CM only moderately increased G:F and did not affect ADFI in weaned pigs, which caused only a trend of increasing ADG.

In summary, based on the result from chapter 3 and 4, the general hypothesis that feeding of low-fibre CM products would increase energy and AA digestibility and growth

performance in pigs was accepted. However, feeding low-fibre canola co-products only moderately increased growth performance. The greater glucosinolate content in *B. juncea* CM was a major limiting factor to pig growth by reducing feed intake, and thus needs to be further reduced by breeding or processing. The extent of fibre reduction by air-classification might not be sufficient to increase growth performance meaningfully. However, the increased energy value and SID of AA in the light-particle fraction may spare supplementation of oil and crystallized AA in the diet that reduces feed cost.

8.2 High fat canola co-products

Due to increasing demand for biodiesel and virgin canola oil production, more canola seed is merely processed by mechanical pressing without solvent-extraction (CRFA, 2013; Matthäus, 2010), producing canola expeller (CE) and canola press-cake (CPC) as co-products. The CE and CPC contain more remaining oil and therefore have a greater energy values than CM. Canola expeller and CPC can therefore be fed to pigs as source of both supplemental protein and energy.

In Chapter 5, low-fibre *B. juncea* canola seed was extruded and expeller-pressed without flaking, cooking, and solvent-extraction, which produced cake with 168 g remaining fat/kg. The seed was extruded prior to expeller-pressing by a single-screw extruder without external heat and steam treatments. The extrusion was expected to resemble the cooking processes that ruptures the cell walls and inactivates myrosinase enzyme. The shearing force and autogenous heat generated during extrusion could also increase AA digestibility by opening

up the fibre matrix and denaturing protein (Camire 1991; Liang et al. 2002). However, feeding 0–200 g extruded *B. juncea* CE/kg to growing-finishing pigs linearly reduced ADFI, ADG, carcass weight, and loin depth but did not affect G:F. The reduction in ADFI was attributed to the greater content of glucosinolates, especially bitter 3-butenyl in *B. juncea* canola, and consequently reduced other performance and carcass variables. Extrusion processing utilized in this study did not eliminate the negative effects of glucosinolates on pig feed intake. Although the extrusion temperature reached 90ºC, the time for the canola seed to pass through the extruder may not have been long enough to inactivate the myrosinase. Dietary inclusion of high-fat canola co-products may reduce carcass fat firmness and pork quality due to the greater unsaturated fatty acid content of canola oil than tallow. Feeding increasing inclusion of extruded *B. juncea* CE indeed increased the unsaturated fatty acid content of jowl fat, but iodine value was still within the acceptable limit of 70g/100g of fat (Benz et al., 2010).

In Chapter 6, conventional *B. napus* canola seed was expeller-pressed without conditioning, flaking, cooking, or extrusion. The resulting CPC contained even greater remaining fat (202 g/kg) and thus energy value than the CE. The CPC was exposed to less heat during processing and therefore may have greater AA availability than CM and CE. However, reduced heat may cause insufficient inactivation of myrosinase and greater glucosinolate content in CPC. To evaluate the feeding value of CPC, diets formulated with 0–200 g CPC/kg replacing SBM balanced for NE and SID AA content were fed to weaned pigs. Increasing inclusion of CPC linearly reduced the ATTD of DM, GE, and CP, did not affect

ADFI and ADG, and linearly increased overall G:F. Feeding CPC with crystallized AA to replace SBM in pig diets could reduce the dietary CP content while still meeting the AA requirements. This replacement may lead to reduced excessive dietary AA content in the pig, better dietary AA balance, and increased post-absorption AA utilization that may offset the negative effect of lower ATTD of nutrient on growth performance. Although the CPC had greater glucosinolate content than CM, the diet with 200 g CPC/kg contained 2.2 μmol glucosinolate/g that was still within the 2.5 μmol/g limit (Schone et al., 1997), therefore it did not reduce feed intake.

