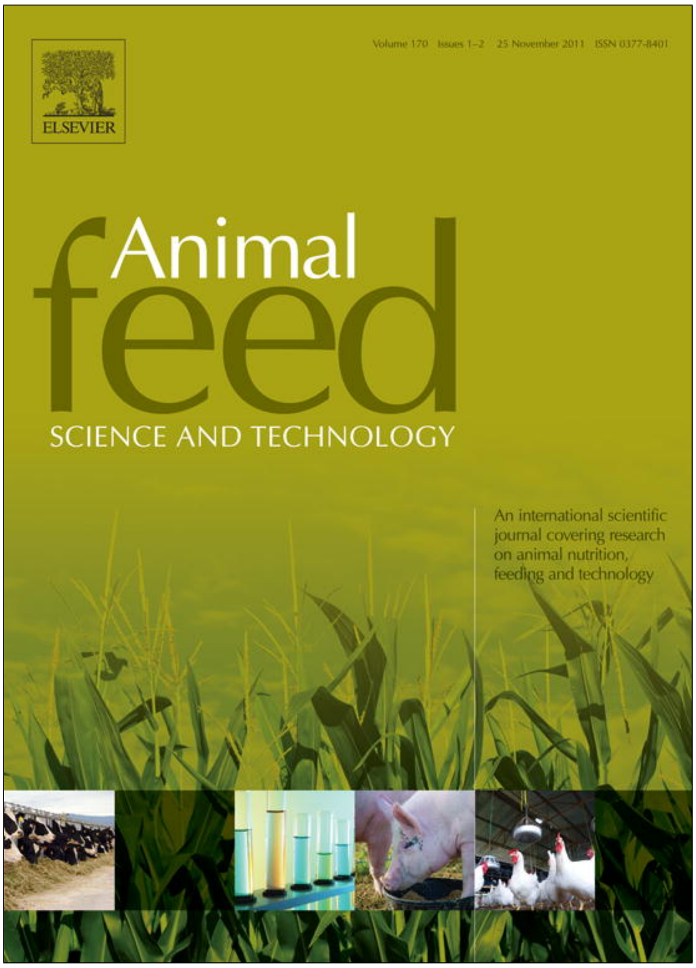
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Chemical characteristics, feed processing quality, growth performance and energy digestibility among wheat classes in pelleted diets fed to weaned pigs

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ABSTRACT

Among wheat classes based on end use, the nutritional quality of wheat for pigs is expected to vary. Therefore, Canada Prairie Spring Red (CPSR), Canada Prairie Spring White (CPSW), Canada Western Amber Durum (CWAD), Canada Western Hard White Spring (CWHWS) and Canada Western Red Winter (CWRW) wheat are separated out from Canada Western Red Spring (CWRS) wheat, which is the standard wheat for bread also known as hard red spring wheat. Two cultivars from these six wheat classes were characterised for their physico-chemical, feed milling properties and nutritional value for young, growing pigs. Growth and energy digestibility were studied for 3 wk with weaned pigs (12.8 ± 1.2 kg initial body weight) fed diets containing 650 g/kg wheat [14.6 MJ digestible energy (DE)/kg; 14.2 g digestible lysine/MJ DE]. Wheat crude protein (on dry matter basis) ranged from 124 to 174 g/kg among classes: 127–165 g for CPSW and CPSR, and 165–170 g/kg for CWAD. Total non-starch polysaccharides ranged from 90 to 115 g/kg among classes. For days 0–21, average daily gain, average daily feed intake and feed efficiency did not differ among wheat cultivars and classes (P>0.05). The coefficient of apparent total tract digestibility of energy in the diet was lowest (P<0.05) for CPSR (0.87), intermediate for CPSW, CWRS, CWHWS (0.87–0.88) and highest for CWAD and CWRW (0.89). Feed pelleting speed and pellet durability did not differ (P>0.05) among wheat diets but pelleting increased viscosity of diets (P<0.001). Principle component analysis revealed the negative impact of fibre components on feed efficiency. In conclusion, despite variations in chemical characteristics and DE content among wheat classes, young pigs fed all classes of wheat including CPSW, CPSR and CWAD may perform effectively.

Abbreviations: AA, amino acid; ADF, acid detergent fibre; ADFI, average daily feed intake; ADG, average daily gain; BW, body weight; CATTD, coefficient of apparent total tract digestibility; CP, crude protein; cPs, centipoise standard; CPSR, Canada Prairie Spring Red; CPSW, Canada Prairie Spring White; CV, coefficient of variation; CWAD, Canada Western Amber Durum; CWB, Canadian Wheat Board; CWHWS, Canada Western Hard White Spring; CWRS, Canada Western Red Spring; CWRW, Canada Western Red Winter; DE, digestible energy; DM, dry matter; GE, gross energy; G:F, feed efficiency (gain:feed ratio); NDF, neutral detergent fibre; NSAC, non-starch available carbohydrate; NSP, non-starch polysaccharide; PCA, principle component analysis; PDI, pellet durability index.

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1. Introduction

The Canadian Wheat Board (CWB, 2006) uses nine classes to segregate Western Canadian wheat for specific markets: Canada Prairie Spring Red (CPSR), Canada Prairie Spring White (CPSW), Canada Western Amber Durum (CWAD), Canada Western Extra Strong, Canada Western Feed Wheat, Canada Western Hard White Spring (CWHWS), Canada Western Red Spring (CWRS), Canada Western Red Winter (CWRW) and Canada Western Soft White Spring. Each of these classes has unique grain functional characteristics with regard to their use in bread, bakery, noodle and pasta application (Hoseney, 1994).

