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Review article

Nutritional value of feed ingredients of plant origin fed to pigs

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ABSTRACT

Since the 1950'ties, most diets fed to commercially raised pigs have been formulated based on plant feed ingredients and without using animal feed sources. Cereal grains have historically been the main stable in pig diets, but because pigs require nutrients rather than specific feed ingredients, it is possible to provide a well-balanced diet that includes all necessary nutrients using a large number of different feed ingredients. Many of these ingredients are co-products from the human food industry, which often are excellent sources of nutrients. Co-products from other industrial processes, such as production of fuel ethanol, are also available and may be used in diet formulations. Over the last few years, new fermentation or processing technologies have been introduced as a way to improve the nutritional value of certain feed ingredients, which may broaden the usage of such ingredients. However, regardless of the ingredient being fed, the value of the ingredient is primarily determined by the concentration of metabolizable or net energy, the concentration and digestibility of indispensable amino acids, and the concentration and digestibility of phosphorus because energy, amino acids, and phosphorus are the most expensive components of diets fed to pigs. Ingredients may also contain anti-nutritional factors that limit the inclusion rate in the diet to all or some categories of pigs and knowledge about acceptable inclusion levels of ingredients is, therefore, required for successful use of these ingredients in diets fed to pigs. Inclusion rate of some feed ingredients may also be limited because of effects on the final products that are marketed from pigs and because any changes in the composition or characteristics of the final products may reduce the value of the product, knowledge about effects on final products are also important. Thus, for successful usage of feed ingredients in diets fed to pigs, it is required that knowledge about the chemical composition, the digestibility of energy and nutrients, and acceptable inclusion rates in diets fed to different categories of pigs is available. It is the objective of the present review to provide this knowledge for a number of plant feed ingredients that are commonly used in diets fed to pigs.

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Abbreviations: AA, amino acids; CP, crude protein; DDGS, distillers dried grains with solubles; SBM, soybean meal; SID, standardized ileal digestibility.

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1. Introduction

Pigs are omnivorous animals and are generally capable of consuming a wide variety of feed ingredients. However, most commercially fed pigs are provided diets that are fairly simple in composition consisting of one or two sources of cereal grains, one or two protein sources, and vitamins and minerals. Following the discovery of cobalamine (vitamin B_{12}) in 1948 and the subsequent production of synthetic vitamin B_{12} (McDowell, 2013), it became possible to formulate diets for pigs based on only plant ingredients, minerals, and synthetic vitamins. In the 1950'ties it was documented in the United States that pigs thrive on a diet based on maize and soybean meal (**SBM**) as long as sufficient quantities of vitamins and minerals are added to the diet (Cromwell, 2000). The popularity of the maize-SBM diet spread to many other countries in the world and this combination of ingredients is the most common diet fed to pigs in the Americas, in many countries in Asia, and in many central and southern European countries. In regions of the world where climatic conditions preclude economic production of maize, other cereal grains such as wheat, barley, triticale, sorghum, and rye may be used in combination with SBM or other protein sources. The rapid increase in the production of soybeans during the last 50 years has made it possible to use SBM as the primary source of crude protein (**CP**) and amino acids (**AA**) in most countries in the world and because of the increased demand for SBM, production of soybeans is now the fastest growing agricultural crop in the world (Goldsmith, 2008). However, despite the favorable nutritional value of the grain-SBM diet, a number of other feed ingredients are often used in diets fed to pigs. The reason for using other ingredients is primarily to reduce costs of diets by taking advantage of the large number of co-products that are generated from the food industry and other industries (Zijlstra and Beltranena, 2013; Woyengo et al., 2014). There are, therefore, numerous feed ingredients that may be included in diets fed to pigs.

The objective of the present contribution is to review current knowledge about energy and nutrient composition, energy and nutrient digestibility, and recommended inclusion rates of feed ingredients of plant origin that may be used in diets fed to pigs. Data for composition and digestibility of energy and nutrients that are presented are primarily from the feed nutrient database that is maintained at the University of Illinois (http://nutrition.ansci.illinois.edu)

2. Cereal grains

Pigs do not have a requirement for cereal grains in the diet, but in all commercial diets fed to pigs, one or more cereal grains are included and in most cases, cereal grains provide the majority of the energy in the diets. Cereal grains differ in concentrations of lipids, fiber, and CP, and the nutritional value, therefore, is different among cereal grains (Tables 1 and 2). Although pigs generally digest starch very efficiently, differences among cereal grains in starch digestibility have been reported (Cervantes-Pahm et al., 2014a), and differences in the digestibility of AA also have been reported (Tables 3 and 4).

2.1. Barley

Barley is grown in many countries in Europe, Canada, the United States, and Australia, where it is used for malting or for feeding of livestock. Total global production is around 140 million tons per year (Statista, 2015), which is 4th in terms of volume after maize, rice, and wheat. Barley has a greater concentration of AA and fiber and a reduced concentration of starch

Table 1
Composition of barley, maize, oats, and polished rice.

Item	Ingredient											
	Barley			Maize			Oats			Polished rice		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	56	16.1	1.3	157	16.7	0.7	4	17.5	0.3	6	15.3	0.7
Dry matter, g/kg	104	891.0	37.0	329	882.0	22.0	19	903.0	27.0	7	870.0	9.0
Crude protein, g/kg	159	108.0	17.0	364	81.0	11.0	23	113.0	17.0	8	81.0	22.0
Acid hydrolyzed ether extract, g/kg	7	30.0	15.0	17	29.0	19.0	–	–	–	1	9.0	–
Ash, g/kg	94	41.0	31.0	190	14.0	10.0	13	26.0	8.0	5	5.0	3.0
Starch, g/kg	64	497.0	59.0	66	621.0	51.0	13	401.0	83.0	6	753.0	73.0
Acid detergent fiber, g/kg	69	58.0	17.0	135	29.0	10.0	9	119.0	57.0	4	6.0	1.0
Neutral detergent fiber, g/kg	65	185.0	46.0	150	102.0	31.0	7	227.0	124.0	4	9.0	4.0
Total dietary fiber, g/kg	7	188.0	21.0	5	95.0	9.0	2	228.0	157.0	2	12.0	2.0
Calcium, g/kg	40	0.6	0.2	117	0.2	0.3	3	1.6	1.7	1	0.4	–
Phosphorus, g/kg	48	3.6	0.5	142	2.6	0.5	4	3.2	1.0	1	1.8	–
Phytate, g/kg	17	7.8	1.4	10	7.4	1.4	2	6.7	–	–	–	–
Indispensable amino acids, g/kg												
Arginine	42	5.3	0.9	252	3.8	0.6	5	7.9	1.4	2	7.2	1.5
Histidine	38	2.6	0.7	246	2.4	0.5	5	2.6	0.5	2	2.5	0.5
Isoleucine	48	3.6	0.7	257	2.8	0.6	5	4.4	0.9	2	3.9	0.6
Leucine	40	7.2	1.2	246	9.6	1.6	5	8.4	1.4	2	7.4	1.1
Lysine	54	4.1	0.8	264	2.6	0.5	5	4.8	0.8	2	4.4	2.0
Methionine	50	2.0	0.3	256	1.7	0.4	5	3.9	2.7	2	2.2	0.1
Phenylalanine	38	5.3	1.2	245	3.9	0.6	5	5.7	1.1	2	4.6	0.5
Threonine	51	3.6	0.6	258	2.8	0.5	5	4.2	0.5	2	3.6	1.2
Tryptophan	32	1.2	0.2	219	0.6	0.1	2	1.3	0.1	2	1.0	0.4
Valine	48	5.1	0.9	256	3.8	0.6	5	6.4	1.1	2	6.2	1.8
Dispensable amino acids, g/kg												
Alanine	34	4.3	0.7	198	6.0	0.9	2	5.7	1.4	1	4.4	–
Aspartic acid	34	6.4	1.0	198	5.4	0.9	2	10.0	2.1	1	6.8	–
Cysteine	48	2.6	0.5	232	1.8	0.3	3	3.8	0.7	2	2.1	0.2
Glutamic acid	34	24.6	6.2	190	14.8	2.7	2	21.7	6.9	1	14.1	–
Glycine	36	4.4	0.7	196	3.2	0.6	2	6.1	1.5	1	3.5	–
Proline	32	11.1	3.1	182	6.9	1.2	2	6.7	1.0	1	3.3	–
Serine	36	4.4	0.9	192	3.8	0.6	2	6.1	1.8	1	3.4	–
Tyrosine	36	2.8	0.6	216	2.6	0.7	2	3.8	0.4	2	3.4	1.5

compared with maize, but the digestibility of starch and AA in barley is less than in wheat and maize (Stein et al., 2001; Pedersen et al., 2007a; Cervantes-Pahm et al., 2014a). The standardized ileal digestibility (**SID**) of most indispensable AA is between 70 and 80% (Table 2) and a meta-analysis including data for SID of AA in barley from 26 different peer-reviewed journal articles was recently published (Spindler et al., 2014).

Barley fiber contains mixed linked beta glucans in addition to arabinoxylans and cellulose and is, therefore, more fermentable than fiber from wheat and maize (Bach Knudsen, 1997). Because of the greater concentration of fiber in barley than in most other cereal grains, the concentration of digestible and metabolizable energy in fiber is less than in most other cereal grains. However, there is significant variability in the concentrations of fiber in barley and in general, the greater the concentration of fiber is, the less digestible energy is present in barley (Fairbairn et al., 1999).

Barley may be included in diets fed to all categories of pigs. In starter diets, it has been demonstrated that barley may replace sorghum (Goodband and Hines, 1988) or wheat (Yin et al., 2001; Nasir et al., 2015) without any impact on growth performance, but if pigs are fed diets containing barley rather than maize, ADG may be improved (Medel et al., 1999; Yin et al., 2001). However, weanling pig performance is improved if barley is ground to 635 μm rather than 768 μm (Goodband and Hines, 1988) and pigs fed micronized barley or barley that is heat treated have improved performance compared with pigs fed raw barley (Medel et al., 2000, 2002). It has been demonstrated that inclusion of barley in diets fed to weanling pigs may reduce the occurrence of diarrhea possibly due to prebiotic effects of the beta-glucans in barley, which may result in reduced colonic pH (Paulicks et al., 2000; Montagne et al., 2003; O'Connell et al., 2005). Pigs fed barley also have an increased Lactobacillus spp. to Enterobacteriaceae ratio in the small intestine compared with pigs fed wheat, indicating a favorable shift in intestinal microbiota (Weiss et al., 2016).

Pigs fed diets based on barley during the growing or finishing phases have been reported to have growth performance that is not different from that of pigs fed diets based on wheat or maize (Yin et al., 2001), but reduced average daily gain and gain to feed ratio of pigs fed barley rather than maize has also been reported (Carr et al., 2005; Kim et al., 2014). Reduced dressing percentage of pigs fed barley rather than maize was also observed, whereas concentration of saturated fatty acids in the back fat of pigs was linearly increased in pigs fed barley compared with pigs fed maize (Kim et al., 2014).