In summary, based on the results from Chapter 5 and 6, the general hypothesis: feeding diets with increasing dietary inclusion of high-fat canola products balanced for NE and SID AA content would not affect growth performance and carcass traits was conditionally accepted. Feeding up to 200 g *B. napus* CPC/kg did not affect growth performance in weaned pigs. However, feeding up to 200 g extruded *B. juncea* CE/kg reduced growth performance and some carcass characteristics due to its greater content of 3-butenyl glucosinolate. Formulating diets based on NE value and SID AA content may not eliminate the negative effect of anti-nutritional factors on growth performance. The other hypothesis: feeding increasing dietary inclusion of high-fat canola products would increase jowl fatty acid unsaturation was accepted. Pork fatty acid profile can be affected by dietary fatty acid intake and should be monitored when canola fat content is increased in the diet.

8.3 Fat digestibility in canola oil and CPC

The digestibility of remaining fat in high-fat canola co-products may be less than that in added liquid canola oil due to physical entrapment of oil droplets in seed matrixes (Thacker and Petri, 2009). In Chapter 7, canola oil and CPC were produced from the same canola seed. Regression was used to estimate the total endogenous fat loss, true ileal digestibility of fat (TID), and true total tract digestibility of fat (TTTD) in canola oil and CPC. The TID and TTTD of fat in canola oil were greater than fat in CPC. However, the difference was small (within 5%-points). The total endogenous fat loss was greater for the total tract than at the ileum, which was likely due to the greater excretion of lipids from microbes and sloughed-off cells in faeces. This study also confirmed that dietary inclusion of canola oil increased the AA and energy digestibility in other dietary components. During diet formulation, the energy and AA contribution of each ingredient was usually considered independent without interacting with each other. However, the result from this study indicated that canola oil may reduce digesta passage rate in the gut, thereby increasing retention time for the digestive enzymes to digest AA, starch, and lipids.

In summary, the hypothesis: the digestibility of remaining fat in high-fat canola co-products would be lower than that in liquid extracted canola oil was accepted. The reduced fat digestibility in CPC needs to be accounted for when using prediction equations to estimate the NE value of CPC.

8.4 Limitations of studies

In general, the 5 studies were well designed and conducted. However, some limitations did exist. In Chapter 3 and 4, the effect of lower fibre content in the light-particle fraction on digestibility and growth performance was confounded by reduced particle size. Although reduced fibre content in the light-particle fraction was believed to be the major cause of its increased nutrient digestibility, it could not be separated into effects of reduced fibre or particle size. Grinding the parent meal, light-particle and heavy-particle fractions to similar particle size after air-classification may have removed this confounding effect. However, this might be difficult to achieve since the heavy-particle fraction would resist fine grinding due to the concentration of rigid hull materials. Also, the growth experiment (Chapter 3) was conducted before the digestibility experiment (Chapter 4). It might be better to conduct the digestibility experiment first and use the obtained digestibility coefficient of nutrients in CM fractions to formulate diets for the growth trial.

In Chapter 4, NE values of test ingredients were calculated using prediction equations from Noblet et al. (1994) that included DE, ADF, starch, CP, and EE. However, CM contains about 6–9% of sugars that were not included in the equation, which might have underestimated the NE value of CM.

In chapter 5, the study indicated that the extrusion did not eliminate the negative effect of glucosinolate on growth performance. If canola samples had been collected both prior and after extrusion, the effect of extrusion on glucosinolate contents in CE could have been quantified. However, for logistic reasons, such samples were not collected. Pig jowls were

collected to measure fatty acid profile, because jowl is a relatively low-value cut of the carcass. Backfat and belly fat are more popular on the market and their fatty acid profile may be different from jowl in spite that they all response similarly to dietary fatty acid profile (Benz et al., 2010).