Wheat is commonly fed to pigs (Patience et al., 1995) as a main source of energy and can be efficiently utilised by pigs of all ages. Consideration must be given to nutrient composition, method of processing and quality and price of wheat for use in pig diets (Myer et al., 1996). Wheat is one of the most variable in fibre and crude protein (CP) content among cereal grains (Choct et al., 1999), in part a reflection of genetic selection to meet protein (gluten) or starch specifications for each class and market (Dick and Youngs, 1988), and also due to environmental and agronomic effects (Van Barneveld, 1999). The range in chemical characteristics of Canadian wheat, especially CP, starch and non-starch polysaccharides (NSP), causes variation in chemical composition and digestible energy (DE) content of wheat for pigs (Zijlstra et al., 1999) and perhaps feed processing quality. The CWRS wheat, also known as hard red spring wheat, is considered the standard for feed application; however, wheat from all classes may be used in feed, including off-grade wheat. Concerns exist about the nutritional and feed processing quality of CPSR, CPSW and CWAD wheat, and these classes are therefore currently separated out and discounted in the market place for animal feed, even though evidence for these concerns does not exist to date.

To test the hypothesis that feed processing quality and nutritional value for pigs varies among Western Canadian wheat classes (and cultivars), samples of two prominent cultivars were collected from each of six wheat classes (CPSR, CPSW, CWAD, CWHWS, CWRS and CWRW). Therefore, variation in chemical, physical and nutritional characteristics due to genetic differences was maximised and collected data had a high relevance for commercial practice, because cultivars with the highest acreage in the Canadian Prairies were selected. The specific objectives were to characterise the wheat samples for chemical and physical characteristics, to describe the grain functional characteristics (nutritional value for pigs and feed processing quality) of each wheat sample, to relate the chemical and physical characteristics to functional characteristics that differed among six wheat classes.

2. Materials and methods

2.1. Wheat samples and diets

Twelve 1500 kg wheat samples representing two cultivars for each of six wheat classes (CWB, 2006) were collected in Western Canada. The selected cultivars were the cultivars with the highest acreage within each wheat class. Each sample was grown at a single location (none on the same farm) and samples were harvested at the same stage of maturity. The samples were collected through the logistical system of Canadian Wheat Board, were each of the highest grading class and were cleaned to seed grower standards. The specific classes (and cultivars) were: CPSR (AC Crystal and AC Taber), CPSW (AC 2000 and AC Vista), CWAD (AC Avonlea and AC Navigator), CWHWS (AC Kanata and AC Snowbird), CWRS (AC Barrie and CDC Teal) and CWRW (CDC Kestrel and CDC Osprey).

At a commercial feed processing facility (FeedRite, St. Paul, AB, Canada), wheat samples were ground through a 4.0-mm screen of a hammer mill (Jacobson Machine Works, Minneapolis, MN, USA; XIT 42320, 200 hp) at constant amperage. Ground wheat samples were mixed using a horizontal double ribbon mixer (Scott Equipment Company, New Prague, MN, USA; 3 tonne, 1.37 × 3.66 m) into 2000 kg batches of phase-3 starter diets (Table 1). Mixed diets were subsequently pelleted (5 mm diameter) using a steam pellet mill with a 0.53 m diameter with 2 rolls and 200 hp (Sprout Waldron Company, Muncy, PA, USA). Diets were formulated to contain 14.6 MJ DE/kg, 14.2 g apparent ileal digestible lysine/MJ DE using least-cost feed formulation software. Diets were formulated to be non-limiting in amino acids (AA) to enable better detection of differences in energy intake and energy digestibility and therefore average daily gain (ADG). Wheat was analysed prior to feed formulation for CP content. The total content of the first four limiting AA of wheat samples was predicted using the regression equation using CP content (NRC, 1998). Digestible AA profile of wheat was predicted using digestibility coefficients (NRC, 1998). The total AA profile of wheat samples was analysed upon completion of the animal trial. Diets were supplemented with crystalline AA to an ideal amino acid ratio (NRC, 1998). Diets were fortified with minerals and vitamin and mineral premixes to meet or exceed vitamins and minerals requirements (NRC, 1998). Energy supplied by the vitamin and mineral premixes was considered to be negligible. Diets contained 8 g Celite 281 (acid-insoluble ash; Celite Corporation, World Minerals Co., Lompoc, CA, USA)/kg as an indigestible marker to determine digestibility of energy.

2.2. Experimental protocol

Animal use and procedures were approved by the University Committee on Animal Care and Supply at the University of Saskatchewan and followed principles established by the Canadian Council on Animal Care (CCAC, 1993). The animal trial was conducted at Prairie Swine Centre Inc. (Saskatoon, SK, Canada). A total of 576 pigs (288 barrows and 288 gilts;

Table 1
Ingredient composition and nutrient content of experimental diets containing 12 wheat cultivars belonging to six wheat classes.[a]