Table 2
Composition of rye, sorghum, triticale, and wheat.

Item	Ingredient											
	Rye			Sorghum			Triticale			Wheat		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	2	16.3	0.2	10	16.3	0.3	6	14.2	2.8	86	16.2	1.3
Dry matter, g/kg	7	895.0	7.0	36	889.0	21.0	16	851.0	62.0	118	899.0	25.0
Crude protein, g/kg	12	102.0	14.0	78	112.0	21.0	19	114.0	24.0	160	140.0	21.0
Acid hydrolyzed ether extract, g/kg	1	27.0	–	2	31.0	28.0	–	–	–	1	11.0	19.0
Ash, g/kg	5	17.0	2.0	62	18.0	6.0	9	20.0	6.0	88	20.0	7.0
Starch, g/kg	4	563.0	19.0	10	692.0	77.0	13	564.0	61.0	77	576.0	63.0
Acid detergent fiber, g/kg	1	25.0	–	20	46.0	14.0	9	32.0	5.0	89	36.0	17.0
Neutral detergent fiber, g/kg	1	123.0	–	22	101.0	33.0	10	106.0	9.0	94	149.0	90.0
Total dietary fiber, g/kg	1	117.0	–	4	39.0	39.0	–	–	–	11	98.0	23.0
Calcium, g/kg	4	1.6	1.8	13	0.2	0.1	12	1.6	2.3	54	0.6	0.9
Phosphorus, g/kg	4	2.7	0.7	14	2.8	0.7	13	3.8	1.1	67	3.6	1.0
Phytate, g/kg	–	7.0	–	2	6.4	1.8	5	7.4	–	14	7.8	2.5
Indispensable amino acids, g/kg												
Arginine	5	5.8	21.1	27	3.6	0.5	4	7.3	2.0	64	6.6	1.3
Histidine	5	2.4	10.6	26	2.1	0.3	4	3.1	0.5	65	3.5	0.8
Isoleucine	5	3.5	15.5	28	3.7	0.5	4	4.5	0.9	66	4.9	1.0
Leucine	5	6.5	27.1	28	12.4	1.7	4	8.6	2.0	65	9.7	1.6
Lysine	5	4.0	16.6	28	2.1	0.4	7	5.0	0.8	73	4.1	0.9
Methionine	5	1.6	6.9	26	1.6	0.3	7	2.5	0.4	63	2.4	0.4
Phenylalanine	5	4.8	19.8	24	4.9	0.6	4	5.2	1.9	65	6.8	1.2
Threonine	5	3.4	13.2	28	3.0	0.4	7	4.1	0.7	68	4.2	0.6
Tryptophan	4	1.0	4.6	23	0.7	0.2	3	1.6	0.3	33	1.7	0.4
Valine	5	4.9	20.7	28	4.7	0.6	4	5.9	1.3	65	6.2	1.2
Dispensable amino acids, g/kg												
Alanine	4	4.3	19.9	25	8.6	1.1	4	5.4	1.0	52	5.1	1.1
Aspartic acid	4	7.4	32.8	25	6.1	1.0	4	8.0	1.3	51	7.6	1.6
Cysteine	5	2.0	9.0	26	1.8	0.2	7	2.6	0.8	55	3.4	1.0
Glutamic acid	4	24.7	114.0	25	18.9	2.8	4	37.5	8.2	51	42.3	12.4
Glycine	4	4.5	20.3	25	3.1	0.4	4	5.6	1.1	51	5.9	1.1
Proline	3	11.6	50.1	24	7.6	1.1	1	10.6	–	47	14.8	3.8
Serine	4	4.2	17.9	25	3.9	0.5	4	6.4	1.2	52	6.6	1.3
Tyrosine	5	2.4	8.8	24	3.2	0.5	4	3.9	1.1	36	3.7	1.0

Table 3
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in barley, maize, oats, and polished rice.

Item	Ingredient											
	Barley			Maize			Oats			Polished rice		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	17	12.8	0.7	73	14.6	0.5	1	11.0	–	1	15.1	–
Metabolizable energy, MJ/kg	7	12.2	0.5	67	14.2	0.5	1	10.9	–	5	14.8	0.2
Net energy, MJ/kg	6	9.2	0.5	5	10.3	0.4	1	7.7	–	1	10.7	–
SID indispensable amino acids												
Arginine	24	0.840	0.062	45	0.880	0.073	2	0.890	0.007	2	0.890	0.053
Histidine	23	0.810	0.049	45	0.830	0.054	2	0.840	0.014	2	0.870	0.066
Isoleucine	24	0.790	0.091	45	0.810	0.066	2	0.800	0.007	2	0.800	0.179
Leucine	24	0.810	0.051	45	0.870	0.061	2	0.820	0.014	2	0.810	0.176
Lysine	23	0.750	0.086	45	0.740	0.099	2	0.750	0.021	2	0.820	0.144
Methionine	21	0.810	0.076	39	0.840	0.087	2	0.840	–	2	0.850	0.139
Phenylalanine	23	0.810	0.066	45	0.840	0.069	2	0.850	0.014	2	0.820	0.193
Threonine	24	0.750	0.100	45	0.760	0.099	2	0.700	0.014	2	0.790	0.167
Tryptophan	11	0.730	0.246	25	0.780	0.133	2	0.780	–	2	0.810	0.196
Valine	24	0.800	0.074	45	0.810	0.068	2	0.780	0.014	2	0.810	0.193
SID dispensable amino acids												
Alanine	22	0.730	0.086	37	0.840	0.038	1	0.690	–	1	0.890	–
Aspartic acid	22	0.750	0.097	37	0.810	0.064	1	0.760	–	1	0.930	–
Cysteine	18	0.820	0.082	32	0.830	0.053	2	0.750	–	2	0.800	0.208
Glutamic acid	22	0.860	0.066	37	0.870	0.058	1	0.860	–	1	0.950	–
Glycine	22	0.830	0.153	37	0.840	0.187	1	0.700	–	1	0.930	–
Proline	17	0.890	0.284	32	0.960	0.313	1	0.720	–	1	0.560	–
Serine	22	0.810	0.081	37	0.850	0.052	1	0.740	–	1	0.930	–
Tyrosine	18	0.780	0.125	36	0.830	0.060	1	0.810	0.014	1	0.830	0.136
STTD phosphorus	12	0.425	0.094	30	0.406	0.129	3	0.389	0.035	–	–	–

Table 4
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in rye, sorghum, triticale and wheat.

Item	Ingredient											
	Rye			Sorghum			Triticale			Wheat		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	1	14.3	–	1	16.6	–	2	14.1	0.2	54	14.2	0.8
Metabolizable energy, MJ/kg	2	13.7	0.3	4	13.9	0.4	3	13.6	0.3	25	13.8	0.9
Net energy, MJ/kg	1	10.1	–	1	10.3	–	1	9.9	–	1	10.8	–
SID indispensable amino acids												
Arginine	5	0.840	0.046	18	0.790	0.101	7	0.840	0.064	22	0.910	0.046
Histidine	5	0.810	0.061	17	0.740	0.080	7	0.820	0.072	22	0.890	0.051
Isoleucine	5	0.770	0.087	18	0.770	0.065	7	0.820	0.067	22	0.880	0.064
Leucine	5	0.810	0.052	18	0.820	0.058	7	0.840	0.054	22	0.890	0.053
Lysine	5	0.750	0.073	18	0.720	0.124	7	0.770	0.089	22	0.820	0.102
Methionine	5	0.830	0.049	18	0.790	0.072	7	0.860	0.043	20	0.890	0.065
Phenylalanine	5	0.840	0.042	17	0.810	0.069	7	0.850	0.078	22	0.900	0.061
Threonine	5	0.750	0.096	18	0.740	0.085	7	0.680	0.141	22	0.830	0.104
Tryptophan	3	0.790	0.066	4	0.700	0.167	2	0.760	0.016	14	0.870	0.066
Valine	5	0.780	0.065	18	0.760	0.076	7	0.800	0.064	22	0.870	0.060
SID dispensable amino acids												
Alanine	5	0.720	0.082	18	0.780	0.055	7	0.780	0.065	14	0.830	0.102
Aspartic acid	5	0.790	0.066	18	0.780	0.074	7	0.800	0.045	14	0.840	0.089
Cysteine	5	0.830	0.090	18	0.660	0.086	7	0.830	0.055	12	0.890	0.067
Glutamic acid	5	0.900	0.026	18	0.790	0.106	7	0.910	0.045	14	0.920	0.058
Glycine	5	0.780	0.246	18	0.660	0.184	7	0.830	0.156	14	0.930	0.139
Proline	4	1.020	0.160	17	0.700	0.310	5	1.040	0.224	10	1.100	0.167
Serine	5	0.820	0.062	18	0.810	0.062	7	0.820	0.075	14	0.890	0.077
Tyrosine	4	0.750	0.107	17	0.740	0.075	6	0.820	0.070	15	0.870	0.085
STTD, phosphorus	3	0.500	0.116	4	0.399	0.073	6	0.558	0.035	14	0.600	0.131

2.2. Maize

Maize is the most common cereal grain used in the feeding of commercial pigs and with global production exceeding 1000 million tons, there is more maize produced in the world than that of any other cereal grain (Statista, 2015). The high concentration of starch and the low concentration of fiber in maize results in most nutrients being easy to digest by pigs, and the apparent total tract digestibility of dry matter in maize is close to 90% (Rojas and Stein, 2015b). The apparent total tract digestibility of starch is between 90 and 96% and is increased by reducing the particle size (Rojas and Stein, 2015b). The concentration of CP is between 7 and 9% and less than in most other cereal grains, but the SID of most indispensable AA in maize is slightly greater than in barley and sorghum and comparable to wheat (Pedersen et al., 2007a,b; Cervantes-Pahm et al., 2014b). The concentration of total dietary fiber is less than 10% with the majority being arabinoxylans and cellulose (Bach Knudsen, 1997; Jaworski et al., 2015).

Maize contains approximately 2.5 g/kg of phosphorus, but at least two thirds of that amount is bound to phytate, and the standardized total tract digestibility of phosphorus in maize is therefore, only between 25 and 35% (Almeida and Stein, 2010, 2012). However, if microbial phytase is added to diets based on maize, the digestibility of phosphorus will increase to between 45 and 60% (Almeida and Stein, 2010, 2012).