In Chapter 7, CPC and canola oil were produced from the same canola seed. The CPC should have been solvent-extracted to produce CM. The extracted canola oil could have been added to CM to produce CM-oil mixture (fat in free form) with the same fat content as CPC (fat in inherent form). Increasing levels of CM-oil mixture and CPC could be added to a wheat and barley-based basal diet to test digestibility of fat in different forms; the effects of increasing different forms of fat on AA digestibility of other dietary components; and compare the AA digestibility in CM-oil mixture and CPC. However, solvent-extraction of CPC was not performed due to practical limitations. The current design still allowed to measure fat digestibility in canola oil and CPC, which was the main study objective.

8.5 Future studies

In Chapter 3, air-classification of CM was not entirely effective to increase growth performance of pigs, which may be attributed to the incomplete hull separation due to tight adherence between canola hull and cotyledons (Mustafa et al., 1996). Further research may perform conditioning (adjusting moisture and temperature of CM) prior to air-classification that could loosen this adherence and further reduce fibre content in the light-particle fraction (Clark et al. 2001). Also, tail-end dehulling techniques such as air-classification and sieving

could be combined with feed enzyme supplementation. The low-fibre fractions may have reduced lignin content and therefore increase the efficiency of supplemental carbohydrase hydrolysing the non-starch polysaccharides (NSP) in CM (Bach Knudsen et al., 2013). Future studies should also investigate effects of different processing variables during extrusion (extruder type, temperature, steam addition, screw speed) on the feeding value of CM. Feed enzymes may also be more effective when applied to feedstuffs after extruded (de Vries et al., 2014).

Processing variables during oil extraction may affect nutrient composition in CE and CPC greatly. Although the effect of screw speed (44 and 103 rpm) and barrel temperature (53 and 60°C) on nutrient digestibility in CPC was studied (Seneviratne et al., 2011), these processing conditions could be adjusted across a greater range. Although the energy value of CE and CPC can be calculated by prediction equations, the NE value of CE and CPC still requires determination by indirect calorimetry to measure the energy contribution of remaining oil to pigs.

In Chapter 7, it was proposed that fat in CPC was encased in the seed matrixes and thereby resisted digestion. Confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SCEM) can be performed on CPC, faecal, and digesta samples to detect the extent of fat encasement within different samples (Li et al., 2014; Jha et al., 2015). Also, based on the data of this study was speculated that dietary fat may reduce digesta passage rate and increase digestibility of other dietary components. The detailed mechanisms should be studied by measuring the physiochemical properties of the digesta and digesta passage rate.

Also, digestibility of fat can be determined for canola co-products that differ in fat content. In the same chapter, increasing dietary canola oil increased energy digestibility of other dietary components. However, the increased energy digestibility could not be accurately quantified based on the current design. A basal diet with highly-digestible ingredients (starch and casein) can be mixed with canola oil to measure the energy value of canola oil using the difference method. Then, canola oil can be mixed with grain-based basal diet to quantify the extra energy that canola oil releases from the basal diet.

8.6 Conclusions and implications

In conclusion, current limitations of feeding CM to pigs could be mitigated by canola breeding and processing. Low-fibre canola co-products had greater nutrient digestibility and growth performance when fed to pigs. The high-fat canola co-products CE and CPC could be fed as source of dietary supplemental protein and cost-effective source of dietary fat. The inherent fat in CPC is highly digestible (94.5% TTTD) although being lower than that in extracted canola oil (100% TTTD). Feeding increasing level of high-fat canola co-products from conventional *B. napus* species replacing SBM and canola oil in the diet did not affect growth performance of pigs. However, the bitterer glucosinolates in *B. juncea* canola co-products cancelled out the benefits of lower fibre and higher fat content.

Canola co-products can be included into swine diets to replace SBM while maintaining acceptable growth performance and reducing feed cost. The feeding value of canola co-products can be increased further by reducing its fibre and increasing fat content. Feeding

low-fibre and high-fat canola co-products to pigs resulted in similar or greater nutrient digestibility, growth performance when diets were formulated based on NE value and SID AA content. However, cautions still should be taken on controlling the dietary glucosinolate content within acceptable limits. Also, dietary inclusion of high-fat canola co-products needs to be limited in finishing pig diets to avoid negative effects on pork firmness.

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