Ingredient (g/kg)	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS	
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird
Wheat	647.1	646.4	645.3	646.6	647.4	646.5	646.9	647.0	645.2	646.0	647.2	647.2
Soybean meal	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270.0	270.0
Canola oil	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Fish meal	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Dicalcium phosphate	11.8	11.8	11.9	11.8	11.8	11.8	11.8	11.8	11.9	11.9	11.8	11.8
Limestone	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
Celite[b]	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
L-Lysine-HCl	3.5	3.7	3.9	3.7	3.5	3.7	3.6	3.6	4.0	3.8	3.5	3.5
Sodium bicarbonate	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Salt	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Mineral premix[c]	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
L-Threonine	0.9	1.1	1.4	1.1	0.9	1.1	1.0	0.9	1.4	1.2	0.9	0.9
Vitamin premix[d]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Choline chloride	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
DL-Methionine	0.4	0.8	1.2	0.6	0.3	0.7	0.5	0.4	1.2	0.9	0.4	0.4
L-Tryptophan	0.1	0.2	0.2	0.2	–	0.2	0.1	0.1	0.2	0.2	0.1	0.1
Analysed composition (g/kg DM)												
Dry matter (g/kg)	914	909	905	907	907	907	904	909	899	908	906	901
Crude protein	265	250	242	263	272	260	273	263	239	249	273	271
Ether extract	63	57	57	64	60	58	61	58	51	57	61	60
Ash	68	62	66	63	63	65	68	64	77	63	65	65
Starch	391	408	397	380	375	386	391	397	391	391	380	391

[a] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.

[b] Acid-insoluble ash (Celite Corporation, World Minerals Co., Lompoc, CA).

[c] Provided the following per kilogram of diet: zinc, 289 mg; copper, 125 mg; iron, 75 mg; manganese, 55 mg; iodine, 1.0 mg; cobalt, 0.5 mg; selenium, 0.3 mg.

[d] Provided the following per kilogram of diet: vitamin A, 13,000 IU; vitamin D, 1500 IU; vitamin E, 80 IU; niacin, 33 mg; D-pantothenic acid, 20 mg; riboflavin, 9.0 mg; vitamin B_6, 3.3 mg; menadione, 3.0 mg; thiamine, 2.5 mg; folic acid, 1.0 mg; D-biotin, 0.25 mg; vitamin B_{12}, 0.024 mg.

Camborough-15 × Canabrid; PIC Canada Ltd., Winnipeg, MB, Canada) that were weaned at 3 wk of age and subsequently housed in an all-in-all-out nursery were used in a 21-day growth performance and digestibility trial.

At weaning, pigs were placed in one of six nursery rooms, each containing 24 pens (1.27 × 1.04 m) housing four pigs per pen. Each room represented a farrowing group of the herd. Pigs were assigned randomly within gender to pens containing either four barrows or gilts. Each pen was equipped with fully-slatted floors, a nipple drinker and an adjustable multiple-space dry feeder (0.49 × 0.39 m), creating an effective floor area of 1.18 m^2 or 0.30 m^2 per pig. Rooms were equipped with automatic control of ventilation and temperature to maintain a thermo-neutral environment. Each room included 12 pens of barrows and 12 pens of gilts, and a total of 12 pen observations per wheat cultivar diet were reached.

After weaning, pigs were fed a pelleted phase-1 starter diet (HND Start, Co-Op Feeds, Saskatoon, SK, Canada) for 4 days, then mixed 50% phase-1 and 50% phase-2 for 3 days, and a pelleted phase-2 starter diet (Co-op Feeds, Saskatoon, SK, Canada) for 11 days. At 39 days of age, pigs [initial body weight (BW) 12.8 ± 1.2 kg] were fed one of 12 experimental, phase-3 starter diets for 21 days. Pigs had free access to diet and water throughout the experiment.

Pigs were weighed at day 0, 7, 14 and 21. Feed consumption was measured on each weigh day. From this data, ADG, average daily feed intake (ADFI) and feed efficiency as gain:feed ratio (G:F) were calculated. Freshly voided faeces were collected by grab sampling from the pen floor for 2 days during the third wk of the experimental period, pooled per pen and stored at −20 °C. At the end of the collection period, faecal samples were thawed, homogenised, sub-sampled, freeze-dried and stored at 4 °C until analyses.

2.3. Physical and chemical analyses

Whole wheat was analysed for density (Canadian Grains Commission, Winnipeg, MB, Canada). Particle size of the ground wheat was measured using 10 sieves on a sieve shaker using method S319.3 of American Society of Agricultural Engineers (ASAE, 2001). Pellet durability index (PDI) of diets was measured using method S269.4 of ASAE (ASAE, 1997). Viscosity of the wheat and diets was measured pre- and post-pelleting was measured at 20 °C using a Brookfield viscometer in a model digestion system (Bedford and Classen, 1993).

Wheat samples, diets and freeze-dried faeces were ground through a 1-mm screen in a centrifugal mill (Retsch, Haan, Germany) to reach homogeneity. Wheat samples were analysed with a duplicate analysis for dry matter (DM), ash, ether extract using acid hydrolysis, acid detergent fibre (ADF) without amylase and expressed inclusive of residual ash, crude fibre, lignin and the minerals Ca, Na, K, Mg and P using atomic absorption spectrometry by standard procedures of Association of Official Analytical Chemists (AOAC, 2006) and for neutral detergent fibre, NDF (Van Soest et al., 1991), NSP including individual sugar moieties and uronic acid and their soluble and insoluble fractions (Englyst and Hudson, 1987) and enzymatically for starch (Salomonsson et al., 1984).