Maize can be included in diets fed to all categories of pigs as the sole cereal grain and with the exception of diets fed during the initial 2–3 weeks post-weaning, growth performance of pigs fed diets based on corn is usually superior to that of pigs fed diets based on other cereal grains. There are, therefore, very few restrictions in the feeding of maize to growing-finishing pigs, but if fed in diets for gestating sows, it is recommended to include a source of fiber in the diet to avoid constipation. Energy digestibility in maize is improved if particle size is reduced to less than 500 μm (Wondra et al., 1995; Rojas and Stein, 2015b) and it is possible to reduce the amount of added fat in the diet if particle size is reduced, without affecting growth performance of weanling or growing-finishing pigs (Rojas and Stein, 2016; Rojas et al., 2016). Dressing percentage of pigs fed diets containing maize ground to less than 500 μm is also greater than that of pigs fed diets containing maize ground to a coarser particle size (Rojas et al., 2016). It is also possible that extrusion of corn grain may improve growth performance of weanling pigs (Liu et al., 2015b).

2.3. Oats

Oats is produced in relatively small quantities and global production is less than 25 million tons (Statista, 2015) with the European Union, Russia, and Canada being the biggest producers. Oats is primarily used for human consumption and only smaller quantities are used in animal feeding. The concentration of fiber in oats is greater than in all other cereal grains, and as is the case for barley, oat fiber contains significant quantities of beta-glucans along with arabinoxylans and cellulose (Bach Knudsen, 1997). Because of the relatively high fiber concentration, oats has less digestible and metabolizable energy than other cereal grains. However, if oats are dehulled, the SID of AA is greater in oats than in many other cereal grains, and oat protein has a more favorable AA balance than all other cereal grains (Cervantes-Pahm et al., 2014b). It is also believed that oat fiber may have beneficial effects in terms of improving intestinal health and oats are, therefore, often included in diets fed to weanling pigs in amounts of up to 20%. Inclusion of 30% oats in diets fed during the immediate post-weaning period does not reduce growth performance compared with pigs fed diets based on maize or sorghum (Stein and Kil, 2006) and improved gain to feed ratio of pigs fed oat-based diets compared with diets based on maize has been reported (Mahan and Newton, 1993). However, if oats are included in starter diets for pigs in greater amounts, growth performance will be reduced compared with that of pigs fed diets based on maize (Wahlstrom et al., 1977). Up to 40% oats may be included in diets for growing-finishing pigs if diets are balance for metabolizable energy by addition of dietary fat (Myer and Combs, 1991). Oats may also be included in diets for gestating and lactating sows by at least 20%.

2.4. Polished rice and broken rice

Rice (*Oriza sativa*) is the most important food crop in the world and among cereal grains, rice ranks second only after maize in terms of area and production (Singh et al., 2013a), and the annual global production of paddy rice is approximately 750 million tons (Statista, 2015). Unlike maize, which is primarily produced as a source of feed or for fuel ethanol production, rice is primarily grown for human consumption and rice is the main source of carbohydrates for humans worldwide. However, use of rice in pig feeding is limited because of relatively high price and limited availability (Vicente et al., 2009). Rice is, therefore, usually not fed to pigs or other animals unless the quality of the rice prevents usage as human food, but white polished rice that does not meet quality specifications for human food is an excellent source of energy in diets fed to pigs. During milling, some of the rice kernels may be broken and kernels that have a length that is less than 25% of the original length cannot be sold as polished white rice, and these kernels are therefore, sometimes used in the animal feed industry and sold as broken rice or brewers rice (USA Rice Federation, 2011). There is, however, no difference in the nutritional value between polished white rice and broken rice. Polished white rice contains only around 1% total dietary fiber, which is much less than all other cereal grains, but the concentration of starch is greater than in all other cereal grains (Cervantes-Pahm et al., 2014a). The digestibility of starch in polished white rice is also greater than in other cereal grains because the concentration of resistant starch is low (Cervantes-Pahm et al., 2014a; Solà-Oriol et al., 2014). The SID of AA in polished white rice and broken rice is between 90 and 98%, which is greater than in most other plant feed ingredients (Brestenský et al., 2013; Cervantes-Pahm et al., 2014b; Casas et al., 2015). The concentration of metabolizable energy in polished white rice is similar to that in de-hulled barley, but greater than in maize, wheat, and sorghum (Cervantes-Pahm et al., 2014a). Polished rice has a low concentration of phosphorus and phytate, but the standardized total tract digestibility of phosphorus is approximately 75% (Casas and Stein, 2015).

Broken rice and polished white rice are usually not used in diets fed to growing-finishing pigs or for sows because of the high cost of these ingredients. However, there is considerable interest in using these ingredients in diets fed to newly weaned pigs because the low fiber concentration is believed to reduce substrates for pathogens in the intestinal tract, and therefore, reduce enteric diseases in piglets (Pluske et al., 1996; Che et al., 2012). Indeed, increased feed intake and increased average daily gain has been demonstrated in weanling pigs fed diets based on polished white rice or broken rice compared with pigs fed diets based on maize (Pluske et al., 2003; Mateos et al., 2007).

2.5. Rye

Rye is produced in a number of Northern European countries and the primary production is intended for human consumption. However, with the advent of hybrid rye, which has increased yields compared with conventional rye, production of rye for feed is increasing in some parts of Europe and global production now is close to 20 million tons per year (Statista, 2015). New varieties of hybrid rye also have reduced concentrations of anti-nutritional factors such as alkaloids and trypsin inhibitors and are less susceptible to be contaminated with ergot compared with older varieties of rye (Schwarz et al., 2014). The digestibility of starch and AA in rye is less than in wheat and broken rice (Brestenský et al., 2013; Cervantes-Pahm et al., 2014a; Strang et al., 2014) and rye fiber primarily consists of arabinoxylans and cellulose (Schwarz et al., 2014). The concentreation of metabolizable energy is less in rye than in wheat, maize, and sorghum (Cervantes-Pahm et al., 2014a), but the digestibility of energy in rye may be improved by addition of microbial xylanase to the diet (Nitrayová et al., 2009).

Historically rye was included in diets for pigs at relatively low amounts due to reduced palatability and concentrations of anti-nutritional factors. However, hybrid rye may be included in diets fed to weanling, growing, and finishing pigs by 10, 25, and 50%, respectively, without causing reductions in growth performance or carcass quality (Schwarz et al., 2014).

2.6. Sorghum

Sorghum is grown in a number of countries around the world and total global production is close to 60 million tons per year (Deb et al., 2004). Sorghum is used for human consumption as well as for animal feed. The nutritional value of sorghum for pigs was recently reviewed (Tokach et al., 2012). The concentration of starch and AA in sorghum is greater than in maize and wheat, but the concentration of lipids is slightly less than in maize (Jaworski et al., 2015). The starch in sorghum has a reduced digestibility compared with the starch in wheat and maize (Cervantes-Pahm et al., 2014b) and the glycemic index, therefore, is reduced in starch from sorghum compared with starch from wheat (Prasad et al., 2014). The concentration of total dietary fiber in sorghum is comparable to that in maize with the majority being cellulose and arabinoxylans (Jaworski et al., 2015). However, the fiber in sorghum is more tightly bound to protein (Bach-Knudsen and Munck, 1985) than is the case for other cereal grains, which may be the reason why the SID of AA is slightly less in sorghum than in wheat and maize (Pedersen et al., 2007a; Cervantes-Pahm et al., 2014b). Amino acid digestibility in sorghum is negatively influenced by the concentration of tannins in sorghum (Jansman et al., 1993), but it appears that the concentration of tannins needs to be greater than 1% before a negative effect on SID of AA is observed (Mariscal-Landín et al., 2004). The concentration of phosphorus in sorghum is close to that in maize, but as is the case for most cereal grains, the majority of the phosphorus is bound to phytate and the standardized total tract digestibility of phosphorus in sorghum is, therefore, relatively low. However, addition of microbial phytase to the diet will increase the digestibility of phosphorus (Cervantes et al., 2011). The concentration of gross energy in sorghum is similar to that in wheat and maize, and the same is the case for the concentration of digestible and metabolizable energy (Cervantes-Pahm et al., 2014a; Bolarinwa and Adeola, 2016). It is, however, possible to increase metabolizable energy in sorghum by grinding to a fine particle size rather than a coarser particle size (Owsley et al., 1981).

As is the case for maize and wheat, sorghum may be used as the sole cereal grain in diets fed to pigs without reducing growth performance of weanling or growing-finishing pigs (Hongtrakul et al., 1998; Shelton et al., 2004; Benz et al., 2011). However, if sorghum replaced maize in diets fed to lactating sows, a slight reduction in feed intake and litter weight gain has been reported, whereas subsequent reproductive performance was not impacted by inclusion of sorghum in the diets. Overall, there does not seem to be much difference in feeding value between maize, wheat and sorghum, and it was recently estimated that the feeding value of sorghum compared with maize is 98–99% (Tokach et al., 2012).

2.7. Triticale

Triticale is one of the few cereal grains that is produced primarily for livestock feed and annual global production is relatively modest at about 15 million tons (Triticale-Infos, 2015). Triticale was developed as a cross between wheat and rye (Ammar et al., 2004) and the nutritional composition, therefore, is close to that of wheat and rye (NRC, 2012). However, some variability in chemical composition, specifically of fiber concentration, among cultivars of triticale has been reported (Farrell et al., 1983; Leterme et al., 1991).

The apparent total tract digestibility of energy and the SID of AA is less in triticale than in maize (Adeola et al., 1986). In agreement with these results, it was demonstrated that inclusion of triticale in diets fed to growing-finishing pigs at the expense of maize resulted in a linear reduction in feed intake and therefore in average daily gain (Nishimuta et al., 1980). Likewise, Myer et al. (1989) reported a reduction in average daily gain and gain to feed ratio if triticale replaced maize in diets for growing pigs, but during the finishing phase, no difference between triticale and maize was observed. However, results of several experiments in Australia demonstrated that between 50 and 100% of the wheat in diets fed to growing-finishing pigs may be replaced by triticale without detrimental effects on growth performance (Farrell et al., 1983; Batterham et al., 1990).

Most of the research with triticale fed to growing pigs was conducted 25–40 years ago. Since that time, new cultivars of triticale have become available and in experiments with broiler chickens it was demonstrated that some of these new cultivars may support growth performance that is not different from that of diets based on maize (Widodo et al., 2015). However, to our knowledge, no data from experiments in which the new varieties have been fed to pigs have been reported.