Wheat samples were analysed for phytin-phosphorus (Xu et al., 1992) and for wet gluten and gluten index using methods 137 and 155 of the International Association for Cereal Science and Technology (IACST, 1994a, 1994b, respectively). Gluten is a visco-elastic proteinaceous substance obtained after washing out starch granules from wheat flour dough and indicates wheat baking potential (Bloksma and Bushuk, 1988). Gluten index is the ratio of the wet gluten remaining on a sieve after centrifugation relative to total wet gluten content. Wheat samples were analysed for CP (macro-Kjeldahl; $N \times 6.25$) and AA (method 982.30) including methionine and cysteine (method 994.12) using standard procedures of AOAC (2006). Tryptophan was not analysed.

Diets and faeces were analysed for DM, acid-insoluble ash (McCarthy et al., 1974) and gross energy (GE) using an adiabatic bomb calorimeter (model 1281, Parr Instrument Co., Moline, IL, USA) for calculation of the coefficient of apparent total tract digestibility (CATTD) of energy using acid-insoluble ash content in diets and faeces by the indicator method (Adeola, 2001).

2.4. Statistical analyses

For wheat characteristics, the coefficient of variation (CV) among cultivars was calculated so that variation among samples can be compared to other studies. A CV larger than 10% was considered wide variation, a CV <5% was considered little variation and a CV of 5–10% was considered medium variation. For pig data, pigs removed from the study did not result in removal of the data from the pen. For pig growth performance and digestibility variables, a gender × diet interaction was not observed; hence, the interaction term was removed from the model, resulting in two randomised complete blocks per room. Pen was considered the experimental unit. Variables were analysed by analysis of variance using the MIXED model procedure of SAS (SAS, 2003). The statistical model included effects for wheat class as main factor in the model; initial BW was included as covariate for analyses of growth performance data. Data are reported as least square means. In case of a wheat class effect, wheat classes were separated using least significant difference analysis with the pdmix800 statement within the MIXED model procedure. Overall, differences were considered significant at $P<0.05$. The MIXED model procedure was also used to analyse the effect of pelleting on viscosity with pelleting as main effect and wheat class as random variable in the model. To explain interrelationships among multiple physico-chemical properties of wheat cultivars and pig performances, a principle component analysis (PCA) was conducted using JMP software (SAS, 2009). A step-wise regression procedure of SAS (SAS, 2003) was used to calculate regression equations between performance and chemical and physical characteristics.

3. Results

3.1. Characteristics of wheat samples

The DM, starch and GE content varied little among cultivars (Table 2), whereas the variation was wide for crude fibre and ADF content. The CP content varied widely and ranged from 124 to 174 g/kg for CDC Kestrel (CWRW) and AC Kanata (CWHWS), respectively.

The insoluble portion of total NSP and individual monosaccharides was generally larger than the soluble portion (Table 3). The variation was medium among cultivars for total NSP. The variation among wheat cultivars was generally wider for the soluble than insoluble portion of NSP, constituent monosaccharides and cellulose content. The wide variation in CP content was reflected in changes in AA content among wheat cultivars (Table 4).

Density among the wheat cultivars ranged from 76.7 kg/hL for AC Snowbird (CWHWS) to 84.0 kg/hL for AC Kanata (CWHWS), and varied little among cultivars (Table 5). Phytin-P, viscosity, wet gluten and gluten index varied widely among wheat cultivars.

3.2. Feed processing characteristics

Wheat grinding speed varied little among wheat cultivars, and mean particle size ranged from 536 to 734 μm (Table 5). Feed pelleting speed and PDI varied little among the wheat diets. Interestingly, feed pelleting increased ($P<0.001$) viscosity of diets from a range of 4.71–6.09 cPs to a range of 4.82–9.94 cPs among diets and pelleting increased the CV of viscosity among cultivars. However, viscosity pre- and post-pelleting did not differ ($P>0.05$) among wheat classes.

3.3. Growth performance and energy digestibility

Pigs fed the six wheat classes did not differ ($P>0.05$) in ADG, ADFI and G:F during the entire experiment period (Table 6). Final BW ranged from 26.3 to 27.1 kg among cultivars and did not differ ($P>0.05$) among wheat classes. The CATTD of energy and DE content of diets differed ($P<0.001$) among wheat classes. The CATTD of energy ranged from 0.857 to 0.898 for AC Taber (CPSR) and AC Avonlea (CWAD), respectively. Dietary DE content ranged from 16.19 to 16.99 MJ/kg DM for AC Taber (CPSR) and AC Avonlea (CWAD), respectively.

3.4. Principle component analysis

The PCA loading plot (Fig. 1) indicates relationships among physico-chemical and functional characteristics of wheat cultivars and growth performance of piglets. In the loading plot, the insoluble fibre components (ADF, NDF, lignin and total NSP) were clustered closely together opposite to G:F, while ADFI and ADG were correlated to starch content and density of wheat. Soluble NSP was associated with viscosity and gluten index. Wet gluten content was in the quadrant opposite to ADFI and ADG, whereas G:F and energy digestibility were in quadrant opposite to soluble NSP, gluten index and viscosity. The ADG was correlated positively with energy digestibility and ADG and ADFI were correlated negatively with wheat particle size. Energy digestibility was not related to wheat particle size.

3.5. Prediction of ADFI, growth performance, energy digestibility and digestible energy

Prediction models of final BW, overall ADG, ADFI and G:F of pigs, and energy digestibility and DE content of experimental diets by physical and chemical characteristics of wheat were established. Wheat density was the best predictor for final BW ($R^2 = 0.53$; $P=0.007$) and ADG ($R^2 = 0.51$; $P=0.009$). The ADFI was best predicted by wet gluten ($R^2 = 0.43$; $P=0.021$). Viscosity was the best single predictor for DE content ($R^2 = 0.37$; $P=0.036$).