2.8. Wheat

Wheat is the third most produced cereal grain in the world with global production at approximately 715 million tons (Statista, 2015). In most countries, wheat is produced primarily for human consumption, but in Canada, Australia, and some Northern European countries wheat is also produced as a feed ingredient. The use of wheat in diets fed to pigs was recently reviewed (Kim et al., 2005; Rosenfelder et al., 2013). In general, wheat may be used as the sole cereal grain in diets fed to pigs, and there are not many restrictions to the use of wheat. The concentration of AA in wheat is greater than in maize and rice, but may vary according to variety and growing conditions (Zijlstra et al., 1999). However, the concentration of starch and fiber is close to that in maize (Pedersen et al., 2007a; Cervantes-Pahm et al., 2014b; Jaworski et al., 2015). As is the case for maize, the majority of the fiber in wheat consists of arabinoxylans and cellulose, but total tract fermentability of dietary fiber in wheat is greater than in sorghum and maize (Jaworski et al., 2015). Lysine is the first limiting AA in wheat (Pichardo et al., 2003), and the SID of AA in wheat is also usually greater than in barley and sorghum and close to values observed in maize (Pedersen et al., 2007a; Cervantes-Pahm et al., 2014b; Rosenfelder et al., 2015). The concentration of phosphorus in wheat is slightly greater than that in most other cereal grains, and due to intrinsic phytase, the standardized total tract digestibility of phosphorus is greater in wheat than in most other cereal grains (NRC, 2012). The energy in wheat is relatively easy digestible and concentrations of digestible and metabolizable energy is usually close to that of maize (NRC, 2012). However, differences in energy digestibility due to differences in growing conditions and among varieties have been reported (Zijlstra et al., 1999; Kim et al., 2005) and in general, the greater the concentration of dietary fiber in wheat is, the lower is the concentration of digestible energy (Kim et al., 2005). Storage of wheat for 6–12 month may also reduce the concentration of digestible and metabolizable energy in some, but not all, varieties of wheat (Guo et al., 2015). Energy digestibility in wheat may sometimes be improved by addition of a microbial xylanase to wheat based diets (Barrera et al., 2004), but that is not always the case (l'Anson et al., 2013).

3. Cereal co-products

3.1. Maize co-products

Maize is processed for the production of ethanol or human food using wet milling, dry milling, or dry grinding processes (NRC, 2012; Rojas et al., 2013). The main co-products from the wet milling industry include maize gluten meal, maize germ meal, and maize gluten feed (Tables 5–8). Maize gluten meal is a high protein ingredient that is primarily used in diets for ruminants, and the protein quality is relatively poor for monogastric animals (Almeida et al., 2011). However, due to the low concentration of fiber in maize gluten meal (Jaworski et al., 2015), the concentration of metabolizable energy is greater than that of other maize co-products (Ji et al., 2012; Rojas et al., 2013) and the SID of AA in maize germ meal is greater than in maize (Almeida et al., 2011; Ji et al., 2012).

Maize germ meal has a greater concentration of fiber and contains less protein than maize gluten meal and the metabolizable energy of maize germ meal is, therefore, less than in maize gluten meal (Rojas et al., 2013). However, maize germ meal is often used in diets for gestating sows, but unlike what has been observed for some other ingredients, the concentration of metabolizable energy of maize germ meal fed to gestating sows is not greater than for growing pigs (Lowell et al., 2015).

Maize gluten feed contains a number of product streams from the wet milling industry and the nutrient concentration, therefore, is more variable than that of other maize co-products. The concentration of CP is usually between 20 and 24%, but the concentration of fiber is relatively high and the metabolizable energy is comparable to that of maize germ meal (Rojas et al., 2013).

In addition to maize gluten meal, maize germ meal, and maize gluten feed, other co-products from the wet milling industry include high-oil maize germ, liquid maize extracts, and maize bran (Anderson et al., 2012; Liu et al., 2014a). However, the quantities produced of these co-products are small and the ingredients, therefore, are available only in local markets.

The main co-product from the maize dry milling industry is hominy feed, which contains more starch and less fiber and protein than most other maize co-products (Almeida et al., 2011). Hominy feed can, therefore, be used as a substitute for maize in diets for pigs, and the digestibility of nutrients and the concentration of metabolizable energy in hominy feed is comparable to that in maize (Almeida et al., 2011; Rojas et al., 2013).

The maize dry grind industry is used to produce the majority of ethanol and the co-products from this industry include distillers dried grains with solubles (**DDGS**), which has a low concentration of starch, but contains fiber that is equivalent to maize germ meal. The concentration of fat may vary from less than 5% to more than 10% depending on the degree of fat removal from the solubles before they are added to the distilled grain (Anderson et al., 2012). The digestibility of most AA in maize DDGS is less than in maize and the digestibility of lysine may sometimes be low because of heat damage during fermentation or drying (Pahm et al., 2008; Kim et al., 2012). Concentrations of metabolizable energy in maize DDGS has been reported to be similar to that of maize (Pedersen et al., 2007b; Stein et al., 2009; Stein and Shurson, 2009), and as is the case for many feed ingredients, the metabolizable energy is increased if particle size is reduced (Liu et al., 2012)

Other co-products from the maize dry-grind industry include high protein distillers dried grain and low fat corn germ (Widmer et al., 2007; Kim et al., 2009; Adeola and Ragland, 2012), but availability of these ingredients is generally low. Maize bran may be produced in the wet milling as well as in the dry grind industry, but has generally little use in diets fed to pigs (Liu et al., 2014a).

The quality of protein in all maize co-products is relatively poor compared with the requirements for pigs because of low concentrations of lysine and tryptophan, but when used in combinations with SBM and crystalline lysine and tryptophan, balanced diets can be produced. The fiber in maize co-products primarily consist of cellulose and arabinoxylans (Jaworski et al., 2015), and the total tract digestibility of dietary fiber in maize co-products is less than 50% (Urriola et al., 2010). The digestibility of AA in many maize co-products is usually less than that in maize (Almeida et al., 2011; Stein and Shurson, 2009). The digestibility of lipids in maize co-products is less than in extracted maize oil and is usually between 50 and 75% (Kil et al., 2010; Kim et al., 2013), and the metabolizable energy of some high-fat maize co-products is, therefore, not as high as expected (Widmer et al., 2007; Liu et al., 2014a). It has also been demonstrated that reduction of fat in DDGS does not always reduce metabolizable energy (Kerr et al., 2013), which is likely a consequence of the relatively low digestibility of lipids in DDGS. Whereas all maize co-products have low concentrations of calcium (Gonzalez-Vega et al., 2015; NRC, 2012), the concentration of phosphorus is relatively high. Most of the phosphorus in maize is bound to phytate and the digestibility is, therefore, usually less than 35% (Almeida and Stein, 2010, 2012; NRC, 2012; Rojas et al., 2013). However, fermentation or soaking in water results in release of most of the phosphorus from phytate and maize co-products from the wet milling industry and DDGS, which has been fermented, have digestibility of phosphorus that is between 55 and 80% (Almeida and Stein, 2010, 2012; Rojas et al., 2013; Widmer et al., 2007).

Distillers dried grains with solubles may be included in diets fed to all categories of pigs by up to 30% without impacting growth performance of pigs (Stein and Shurson, 2009), although fat depots of finishing pigs may contain more unsaturated fatty acids if DDGS is used in the diets (Whitney et al., 2006; Widmer et al., 2008; Benz et al., 2010). This may increase iodine values of belly fat and back fat and reduce shelf life (Leick et al., 2010). Inclusion of up to 45% maize DDGS in diets for finishing

Table 5
Composition of maize coproducts.

Item	Ingredient																	
	Maize germ meal			Maize gluten meal			Maize gluten feed			Maize germ <30% fat			Maize germ >30% fat			Maize extractives, liquid		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	6	17.7	0.3	29	20.8	0.9	11	17.4	0.9	11	19.8	0.6	1	24.8	–	1	8.4	–
Dry matter, g/kg	4	894.0	5.0	28	911.0	12.0	16	895.0	34.0	15	905.0	22.0	1	936.0	–	1	608.0	–
Crude protein, g/kg	6	226.0	20.0	35	575.0	75.0	20	209.0	28.0	18	150.0	9.0	1	170.0	–	1	244.0	–
Acid hydrolyzed ether extract, g/kg	2	18.0	6.0	4	51.0	13.0	2	41.0	1.0	2	174.0	10.0	1	306.0	–	1	20.0	–
Ash, g/kg	6	29.0	8.0	27	21.0	9.0	18	59.0	10.0	11	54.0	11.0	–	–	–	–	–	–
Starch, g/kg	5	147.0	12.0	21	202.0	86.0	16	163.0	68.0	8	229.0	19.0	1	119.0	–	1	240.0	–
Acid detergent fiber, g/kg	5	109.0	4.0	24	32.0	19.0	11	92.0	18.0	9	62.0	17.0	1	182.0	–	–	–	–
Neutral detergent fiber, g/kg	5	493.0	86.0	23	61.0	29.0	16	327.0	69.0	11	205.0	48.0	1	409.0	–	–	–	–
Total dietary fiber, g/kg	4	419.0	9.0	3	58.0	48.0	4	354.0	57.0	2	198.0	37.0	–	–	–	–	–	–
Calcium, g/kg	4	1.4	1.4	17	0.4	0.6	8	1.5	2.1	9	0.4	0.4	1	0.3	–	1	0.7	–
Phosphorus, g/kg	4	20.4	25.1	22	2.4	2.7	7	8.2	1.3	9	12.8	1.2	1	7.0	–	1	27.6	–
Indispensable amino acids, g/kg																		
Arginine	5	15.8	1.8	29	16.8	3.9	7	9.5	1.1	10	10.8	0.8	1	12.6	–	1	10.2	–
Histidine	5	7.6	2.3	28	11.5	2.6	7	6.2	0.8	10	4.2	0.2	1	4.9	–	1	8.5	–
Isoleucine	5	7.8	1.0	29	21.5	3.4	7	6.5	0.8	10	4.5	0.2	1	6.3	–	1	6.1	–
Leucine	5	15.8	4.7	29	90.7	13.9	7	17.9	2.0	10	10.7	0.6	1	13.0	–	1	12.5	–
Lysine	5	11.3	3.2	29	9.8	3.2	7	7.1	2.3	10	7.9	0.4	1	7.3	–	1	7.1	–
Methionine	5	5.3	2.8	28	13.6	2.9	8	3.2	0.3	10	2.5	0.2	1	3.1	–	1	2.2	–
Phenylalanine	5	8.7	2.9	29	34.2	4.9	7	7.3	0.8	10	5.7	0.3	1	7.7	–	1	5.6	–
Threonine	5	8.4	0.6	29	18.1	3.2	7	7.8	2.0	10	5.1	0.2	1	6.3	–	1	7.0	–
Tryptophan	5	3.2	2.6	27	2.8	0.7	6	1.1	0.3	10	1.1	0.2	1	1.2	–	1	1.3	–
Valine	5	11.6	3.1	29	24.3	4.2	7	10.0	1.1	10	7.2	0.4	1	10.4	–	1	10.7	–
Dispensable amino acids, g/kg																		
Alanine	5	13.4	1.2	26	45.6	7.5	5	13.7	2.1	8	9.0	0.4	1	10.4	–	1	16.4	–
Aspartic acid	5	15.9	1.4	26	31.6	5.8	5	12.1	1.9	8	11.1	0.7	1	12.5	–	1	12.0	–
Cysteine	4	3.4	0.1	27	10.8	1.9	8	4.5	0.5	10	3.0	0.3	1	2.1	–	1	6.6	–
Glutamic acid	5	24.5	12.1	26	109.0	18.1	5	29.3	3.8	8	19.4	1.8	1	21	–	1	28.1	–
Glycine	5	15.7	7.3	25	13.4	3.4	5	9.2	1.2	8	7.5	0.5	1	9.6	–	1	13.1	–
Proline	5	10.4	0.8	26	49.8	7.4	5	16.7	2.7	8	9.3	0.6	1	7.6	–	1	22.7	–
Serine	5	9.3	1.3	26	25.6	4.7	5	7.6	1.2	8	5.7	0.5	1	6.7	–	1	6.7	–
Tyrosine	5	6.8	0.8	25	26.6	4.3	7	5.8	0.9	10	4.7	0.3	1	4.9	–	1	5.8	–

Table 6
Composition of maize coproducts, continued.