4. Discussion

Wheat is the ingredient that supplies most dietary energy in pig diets in Western Canada, Australia and the UK. Under normal market conditions, wheat that is graded average or high for its class is used for food products, whereas excess wheat and off-grade wheat are used in animal feeds. Wheat that is not CWRS is used reluctantly in pig diets due to lack of information about its nutritive value. Thus, the present study compared wheat classes for their physico-chemical properties and effects on production performance of young, growing pigs, so that recommendation can be made for the use of all wheat classes in pig diets. In the present study, small differences in energy digestibility among wheat classes were observed but these did not result in changes in growth performance.

Considerable variation exists in the content of DE and other nutrients within samples of a cereal grain (Van Barneveld, 1997). For example, the DE content ranged from 11.2 to 13.1 MJ/kg of 90% DM for 20 samples of covered barley (Fairbairn et al., 1999). This variation within a grain appears mostly due to growing and harvest conditions and less due plant genetic background (Choct et al., 1999; Kim et al., 2005). For example, the DE content of 16 wheat samples ranged from 15.4 to 16.9 MJ/kg of DM (Zijlstra et al., 1999). Most of these 16 wheat samples had been selected from generally poor growing and

Table 2
Chemical composition of 12 wheat cultivars belonging to six wheat classes.[a]

Item (g/kg DM)	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS		CV[b] (%)
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird	
Dry matter (g/kg)	912	904	896	895	906	899	891	909	895	903	905	892	0.8
Crude protein	165	152	127	160	173	157	170	165	124	139	174	174	11.4
Crude fat	16	14	14	14	14	14	14	16	16	16	18	14	9.0
Starch	564	554	584	559	541	579	552	574	582	582	545	553	2.8
Crude fibre	14	15	11	14	17	16	14	13	15	15	14	18	12.5
Neutral detergent fibre	80	89	83	87	90	88	72	72	83	78	83	91	7.8
Acid detergent fibre	23	28	24	32	28	25	22	18	32	25	27	28	15.0
Lignin	14	13	12	14	16	13	11	10	13	14	14	11	14.4
Ash	23	26	21	24	29	26	30	32	38	22	28	24	18.0
Calcium	0.5	0.3	0.4	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.3	17.8
Phosphorus	3.6	2.9	2.9	2.5	2.8	3.5	3.5	3.0	3.2	2.7	3.9	3.2	13.3
Potassium	5.7	5.2	4.9	5.2	4.9	5.2	6.9	6.4	6.4	4.8	5.1	5.2	12.7
Magnesium	1.7	1.3	1.2	1.3	1.5	1.4	1.3	1.3	1.4	1.2	1.6	1.5	11.2
Sodium	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
GE[c], MJ/kg DM	17.0	16.8	16.6	16.8	17.0	16.8	16.8	17.0	16.6	16.9	17.0	16.8	0.9

[a] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.
[b] Coefficient of variation among the 12 wheat cultivars.
[c] Gross energy.

Table 3
Non-starch polysaccharide (NSP) content of 12 wheat cultivars belonging to six wheat classes.[a]

Item (g/kg DM)	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS		CV[b] (%)
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird	
Total NSP	113	114	110	113	108	115	101	90	101	97	109	113	7.2
Insoluble	86	83	82	87	84	83	81	63	81	76	83	91	8.5
Soluble	27	32	28	26	24	31	20	27	29	21	25	22	14.5
Arabinose	28	27	25	27	27	27	25	23	24	24	25	28	6.9
Insoluble	21	19	19	21	19	19	20	15	18	18	19	21	8.6
Soluble	7.0	7.6	6.5	6.5	7.9	8.8	4.6	7.3	6.5	6.0	5.8	6.4	16.1
Xylose	39	41	37	38	38	42	32	28	35	35	35	39	10.5
Insoluble	30	32	29	30	29	30	27	21	27	28	29	33	10.3
Soluble	9.2	9.4	8.4	8.0	8.7	11.4	5.0	7.3	8.1	7.0	6.5	6.6	20.8
Mannose	2.5	3.5	3.1	2.8	2.4	3.0	2.8	2.7	3.0	3.1	3.2	2.7	10.7
Insoluble	1.9	2.4	2.2	2.1	1.9	2.2	2.0	1.9	2.0	2.3	2.4	2.0	8.9
Soluble	0.6	1.1	0.8	0.7	0.5	0.8	0.8	0.8	1.0	0.7	0.9	0.7	21.0
Galactose	3.9	6.3	5.0	5.9	5.2	6.4	6.3	7.4	7.8	5.1	6.9	5.6	18.4
Insoluble	1.3	2.2	1.6	2.2	1.9	2.3	2.7	2.8	3.3	1.9	2.7	2.2	24.6
Soluble	2.6	4.1	3.3	3.6	3.3	4.1	3.6	4.6	4.5	3.2	4.2	3.3	16.3
Glucose	10.6	12.4	13.7	11.3	10.1	11.1	9.3	7.5	11.0	9.6	11.1	9.9	14.7
Insoluble	5.7	6.2	7.7	7.2	9.0	7.8	6.6	4.9	6.3	7.9	6.4	8.3	16.9
Soluble	4.9	6.2	6.0	4.1	1.1	3.3	2.7	2.6	4.7	1.6	4.7	1.6	47.8
Uronic acid	5.6	6.4	5.1	6.3	5.9	5.6	6.0	6.3	6.5	5.1	5.7	6.5	8.5
Insoluble	2.8	2.9	2.4	3.0	3.3	2.7	2.8	2.6	2.9	2.4	2.8	3.1	9.4
Soluble	2.7	3.5	2.8	3.3	2.6	3.0	3.2	3.6	3.6	2.7	2.9	3.4	11.9
Cellulose	24	18	20	22	19	20	20	15	21	16	22	21	12.9

[a] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.