Item	Ingredient														
	Maize hominy feed			Maize DDGS[a] <4% oil			Maize DDGS 5–9% oil			Maize DDGS >9% oil			Maize bran		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	7	17.5	0.8	5	19.6	1.6	23	19.6	0.7	136	19.9	2.5	7	18.1	0.7
Dry matter, g/kg	9	877.0	16.0	6	865.0	44.0	62	889.0	19.0	182	892.0	18.0	7	894.0	14.0
Crude protein, g/kg	13	96.0	16.0	7	278.0	38.0	58	275.0	21.0	213	268.0	29.0	9	109.0	29.0
Acid hydrolyzed ether extract, g/kg	1	64.0	35.0	–	–	–	7	62.0	37.0	8	127.0	22.0	2	27.0	6.0
Ash, g/kg	8	22.0	8.0	5	49.0	8.0	48	41.0	10.0	86	41.0	8.0	6	36.0	14.0
Starch, g/kg	8	483.0	90.0	3	51.0	43.0	19	64.0	39.0	86	65.0	17.0	5	230.0	57.0
Acid detergent fiber, g/kg	7	43.0	8.0	4	142.0	25.0	46	118.0	27.0	168	114.0	28.0	4	92.0	53.0
Neutral detergent fiber, g/kg	7	165.0	36.0	4	367.0	53.0	47	328.0	59.0	181	331.0	58.0	5	411.0	212.0
Total dietary fiber, g/kg	2	118.0	24.0	2	261.0	90.0	4	298.0	42.0	14	292.0	37.0	1	242.0	–
Calcium, g/kg	5	0.6	1.3	3	2.2	3.0	37	1.0	1.0	64	1.5	2.1	5	2.0	1.8
Phosphorus, g/kg	5	4.6	2.8	3	8.0	0.6	38	6.8	1.9	135	7.4	1.2	3	4.1	3.4
Indispensable amino acids, g/kg															
Arginine	7	5.4	1.3	4	12.4	1.0	47	11.8	1.6	190	11.6	2.0	5	6.2	1.4
Histidine	6	2.9	0.5	4	7.6	0.9	45	7.3	0.8	184	7.3	0.9	5	3.4	0.5
Isoleucine	7	3.3	0.6	5	11.0	1.7	50	10.3	1.0	192	10.1	1.4	5	3.6	0.6
Leucine	7	9.7	1.1	4	33.9	4.8	49	32.0	3.7	191	31.4	4.0	5	10.7	0.9
Lysine	7	3.8	0.9	5	8.5	2.5	53	8.3	1.6	193	8.0	1.7	5	4.5	1.0
Methionine	7	1.8	0.3	5	5.3	0.7	53	5.5	0.8	192	5.4	1.0	5	1.9	0.3
Phenylalanine	6	4.4	0.3	4	14.8	2.5	45	13.4	1.4	184	13.0	1.6	5	4.3	1.0
Threonine	7	3.6	0.8	5	10.7	1.3	52	10.0	0.7	192	10.0	1.7	5	4.4	0.8
Tryptophan	7	0.8	0.2	5	2.0	0.5	52	2.1	0.4	177	2.0	0.4	5	0.7	0.1
Valine	7	4.8	0.9	5	14.4	1.7	50	13.6	1.2	192	13.6	1.8	5	5.4	0.9
Dispensable amino acids, g/kg															
Alanine	4	7.1	1.3	4	20.2	2.5	37	19.5	2.4	178	18.9	2.3	5	7.6	1.2
Aspartic acid	4	7.1	1.0	4	18.5	0.5	37	57.0	237.0	178	17.5	2.3	5	7.3	1.5
Cysteine	7	2.0	0.4	5	5.3	0.4	43	5.1	0.9	183	5.0	1.0	5	2.3	0.3
Glutamic acid	4	15.8	2.8	4	39.0	10.6	37	45.1	9.3	168	40.3	8.1	5	15.8	1.9
Glycine	4	4.7	0.8	4	11.6	0.6	35	10.8	1.1	160	10.3	1.2	5	5.3	1.2
Proline	4	7.9	2.1	4	19.8	3.3	36	21.0	4.4	176	20.4	2.6	5	8.6	1.2
Serine	4	4.4	0.9	4	12.9	0.9	37	12.6	1.6	178	11.5	1.7	5	4.7	0.8
Tyrosine	6	3.3	0.6	4	11.0	0.3	30	10.8	1.3	138	9.9	1.8	5	3.2	0.5

[a] DDGS = distillers dried grains with solubles.

pigs did not dramatically reduce growth performance of pigs (Cromwell et al., 2011), whereas 40 or 50% inclusion of maize DDGS in diets fed to lactating sows may result in reduced feed intake and reduced litter performance (Greiner et al., 2015).

As is the case for maize DDGS, low-fat maize germ meal may be used in diets for growing and finishing pigs by up to 30% without changing animal growth performance (Lee et al., 2012). For the remaining maize co-products, there are limited data on optimum inclusion levels in diets for weanling, growing, or reproducing pigs.

3.2. Sorghum co-products

The main co-product available from sorghum is sorghum DDGS, which is produced in the western maize belt in the United States. The concentration of CP in sorghum DDGS is slightly greater than in maize DDGS, but the concentration of most indispensable AA in sorghum DDGS is within the range reported for maize DDGS (Urriola et al., 2009; Sotak et al., 2014), but fiber concentrations may be greater. As is the case for wheat DDGS and maize DDGS, the composition of fiber in sorghum DDGS reflects the composition in the parent grain (Jaworski et al., 2015). The ME and the digestibility of AA is within the range reported for maize DDGS (Urriola et al., 2009; Adeola and Kong, 2014; Sotak et al., 2014). Information about inclusion rates for sorghum DDGS is very limited, but it is believed that up to 30% may be included in diets fed to growing-finishing pigs and reproducing sows (Fioli et al., 2007; Tokach et al., 2012), although it has been concluded that inclusion of sorghum DDGS to diets fed to growing-finishing pigs will linearly reduce growth performance (Sotak et al., 2015). It was also observed that inclusion of sorghum DDGS rather than corn DDGS in diets fed to finishing pigs results in firmer backfat and a whiter color (Sotak et al., 2015).

3.3. Wheat co-products

The main wheat co-products that are available for feeding of animals are the co-products from the wheat flour industry and from the fuel ethanol industry. In most countries, co-products from the wheat flour industry are collectively known as wheat middlings, but due to the variability among the co-products caused by different processing procedures used in the flour industry, wheat middlings is sometimes divided according to protein and fiber concentrations and called wheat shorts, wheat red dog, wheat mill run, and wheat bran (Nortey et al., 2008). However, in most countries only wheat middlings and

Table 7
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in maize coproducts.

Item	Ingredient																	
	Maize germ meal			Maize gluten meal			Maize gluten feed			Maize germ <30% fat			Maize germ >30% fat			Maize extractives, liquid		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Digestible energy, MJ/kg	1	12.9	–	20	19.3	1.2	3	11.5	1.1	2	15.4	–	1	14.2	–	1	7.1	–
Metabolizable energy, MJ/kg	1	11.8	–	19	18.5	0.8	5	10.8	0.4	5	14.5	0.8	1	13.1	–	1	6.3	–
Net energy, MJ/kg	1	8.9	–	1	13.4	–	1	8.0	–	1	10.9	–	1	10.1	–	–	–	–
SID indispensable amino acids																		
Arginine	2	0.890	0.017	24	0.900	0.023	5	0.850	0.098	4	0.850	0.036	1	0.810	–	1	0.750	–
Histidine	2	0.770	0.011	24	0.890	0.037	5	0.740	0.056	4	0.700	0.029	1	0.750	–	1	0.700	–
Isoleucine	2	0.770	0.003	24	0.910	0.026	5	0.770	0.076	4	0.590	0.044	1	0.670	–	1	0.670	–
Leucine	2	0.800	0.009	24	0.940	0.027	5	0.820	0.059	4	0.680	0.005	1	0.710	–	1	0.700	–
Lysine	2	0.650	0.052	24	0.830	0.039	5	0.600	0.179	4	0.610	0.061	1	0.580	–	1	0.450	–
Methionine	2	0.810	0.005	23	0.930	0.045	5	0.800	0.075	4	0.700	0.044	1	0.680	–	1	0.650	–
Phenylalanine	2	0.810	0.011	24	0.930	0.029	5	0.820	0.086	4	0.650	0.018	1	0.710	–	1	0.710	–
Threonine	2	0.690	0.038	24	0.870	0.037	5	0.700	0.093	4	0.550	0.037	1	0.640	–	1	0.530	–
Tryptophan	2	0.830	0.029	23	0.720	0.103	5	0.710	0.119	4	0.650	0.043	1	0.780	–	1	0.770	–
Valine	2	0.760	0.002	24	0.900	0.027	5	0.740	0.069	4	0.640	0.049	1	0.670	–	1	0.690	–
SID dispensable amino acids																		
Alanine	2	0.750	0.018	23	0.910	0.033	3	0.740	0.086	2	0.640	–	1	0.630	–	1	0.710	–
Aspartic acid	2	0.650	0.017	23	0.880	0.027	3	0.640	0.069	2	0.600	–	1	0.590	–	1	0.430	–
Cysteine	2	0.610	0.039	22	0.870	0.029	5	0.610	0.067	4	0.650	0.023	1	0.580	–	1	0.420	–
Glutamic acid	2	0.780	0.003	23	0.920	0.031	3	0.760	0.042	2	0.720	–	1	0.730	–	1	0.540	–
Glycine	2	0.600	0.128	23	0.780	0.108	3	0.600	0.189	2	0.760	–	1	0.650	–	1	0.440	–
Proline	2	0.620	0.528	23	0.810	0.097	3	0.720	0.599	2	0.840	–	1	0.180	–	1	0.600	–
Serine	2	0.730	0.029	23	0.910	0.029	3	0.720	0.081	2	0.650	–	1	0.700	–	1	0.570	–
Tyrosine	2	0.790	0.011	21	0.930	0.028	5	0.820	0.062	4	0.600	0.022	1	0.690	–	1	0.760	–
STTD, phosphorus	1	0.532	–	1	0.804	–	5	0.423	0.249	4	0.372	0.040	–	–	–	–	–	–

Table 8
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in maize coproducts, continued.