[b] CV, coefficient of variation among 12 wheat cultivars.

Table 4
Amino acid (AA) content of 12 wheat cultivars belonging to six wheat classes.[a]

AA (g/kg DM)	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS		CV[b] (%)
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird	
Alanine	6.0	5.8	5.1	6.3	6.3	6.0	6.3	5.9	5.0	5.4	6.3	6.1	8.0
Arginine	8.1	7.9	6.3	7.8	8.4	7.5	8.5	8.3	6.1	6.3	8.4	8.3	11.8
Aspartic Acid	9.0	8.4	7.6	9.4	9.2	9.0	10.2	9.0	7.6	8.0	9.2	8.9	8.7
Cystine	4.5	4.2	3.6	4.7	4.9	4.4	4.6	4.5	3.8	4.0	4.8	4.6	9.2
Glutamic Acid	55.9	50.9	42.7	58.4	59.5	57.4	57.8	55.2	41.1	48.6	60.2	59.1	12.2
Glycine	7.3	7.2	6.1	7.4	7.6	7.2	6.6	6.4	5.9	6.5	7.4	7.4	8.4
Histidine	4.2	3.9	3.1	3.1	4.4	3.9	4.4	4.4	3.1	3.4	4.3	4.3	14.2
Isoleucine	6.3	5.8	4.8	6.4	6.7	6.2	6.6	6.5	4.8	5.5	6.5	6.4	11.1
Leucine	12.0	11.1	9.0	11.7	12.6	11.2	12.8	12.8	8.9	10.0	12.5	12.2	12.3
Lysine	4.6	4.2	3.9	4.6	4.7	4.6	4.6	4.6	3.9	4.1	4.8	4.6	7.2
Methionine	2.9	2.7	2.5	3.2	3.1	3.1	3.0	3.1	2.5	2.7	3.1	2.9	8.5
Phenylalanine	8.6	7.5	6.4	8.4	9.2	8.3	8.9	8.5	6.1	7.0	9.3	9.1	13.6
Proline	18.2	15.9	17.1	22.7	19.9	16.6	18.6	17.8	16.8	18.8	20.0	19.5	10.2
Serine	8.4	7.9	6.8	8.6	8.7	8.3	8.9	8.8	6.6	7.2	9.0	8.9	10.5
Threonine	4.7	4.4	4.4	5.5	5.0	5.3	4.8	4.8	4.2	4.5	5.0	4.7	8.0
Valine	7.7	7.3	6.0	7.7	8.3	7.5	8.1	8.0	5.9	6.6	8.0	7.8	10.9
Total non-essential	105	96	86	113	111	105	108	103	83	95	112	110	10.0
Total essential	63	59	50	63	67	62	66	66	50	54	67	65	10.5
Total	168	155	136	176	178	167	175	169	133	149	179	175	10.1

[a] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.

[b] CV, coefficient of variation among 12 wheat cultivars.

Table 5
Physico-chemical characteristics of wheat and feed processing characteristics of wheat and experimental diets of 12 wheat cultivars belonging to six wheat classes.[a]

Characteristic	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS		CV[b] (%)
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird	
Physico-chemical characteristics of wheat													
Density (kg/hL)	77.3	83.2	84.0	83.6	77.3	83.8	80.7	82.8	79.3	83.2	84.0	76.7	3.6
Phytin-P (g/kg)	2.6	2.0	2.1	1.7	2.0	2.3	2.8	2.1	2.3	2.2	2.9	2.3	15.2
Viscosity (cPs)[c]	6.67	5.96	8.42	5.96	5.81	7.76	3.42	5.47	5.01	6.12	5.06	5.24	22.1
Wet gluten (%)	35.9	31.8	23.0	32.7	35.6	32.7	34.9	34.1	25.7	27.4	41.5	39.2	16.3
Gluten index (%)	73.8	60.8	97.6	78.1	84.2	77.2	48.0	50.8	80.0	94.2	41.7	65.1	25.3
Grinding characteristics of wheat													
Tonne/h	8.61	9.45	9.37	9.44	8.57	9.47	8.87	9.45	8.52	9.25	9.23	9.51	4.3
Particle size													
Mean (μm)	591	700	556	631	640	708	734	624	536	636	724	629	9.9
S_{gw}[d]	1.87	1.89	1.94	2.02	2.02	2.00	2.16	1.95	1.90	1.98	1.78	2.08	5.2
Pelleting characteristics of experimental diets													
Tonne/h	15	15	15	15	15	15	15	15	13.3	15	15	15	3.3
PDI[e] (% DM)	96	96	96	95	96	96	95	95	95	95	96	96	0.5
Viscosity[f] (cPs)													
Pre-pelleting	6.09	5.52	5.51	5.50	5.42	5.69	4.71	5.39	4.78	5.36	4.97	4.85	7.7
Post-pelleting	9.94	7.91	7.53	7.96	6.12	9.44	4.82	7.17	5.79	6.78	6.72	7.20	19.8
Change	3.85	2.39	2.02	2.46	0.70	3.75	0.11	1.78	1.01	1.42	1.75	2.35	56.7

[a] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.
[b] CV, co-efficient of variation among 12 wheat cultivars;.
[c] cPs, centipoise standard.
[d] S_{gw}, standard deviation of particle size.
[e] PDI, pellet durability index.
[f] Pelleting increased viscosity of diets ($P<0.001$) but means did not differ among wheat classes ($P>0.05$).

Table 6
Growth performance and energy digestibility of weaned pigs fed diets based on 12 wheat cultivars belonging to six wheat classes.[f]

Variable	CPSW		CPSR		CWRS		CWAD		CWRW		CWHWS		Pooled	P-value
	AC 2000	AC Vista	AC Crystal	AC Taber	AC Barrie	CDC Teal	AC Avonlea	AC Navigator	CDC Kestrel	CDC Osprey	AC Kanata	AC Snowbird	SEM[g]	Class
Average daily gain (g)														
Day 0–7	540	492	521	499	481	492	498	453	529	535	513	478	27.2	0.188
Day 8–14	689	683	719	702	696	747	706	739	704	704	710	713	27.9	0.715
Day 15–21	762	810	796	809	808	749	776	821	765	800	797	731	32.0	0.799
Day 0–21	664	662	679	669	661	664	660	671	666	679	674	641	15.7	0.880
Average daily feed intake (g)														
Day 0–7	717	723	724	698	703	738	746	704	764	756	706	707	23.2	0.105
Day 8–14	935	930	969	949	991	998	953	980	1,003	919	958	988	26.2	0.193
Day 15–21	1.161	1.236	1.201	1.220	1.183	1.241	1.222	1.216	1.217	1.246	1.198	1.150	34.4	0.773
Day 0–21	938	963	964	957	960	992	973	967	995	975	954	955	19.8	0.450
Feed efficiency (gain:feed ratio)														
Day 0–7	0.77	0.69	0.72	0.72	0.68	0.66	0.66	0.65	0.70	0.71	0.73	0.67	0.035	0.165
Day 8–14	0.75	0.74	0.75	0.75	0.70	0.74	0.74	0.76	0.70	0.77	0.75	0.73	0.029	0.921
Day 15–21	0.66	0.66	0.63	0.67	0.69	0.60	0.64	0.68	0.63	0.64	0.67	0.62	0.024	0.748
Day 0–21	0.71	0.69	0.71	0.70	0.69	0.67	0.68	0.69	0.67	0.70	0.71	0.67	0.017	0.516
Energy digestibility														
CATTD[h]	0.867^{b}	0.877^{b}	0.874^{c}	0.857^{c}	0.863^{b}	0.886^{b}	0.898^{a}	0.880^{a}	0.885^{a}	0.888^{a}	0.873^{b}	0.877^{b}	0.002	<0.001
DE[i] (MJ/kg DM)	16.28^{d}	16.48^{d}	16.28^{e}	16.19^{e}	16.32^{cd}	16.48^{cd}	16.99^{a}	16.48^{a}	16.48^{b}	16.65^{b}	16.57^{bc}	16.53^{bc}	0.04	<0.001

[a–e] Within a row, wheat classes without a common letter differ ($P<0.05$).

[f] CPSW, Canada Prairie Spring White; CPSR, Canada Prairie Spring Red; CWRS, Canada Western Red Spring; CWAD, Canada Western Amber Durum; CWRW, Canada Western Red Winter; CWHWS, Canada Western Hard White Spring.

[g] Pooled standard error of the mean based on twelve 12 pen observations per wheat cultivar. Growth performance variables were analysed using BW at day 0 as covariate and are reported as least-square means.

[h] CATTD, coefficient of apparent total tract digestibility of energy.

[i] DE, digestible energy.

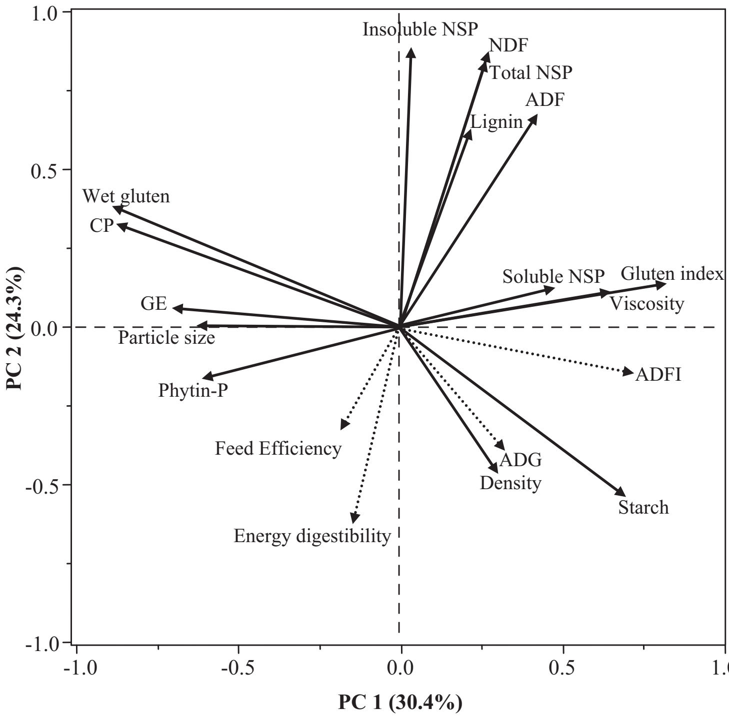

Fig. 1. Loading plot from principle component analysis (PCA) showing interrelationships of physico-chemical and processing properties (solid line) of wheat cultivars and growth performance and digestibility properties (dotted line) of weaned pigs. In PCA, the length, direction, and angle between arrows indicates the correlation between variables or between variables and principle component axes (*e.g.*, $\alpha = 0°$ and $r = 1$; $\alpha = 90°$ and $r = 0$; and $\alpha = 180°$ and $r = 1$). Percentages on *X* and *Y* axes indicate proportions of variability of data that are described with the corresponding principle component in the model.