Item	Ingredient														
	Maize hominy feed			Maize DDGS[a] <4% oil			Maize DDGS 5–9% oil			Maize DDGS >9% oil			Maize bran		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	1	14.2	–	3	12.1	1.6	15	15.1	0.8	62	14.8	1.0	1	12.1	–
Metabolizable energy, MJ/kg	6	14.0	0.5	3	11.2	1.4	14	14.3	1.0	32	14.4	0.9	3	11.5	0.05
Net energy, MJ/kg	1	10.1	–	3	7.9	1.1	1	10.5	–	2	8.0	0.2	1	8.5	–
SID indispensable amino acids															
Arginine	4	0.900	0.049	2	0.830	–	9	81	6.3	100	0.820	0.057	1	0.890	–
Histidine	4	0.790	0.074	2	0.750	–	9	80	2.6	100	0.790	0.046	1	0.830	–
Isoleucine	4	0.770	0.070	2	0.750	–	9	72	12.3	100	0.760	0.059	1	0.810	–
Leucine	4	0.840	0.024	2	0.840	–	9	87	1.9	100	0.840	0.037	1	0.840	–
Lysine	4	0.670	0.088	2	0.500	–	9	62	6.0	100	0.620	0.089	1	0.740	–
Methionine	4	0.850	0.053	2	0.800	–	9	80	9.0	100	0.820	0.049	1	0.860	–
Phenylalanine	4	0.840	0.037	2	0.810	–	9	83	3.3	100	0.820	0.038	1	0.830	–
Threonine	4	0.690	0.073	2	0.690	–	9	71	3.3	100	0.710	0.053	1	0.740	–
Tryptophan	4	0.730	0.157	2	0.780	–	9	67	9.5	100	0.730	0.091	1	0.750	–
Valine	4	0.760	0.067	2	0.740	–	9	79	4.2	100	0.760	0.048	1	0.790	–
SID dispensable amino acids															
Alanine	3	0.810	0.024	2	0.790	–	9	82	2.6	100	0.800	0.046	1	0.800	–
Aspartic acid	3	0.750	0.082	2	0.650	–	9	72	3.5	100	0.700	0.051	1	0.730	–
Cysteine	4	0.720	0.062	2	0.670	–	9	71	71.4	100	0.740	0.057	1	0.730	–
Glutamic acid	3	0.840	0.042	2	0.790	–	9	83	84.3	100	0.810	0.052	1	0.800	–
Glycine	3	0.790	0.176	2	0.650	–	9	66	75.3	100	0.660	0.106	1	0.700	–
Proline	2	1.120	1.111	2	0.880	–	9	74	93.6	100	0.760	0.208	1	0.770	–
Serine	3	0.810	0.042	2	0.770	–	9	79	73.9	100	0.770	0.050	1	0.810	–
Tyrosine	4	0.850	0.049	2	0.820	–	3	78	76.4	65	0.820	0.044	1	0.850	–
STTD, phosphorus	2	0.591	0.219	–	–	–	10	121	57.7	23	0.703	0.083	–	–	–

[a] DDGS = distillers dried grains with solubles.

Table 9
Composition of other cereal coproducts.

Item	Ingredient																	
	Barley DDGS[a]			Sorghum DDGS			Triticale DDGS			Wheat bran			Wheat DDGS			Wheat middlings		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Gross energy, MJ/kg	–	–	–	1	22.2	–	2	18.8	0.3	11	16.9	0.5	27	19.3	0.9	4	16.7	0.5
Dry matter, g/kg	21	879.0	11.0	6	902.0	14.0	3	898.0	4.0	15	886.0	22.0	52	927.0	22.0	26	892.0	14.0
Crude protein, g/kg	31	273.0	21.0	6	308.0	17.0	3	293.0	16.0	19	153.0	14.0	58	364.0	30.0	30	159.0	14.0
Acid hydrolyzed ether extract, g/kg	–	–	–	–	–	–	–	–	–	–	–	–	2	75.0	0.5	1	49.0	–
Ash, g/kg	21	35.0	4.0	4	79.0	46.0	3	39.0	0.9	12	48.0	11.0	40	49.0	5.0	8	33.0	16.0
Starch, g/kg	19	353.0	75.0	–	–	–	–	–	–	9	229.0	95.0	25	22.0	11.0	2	429.0	63.0
Acid detergent fiber, g/kg	16	103.0	10.0	6	227.0	31.0	3	122.0	12.0	11	116.0	16.0	43	127.0	29.0	9	82.0	31.0
Neutral detergent fiber, g/kg	17	131.0	24.0	6	346.0	52.0	3	323.0	51.0	12	349.0	74.0	49	339.0	73.0	22	339.0	83.0
Total dietary fiber, g/kg	–	–	–	–	–	–	–	–	–	1	355.0	–	–	–	–	–	–	–
Calcium, g/kg	2	1.0	–	1	1.2	–	1	0.6	–	4	1.0	0.1	17	1.5	0.5	23	1.2	0.6
Phosphorus, g/kg	2	5.6	2.1	1	7.6	–	1	7.0	–	4	10.2	1.3	20	8.8	0.7	23	10.0	1.7
Indispensable amino acids, g/kg																		
Arginine	19	24.3	3.1	2	11.0	–	2	13.6	0.9	4	8.8	2.9	30	13.7	4.0	21	10.8	1.2
Histidine	21	7.2	0.5	2	7.1	–	2	6.3	0.2	4	4.0	0.5	29	7.2	2.0	21	4.4	0.3
Isoleucine	25	11.3	1.0	4	13.1	0.6	2	11.2	0.3	4	4.8	0.5	30	12.0	3.2	22	5.1	0.3
Leucine	25	19.4	2.0	4	40.5	1.4	2	20.3	0.4	4	8.7	1.7	30	23.0	6.1	21	10.2	0.7
Lysine	25	16.5	2.0	4	7.9	1.3	2	7.6	1.0	4	5.6	0.7	33	7.0	2.4	22	6.5	0.5
Methionine	25	1.9	0.2	4	5.4	0.3	2	4.8	0.1	4	2.3	0.4	27	5.0	1.5	22	2.5	0.1
Phenylalanine	21	11.9	1.1	2	16.8	–	2	14.2	0.1	4	5.4	1.4	30	15.5	4.3	21	6.4	0.5
Threonine	25	9.1	1.3	4	10.7	0.3	2	9.5	–	4	5.5	1.0	32	10.5	2.7	22	5.3	0.3
Tryptophan	15	2.4	0.2	4	2.7	0.9	2	2.4	–	2	2.1	0.2	15	3.0	1.2	20	1.9	0.2
Valine	25	12.2	1.3	4	16.5	0.2	2	14.1	0.3	4	6.8	0.9	30	14.9	3.9	22	7.3	0.5
Dispensable amino acids, g/kg																		
Alanine	19	10.5	1.2	2	29.0	–	2	12.8	0.4	3	14.0	10.3	23	12.3	3.7	3	6.2	0.5
Aspartic acid	19	28.0	3.4	2	21.7	–	2	16.0	0.1	3	25.7	25.9	22	16.3	5.1	1	10.1	–
Cysteine	23	3.4	0.3	4	5.2	0.4	2	6.4	0.1	3	4.6	2.4	22	6.0	2.1	20	3.4	0.3
Glutamic acid	19	44.0	6.5	2	63.1	–	2	66.3	1.8	3	43.5	40.1	23	88.1	28.6	1	31.1	–
Glycine	19	10.9	1.5	2	10.3	–	2	12.8	0.1	3	11.9	7.3	23	13.3	4.0	3	7.0	0.4
Proline	13	9.9	3.4	2	25.0	–	2	26.1	1.0	2	4.9	6.9	22	24.9	9.6	3	14.9	4.3
Serine	19	12.2	2.4	2	14.0	–	2	12.1	–	3	12.3	9.8	23	14.8	4.7	3	8.6	0.9
Tyrosine	7	8.4	1.4	–	–	–	2	8.3	0.2	4	5.4	3.6	15	9.6	3.7	3	3.6	0.6

[a] DDGS = distillers dried grains with solubles.

wheat bran are marketed. A review over composition and nutritional value of wheat co-products was recently published (Rosenfelder et al., 2013). The concentration of total dietary fiber in wheat middlings and wheat bran is usually between 25 and 35% (Tables 9 and 10), and the composition of the dietary fiber in these ingredients is not different from that in wheat (Jaworski et al., 2015). However, there may be between 20 and up to 60% starch left in the co-products, which influences energy digestibility and concentration of metabolizable and net energy (Huang et al., 2012). In general, the lower starch concentration in the wheat co-product, the greater is the concentration of fiber, and there is a negative linear correlation between the concentration of neutral detergent fiber and the concentration of digestible energy in wheat co-products (Huang et al., 2014). However, in most cases, the metabolizable and net energy values in wheat middlings and wheat bran are less than in wheat, but it may be possible to increase the energy value of wheat middlings and other wheat co-products by addition of a carbohydrase enzyme to the diet (Nortey et al., 2008; Cozannet et al., 2012). Likewise, the SID of AA is also less in wheat middlings and wheat bran compared with wheat (Yin et al., 2000; Eklund et al., 2014), which is mainly a result of increased endogenous losses caused by the increased fiber in the wheat co-products (Yin et al., 2000). In contrast, the concentration of phosphorus is relatively high in wheat co-products and as is the case for wheat, due to intrinsic phytases, the digestibility of phosphorus in wheat co-products is greater than in many cereal grains.

Wheat co-products may be included in diets fed to weanling pigs by up to 20% if diets are formulated to similar concentrations of SID AA and net energy (Garcia et al., 2015). However feeding 10 or 20% wheat middlings to growing-finishing pigs may reduce growth performance and dressing percentage of pigs (Salyer et al., 2012).

Production of ethanol from wheat is practiced in China, Canada and some countries in Europe, and the resulting wheat DDGS may also be fed to pigs (Rosenfelder et al., 2013). The concentration of protein in wheat DDGS is greater than in maize DDGS, but the concentration of indispensable AA is not always greater than in maize DDGS (Yang et al., 2010). The SID of most AA is not different between maize DDGS and wheat DDGS although the SID of Lys sometimes is very low in wheat DDGS (Nyachoti et al., 2005; Stein and Shurson, 2009; Cozannet et al., 2010a). The concentration of starch is reduced and the concentration of fiber and crude fat is increased in wheat DDGS compared with wheat (Widyaratne and Zijlstra, 2007; Cozannet et al., 2010b), but the combined effects of these changes results in values for metabolizable and net energy that are within the range of values reported for wheat (Cozannet et al., 2010b).

Conflicting results have been observed in experiments in which wheat DDGS has been included in diets fed to growing finishing pigs. No effect of inclusion of inclusion of up to 20% wheat DDGS were observed in one experiment (Thacker, 2009),

Table 10
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in other cereal coproducts.

Item	Ingredient																	
	Barley DDGS[a]			Triticale DDGS			Sorghum DDGS			Wheat bran			Wheat DDGS			Wheat middlings		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Digestible energy, MJ/kg	–	–	–	1	15.6	–	2	15.5	1.1	2	9.6	0.4	6	13.2	1.3	2	11.3	0.3
Metabolizable energy, MJ/kg	–	–	–	1	13.9	–	2	14.4	1.3	1	9.5	–	3	11.6	1.8	2	11.2	0.06
Net energy, MJ/kg	–	–	–	–	–	–	1	10.0	–	1	6.7	–	3	7.8	0.7	1	8.0	–
SID indispensable amino acids																		
Arginine	17	0.850	0.215	–	–	–	2	0.790	–	4	0.880	0.049	9	0.820	0.043	3	0.910	0.039
Histidine	19	0.800	0.073	–	–	–	2	0.720	–	4	0.780	0.034	10	0.750	0.054	3	0.870	0.057
Isoleucine	24	0.810	0.053	–	–	–	2	0.740	–	4	0.750	0.024	10	0.730	0.063	3	0.830	0.080
Leucine	24	0.820	0.050	–	–	–	2	0.770	–	4	0.750	0.053	10	0.800	0.040	3	0.840	0.077
Lysine	24	0.850	0.042	–	–	–	2	0.640	–	4	0.710	0.104	10	0.510	0.111	3	0.800	0.082
Methionine	23	0.730	0.117	–	–	–	2	0.770	–	3	0.760	0.035	8	0.740	0.084	3	0.860	0.064
Phenylalanine	19	0.800	0.061	–	–	–	2	0.770	–	4	0.810	0.040	10	0.840	0.029	3	0.870	0.071
Threonine	24	0.780	0.063	–	–	–	2	0.700	–	4	0.660	0.047	10	0.710	0.055	3	0.770	0.094
Tryptophan	13	0.630	0.095	–	–	–	2	0.720	–	3	0.740	0.014	5	0.640	0.318	3	0.820	0.082
Valine	24	0.780	0.051	–	–	–	2	0.740	–	4	0.760	0.065	10	0.730	0.052	3	0.810	0.075
SID dispensable amino acids																		
Alanine	17	0.780	0.057	–	–	–	2	0.750	–	3	0.690	0.072	6	0.700	0.021	1	0.720	–
Aspartic acid	17	0.850	0.041	–	–	–	2	0.690	–	3	0.730	0.059	6	0.590	0.056	1	0.760	–
Cysteine	22	0.620	0.109	–	–	–	2	0.670	–	2	0.750	0.035	5	0.760	0.088	3	0.820	0.079
Glutamic acid	17	0.880	0.032	–	–	–	2	0.770	–	3	0.890	0.053	6	0.870	0.015	1	0.890	–
Glycine	17	0.760	0.086	–	–	–	2	0.690	–	3	0.700	0.174	6	0.720	0.042	1	0.730	–
Proline	10	0.830	0.189	–	–	–	2	0.760	0.031	2	0.870	0.079	6	0.900	0.079	–	0.890	–
Serine	17	0.830	0.048	–	–	–	2	0.760	0.031	3	0.770	0.077	6	0.770	0.029	1	0.800	–
Tyrosine	9	0.820	0.068	–	–	–	–	–	–	3	0.720	0.138	5	0.800	0.038	3	0.840	0.079
STTD, phosphorus	1	0.389	–	–	–	–	–	–	–	2	0.545	0.058	3	0.579	0.056	5	0.553	0.105

[a] DDGS = distillers dried grains with solubles.

but inclusion of up to 20 or 40% wheat DDGS has resulted in reduced growth performance of growing-finishing pigs in other experiments (Widyaratne et al., 2009; Thacker, 2012;). Inclusion of carbohydrases in diets containing wheat DDGS has generally not improved growth performance of pigs (Emiola et al., 2009; Widyaratne et al., 2009). It is possible that the differences in responses to feeding wheat DDGS are caused by reduced digestibility of lysine and other AA, because some sources of DDGS may be over-heated during production, which results in reduced SID of AA (Cozannet et al., 2010a).

3.4. Bakery meal

Bakery meal is a co-product from the food industry and consists of unsalable bread, cookies, dough, flour, cakes, and other products (Slominski et al., 2004). Because of differences in the product mixes, there can be great variability in the chemical composition of bakery meal with fat varying from 4 to 12% (Arosemena et al., 1995; Slominski et al., 2004; Tables 11 and 12). On average, bakery meal contains approximately 12% CP, 8% fat, 35–40% starch, and 7–17% NDF (Arosemena et al., 1995; Slominski et al., 2004; Almeida et al., 2011). The concentration of Ca is less than 0.20% and the concentration of P is around 0.50% (Arosemena et al., 1995; Almeida et al., 2011; Rojas et al., 2013). The majority of the P in bakery meal is not bound to phytate, which is likely a consequence of the high concentration of wheat in the product and the heat treatment that has taken place during processing (Rojas et al., 2013).

The SID of most AA in bakery meal is between 70 and 80% and generally similar to that in some maize co-products such as maize DDGS, maize germ meal, and hominy feed (Almeida et al., 2011; Casas et al., 2015). However, the digestibility of lysine is less than for other AA, which is most likely a consequence of overheating during processing (Almeida et al., 2011). The concentration of ME in bakery meal is less than in maize, but close to that in hominy feed (Rojas et al., 2013). The STTD of P in bakery meal has been reported at 58% if no phytase is used and 64% if microbial phytase is added to the diet (Rojas et al., 2013).

There are no published studies indicating how much bakery meal can be included in diets fed to pigs, but because of the relatively high concentrations of sugar and fat, bakery meal generally is palatable and easily consumed by pigs. The greatest challenge in diet formulations with bakery meal, therefore, is the variability in product composition, and the relatively low values for SID lysine.

3.5. Rice co-products

In the process of producing polished white rice for human consumption, co-products that may have nutritional value for animals are also produced. These co-products include broken rice, rice bran, rice hulls, and rice polishings.

Table 11
Composition of bakery meal and rice coproducts.

Item	Ingredient																	
	Bakery meal			Broken rice			Brown rice			Full fat rice bran			Defatted rice bran			Rice mill feed		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	2	17.4	0.4	7	16.2	1.0	1	16.1	–	6	19.3	2.0	2	17.6	0.9	1	17.8	–
Dry matter, g/kg	5	895.0	20.0	12	874.0	16.0	1	881.0	–	7	920.0	30.0	3	912.0	8.0	1	910.0	–
Crude protein, g/kg	9	113.0	18.0	14	80.0	1.0	1	95.0	–	11	141.0	16.0	5	163.0	18.0	1	70.9	–
Acid hydrolyzed ether extract, g/kg	2	74.0	3.0	2	21.0	18.0	1	32.0	–	2	182.0	16.0	1	11.0	–	1	50.1	–
Ash, g/kg	4	53.0	16.0	11	11.0	6.0	1	12.0	–	7	114.0	45.0	2	117.0	3.0	1	142.0	–
Starch, g/kg	3	409.0	25.0	5	754.0	33.0	1	809.0	–	4	318.0	107.0	2	273.0	15.0	1	112.0	–
Acid detergent fiber, g/kg	4	49.0	14.0	4	13.0	7.0	1	14.0	–	2	93.0	2.0	1	120.0	–	1	434.0	–
Neutral detergent fiber, g/kg	4	135.0	48.0	7	38.0	33.0	1	27.0	–	7	221.0	75.0	2	214.0	30.0	1	457.0	–
Total dietary fiber, g/kg	–	–	–	1	14.0	–	1	34.0	–	–	–	–	–	–	–	1	545.0	–
Calcium, g/kg	4	1.6	0.3	2	0.1	0.0	1	0.1	–	7	1.2	0.9	2	1.1	0.0	1	1.1	–
Phosphorus, g/kg	4	3.8	1.0	3	1.7	0.5	1	2.7	–	7	20.0	3.0	2	25.8	0.0	1	6.3	–
Phytate, g/kg	2	2.0	0.3	2	1.7	0.7	1	7.9	–	4	27.6	20.5	1	84.3	–	1	20.1	–
Indispensable amino acids, g/kg																		
Arginine	7	5.0	0.6	6	6.8	1.4	1	6.3	–	9	11.4	1.1	5	12.6	2.1	1	4.3	–
Histidine	7	2.5	0.4	6	2.2	0.6	1	2.4	–	9	3.8	0.4	5	4.4	0.8	1	1.7	–
Isoleucine	7	4.1	0.7	6	3.6	0.6	1	3.7	–	9	4.9	0.3	5	5.6	0.5	1	2.3	–
Leucine	7	8.7	1.6	6	7.4	1.7	1	7.2	–	9	9.9	0.6	5	11.4	1.0	1	4.6	–
Lysine	7	3.0	0.8	6	3.3	0.6	1	3.6	–	9	6.2	0.6	5	7.9	0.7	1	3.2	–
Methionine	7	1.7	0.3	6	6.5	0.7	1	2.2	–	9	2.8	0.3	5	3.3	0.2	1	1.3	–
Phenylalanine	7	5.0	0.7	6	4.7	1.2	1	4.5	–	9	6.2	0.4	5	7.1	0.5	1	2.8	–
Threonine	7	3.5	0.6	6	3.3	1.0	1	3.0	–	9	5.2	0.4	5	6.0	0.6	1	2.5	–
Tryptophan	7	1.1	0.3	5	0.8	0.3	1	0.9	–	9	1.7	0.2	5	2.0	0.3	1	0.5	–
Valine	7	5.0	0.7	6	3.7	1.3	1	5.3	–	9	7.5	0.5	5	8.6	0.9	1	3.6	–
Dispensable amino acids, g/kg																		
Alanine	4	5.5	1.1	5	5.2	1.5	1	5.0	–	6	8.6	0.5	4	10.0	1.3	1	4.6	–
Aspartic acid	4	6.0	1.4	5	8.5	2.6	1	7.8	–	6	12.2	0.7	4	14.4	1.7	1	5.9	–
Cysteine	7	2.2	0.4	6	1.5	0.3	1	1.9	–	9	2.8	0.2	5	3.2	0.3	1	1.4	–
Glutamic acid	4	22.5	6.5	5	17.1	5.6	1	15.0	–	6	19.0	1.6	4	22.1	2.9	1	8.7	–
Glycine	4	5.3	1.8	5	4.1	1.1	1	4.0	–	6	7.7	0.6	4	8.6	1.5	1	3.5	–
Proline	4	9.2	2.3	5	4.4	1.4	1	3.8	–	6	6.5	0.6	4	7.5	0.8	1	3.0	–
Serine	4	4.7	1.2	5	4.7	1.5	1	4.0	–	6	6.4	0.6	4	7.1	1.1	1	2.7	–
Tyrosine	7	3.6	0.9	6	3.4	1.1	1	1.7	–	6	3.5	0.8	4	3.7	1.1	1	1.2	–

Table 12
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in bakery meal and rice coproducts.