harvest conditions as reflected by the density ranging from 45.4 to 77.6 kg/hL and may not have represented the nutritional value of most wheat classes grown in Canada. In the present study, the chemical composition of the wheat cultivars was comparable to values in the literature (Kim et al., 2005; NRC, 1998).

For the present study, with a dietary inclusion rate for wheat of 650 g/kg, the 47 g/kg or 0.78 MJ/kg DM range in diet DE content converts to a 72 g/kg or 1.21 MJ/kg DM range in wheat DE content. Previously, a 1.50 MJ/kg DM range in DE content was observed for wheat (Zijlstra et al., 1999), suggesting that the 12 wheat samples used in the present study did cover 80% of a range that was observed previously. The measured diet DE content was higher than the formulated DE content for 10 out of 12 wheat diets, indicating that the diets had a good nutritional quality, and that likely the wheat samples overall had a higher DE content than reported by NRC (1998).

Diets were corrected for predicted digestible AA in the present study. The correction ensured that the measured range in CP content and thus AA content among wheat samples did not contribute to differences in protein deposition and thus growth performance. Hence, if differences would have been observed, these would then have been due to wheat carbohydrates. However, difference in performance among pigs fed different wheat cultivars and classes were not observed in the present study, likely due to the overall low and limited range in fibre content among the 12 wheat samples used. For example, total xylose content ranged previously from 43 to 65 g/kg DM, and increased total xylose content was related linearly to reduced wheat DE content (Zijlstra et al., 1999); however, total xylose did not exceed 42 g/kg DM in the present study. The NSP data thus suggest that the 12 wheat samples in the present study were good quality wheat samples, compared to the average quality and below average quality wheat samples tested previously (Zijlstra et al., 1999).

Feed processing quality of wheat is an important consideration for feed compounders. For example, quality may determine throughput of the feed processing plant, the amount of feed that is sold as pellets *vs.* fines, cost of the diet, and perhaps growth performance (Beyer et al., 2000). Data of the present study indicated that grinding and pelleting throughput did not differ among wheat classes. The high PDI among wheat classes indicated that pellets remained intact, reflecting the excellent pellet-binding characteristics of all wheat cultivars. Finally, mean particle size varied 10% among samples. However, in contrast to reduced particle size in mash diets being associated with increased nutrient digestibility (Wondra et al., 1995), the PCA indicated that increased particle size was associated with reduced ADFI in pelleted diets in the present study, an observation that requires a future, causal explanation. Overall, the little to medium variation in processing data indicated that wheat class did not affect feed processing characteristics.

The PCA plot provided information about interrelationship among multiple characteristics, including physico-chemical, pig growth performance and feed processing. Variables located close together were positively related while variables located in an opposite quadrant were negatively correlated. The PCA plot thus indicated the wheat physico-chemical characteristics that are important for pig feed application. Strong associations between physical measurements and nutrient composition can be used to predict the DE content of the wheat for pigs (Wiseman, 2000). For example, most fibre measures had a strong negative association with energy digestibility (Fairbairn et al., 1999; Taverner and Farrell, 1981; Zijlstra et al., 1999) and G:F. Instead, soluble NSP was associated strongly with viscosity, gluten index and ADFI. Indeed, soluble wheat NSP may increase digesta viscosity, which in turn, may reduce digesta passage rate and feed intake in pigs (Owusu-Asiedu et al., 2006). Moreover, increased fibre content of the dietary cereal reduced energy and nutrient digestibility (Bach Knudsen, 2001; Noblet and Le Goff, 2001), which in turn, may influence the productive performance of pig. However, the causal effect between fibre and ADG was not proven in the present study.

Wheat cultivars are classified based on their unique functional characteristics with regard to their use in bread, bakery, noodle and pasta application (CWB, 2006). But, these wheat classifications seem less important in pig diets, because growth performance did not differ among wheat classes. Instead, growth performance was associated with physico-chemical properties. Interestingly, wet gluten content of wheat that is considered a positive characteristic for human food products due to their visco-elastic properties (Wieser, 2000) had a negative association with ADG and ADFI of pigs. The present classification of wheat class may thus not have meaning for feed application; therefore, concerns regarding the use of the CPSR, CPSW and CWAD instead of CWRS wheat were not supported by the present study.

5. Conclusion

In diets corrected for wheat protein content, reductions in feed intake or growth for CPSR, CPSW and CWAD compared to CWRS wheat did not exist. Results indicated that energy digestibility differed among classes and is a more sensitive measure of wheat quality than performance measurements, and that the weaned pig might be able to compensate for differences in wheat DE content. In conclusion, wheat across classes can be used effectively and without limitation for inclusion in diets fed to weaned pigs, provided that wheat fibre content is low and wheat AA content has been corrected for in diet formulation. Wheat class did not affect feed processing characteristics.

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