Item	Ingredient														
	Bakery meal			Broken rice			Brown rice			Full fat rice bran			Defatted rice bran		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	2	15.6	1.3	2	16.2	1.8	1	17.2	–	2	14.8	2.6	2	11.0	2.5
Metabolizable energy, MJ/kg	2	14.8	1.8	2	16.0	1.8	1	17.0	–	2	13.6	2.2	2	10.5	2.5
Net energy, MJ/kg	1	12.5	–	1	11.6	–	–	–	–	1	9.5	–	1	6.5	–
SID, indispensable amino acids															
Arginine	4	0.920	0.025	2	0.970	0.029	–	–	–	5	0.890	0.038	2	0.880	0.033
Histidine	4	0.850	0.086	2	0.940	0.020	–	–	–	5	0.860	0.022	2	0.840	0.015
Isoleucine	5	0.870	0.093	2	0.920	0.016	–	–	–	5	0.750	0.075	2	0.750	0.042
Leucine	5	0.880	0.055	2	0.930	0.013	–	–	–	5	0.760	0.068	2	0.760	0.027
Lysine	5	0.710	0.129	2	0.910	0.044	–	–	–	5	0.790	0.068	2	0.770	0.069
Methionine	5	0.870	0.059	2	0.900	0.015	–	–	–	5	0.800	0.071	2	0.760	0.045
Phenylalanine	4	0.890	0.079	2	0.920	0.026	–	–	–	5	0.750	0.058	2	0.750	0.042
Threonine	5	0.760	0.102	2	0.900	0.064	–	–	–	5	0.740	0.061	2	0.750	0.033
Tryptophan	5	0.860	0.037	2	0.910	0.052	–	–	–	4	0.770	0.074	2	0.750	0.069
Valine	5	0.850	0.093	2	0.920	0.032	–	–	–	5	0.760	0.078	2	0.760	0.039
SID, dispensable amino acids															
Alanine	2	0.790	0.079	1	0.950	–	–	–	–	3	0.800	0.088	1	0.820	–
Aspartic acid	2	0.700	0.116	1	0.940	–	–	–	–	3	0.780	0.065	1	0.770	–
Cysteine	5	0.870	0.109	2	0.880	0.086	–	–	–	5	0.720	0.071	2	0.720	0.040
Glutamic acid	2	0.870	0.080	1	0.940	–	–	–	–	3	0.840	0.041	1	0.820	–
Glycine	2	0.880	0.012	1	1.040	–	–	–	–	3	0.750	0.074	1	0.780	–
Proline	2	1.380	0.281	1	1.850	–	–	–	–	3	1.050	0.373	1	1.350	–
Serine	2	0.810	0.076	1	0.960	–	–	–	–	3	0.780	0.071	1	0.780	–
Tyrosine	2	0.850	0.106	1	0.880	–	–	–	–	3	0.780	0.035	1	0.780	–
STTD, phosphorus	1	0.586	–	1	0.578	0.252	1	0.317	–	6	0.285	0.113	1	0.331	–

Intact rice with the hull is called "paddy rice" or "rough" rice. Rice processing is aimed at producing unbroken rice with a specific size, color, and shelf-life. The process consists mainly of drying, grain cleaning, dehulling, decortication, polishing and sizing products (Serna-Saldivar, 2010). The edible portion of polished rice makes up 60–72% of the total weight, with the remaining 28–40% being co-products and waste (Singh et al., 2013a). The percentages of the individual co-products produced depend on milling rate, type of rice, and other factors. On average, the proportions are: hulls, 20%; bran, 10%; polishing, 3%; and broken rice, 1–17% (Heuzé and Tran, 2011).

When paddy rice is dehulled, it passes between 2 rubber-coated rolls that turn in opposite directions and are run at a speed differential. The pressure and shear remove the hulls. The pressure exerted by the rolls can be varied according to the rice variety (Delcuour and Hoseney, 2010). After separation, the hull is removed by aspiration and the remaining rough rice is separated by a technique based on bulk density on a gravity separator. Products produced after these steps are approximately 20% hulls, and 80% brown rice, including broken brown rice (Delcuour and Hoseney, 2010). However, rice hulls contain mainly lignin and silica and has no nutritional value (Casas and Stein, 2015) and rice hulls is therefore not included in diets fed to pigs.

Milling of brown rice results in removal of the bran by pearling and the resulting product is white rice. In the pearler or milling machine, some rice breakage occurs. Dry calcium carbonate (approximately 3.3 g/kg) is added to the brown rice to improve the efficiency of milling because it acts as an abrasive that contribute to removing the bran (Serna-Saldivar, 2010). As a consequence, rice co-products may contain variable quantities of calcium. After milling, the loose bran is removed by an aspirator, and the milled rice can then be polished. After polishing, the head rice is separated from broken rice by screening or by disk separators. The products obtained after these steps are head rice, broken rice, rice bran, and rice polishings (Delcuour and Hoseney, 2010). Most often the whole kernels or head rice are used for direct consumption by humans, but some kernels are broken in the milling process, and rice kernels that are less than 50% of the length of whole kernel, are called second heads. These seconds heads may be used "as is" for a variety of products or ground for rice flour. Kernels that are 25% or less of the original length of grain are called broken rice or brewers rice and are used for brewing and other fermented products, or for animal feeding (USA Rice Federation, 2011).

Rice bran is the outer brown layer of brown rice and includes several sub layers within the pericarp and aleurone layers, but some subaleurone and endosperm material and breakage from white rice is usually included in the bran fraction and can make up 20–25% of the bran (Prakash and Ramaswamy, 1996). Rice bran contains lipases that may cause oxidation of the lipids in rice bran and it is, therefore, important that rice bran is stabilized by heat treatment, which will inactivate the lipase, and therefore, reduce the risk of oxidation of the fat. Alternatively, rice bran can also be de-oiled with a subsequent production of rice oil, which is used in the human food industry, and de-oiled rice bran, that may be used for animal feeding (Hargrove, 1994). An additional category of rice bran is obtained when the starchy endosperm is removed from the rice kernel and is called polished rice bran (Kaufmann et al., 2005). A mixture of rice bran, rice hulls, and broken rice in different ratios are sometimes used for animal feeding (Brazle and Coffey, 1990; Ofongo et al., 2008) and this mixture may be marketed as rice-mill feed.

Despite an annual global production of close to 100 million tons of rice bran and other rice co-products excluding rice hulls, there is limited information about the nutritional value of rice-co-products. However, the SID of AA in rice bran is generally greater than in most other cereal co-products and not different from that in maize (Kaufmann et al., 2005; Casas and Stein, 2015). However, the SID of AA in full fat rice bran may be greater than in defatted rice bran (Casas and Stein, 2015), which may be a consequence of the greater concentration of fat in full fat rice bran compared with defatted rice bran because as the quantity of fat that is consumed increases, the passage rate in the small intestine will be reduced, which results in increased digestibility of protein with a subsequent increase in the digestibility of AA (Cervantes-Pahm and Stein, 2008).

Rice bran contains more phosphorus than most other feed ingredients and the total phosphorus concentration may be between 1.5 and 2.8% (Warren and Farrell, 1990a; Casas and Stein, 2015; Shi et al., 2015). However, up to 90% of the phosphorus in rice bran is bound to phytate and rice bran and rice mill feed contain more phytate than any other feed ingredient commonly included in diets fed to pigs (Stein et al., 2015). Because of the high concentration of phytate, the digestibility of phosphorus in rice bran and rice mill feed is relatively low, but inclusion of microbial phytase in diets containing rice bran will increase the standardized total tract digestibility of rice bran to more than 40% (Abelilla et al., 2015; Casas and Stein, 2015). In contrast, brown rice and broken rice contain very little phytate and the digestibility of phosphorus in these co-products, therefore, is much greater than in rice bran and rice mill feed (Casas and Stein, 2015).

The concentration of digestible and metabolizable energy in full fat rice bran is close to average values for wheat and maize, whereas the concentration in defatted rice bran is less than in full fat rice bran because of the reduced concentration of fat (Warren and Farrell, 1990c; Shi et al., 2015; Casas and Stein, 2016; Table 12). However, inclusion of microbial xylanase in diets containing full fat or defatted rice bran may increase the concentrations of digestible and metabolizable energy by up to 10% (Casas and Stein, 2016).

There are very few published experiments reporting on effects of adding rice co-products to diets fed to pigs. However, it has been indicated that 20 or 30% defatted rice bran may be included in diets fed to weanling pigs without negative impacts on growth performance if added to a basal diet mainly containing sorghum, wheat, and meat meal (Warren and Farrell, 1990b). It has also been speculated that full fat rice bran may improve growth performance of weanling pigs via a probiotic mechanism (Herfel et al., 2013). Recent data from the University of Illinois indicate that at least 20% of both full fat

Table 13
Composition of pulse crops.

Item	Ingredients					
	Field pea			Faba beans		
	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	15	16.5	0.9	1	18.7	–
Dry matter, g/kg	75	882.0	22.0	12	879.0	11.0
Crude protein, g/kg	102	217.0	21.0	13	228.0	35.0
Acid hydrolyzed ether extract, g/kg	1	11.0	–	–	–	–
Ash, g/kg	57	28.0	3.0	4	35.0	6.0
Starch, g/kg	52	421.0	44.0	1	362.0	–
Acid detergent fiber, g/kg	51	70.0	15.0	5	103.0	8.0
Neutral detergent fiber, g/kg	61	133.0	36.0	6	154.0	63.0
Total dietary fiber, g/kg	3	139.0	35.0	–	–	–
Calcium, g/kg	12	0.9	0.4	3	1.4	0.4
Phosphorus, g/kg	17	3.9	0.6	3	4.2	0.1
Indispensable amino acids, g/kg						
Arginine	79	19.0	3.3	10	21.0	3.5
Histidine	85	5.4	0.5	10	6.4	0.8
Isoleucine	85	9.3	1.2	10	9.9	1.5
Leucine	85	15.7	1.4	10	18.0	1.9
Lysine	87	16.3	1.7	10	15.8	1.2
Methionine	74	2.2	0.3	3	2.1	0.3
Phenylalanine	84	10.4	1.4	10	11.5	3.0
Threonine	86	10.1	11.5	10	8.5	0.9
Tryptophan	61	2.0	0.2	7	2.0	0.1
Valine	85	10.2	1.1	10	11.0	1.7
Dispensable amino acids, g/kg						
Alanine	57	9.6	1.1	3	10.7	1.5
Aspartic acid	57	25.5	2.7	3	27.9	4.1
Cysteine	72	3.1	0.4	3	3.2	0.8
Glutamic acid	57	38.7	5.1	3	43.9	6.8
Glycine	57	9.5	1.1	3	11.0	1.8
Proline	37	9.3	1.8	3	11.2	2.1
Serine	56	10.3	1.6	3	13.2	1.4
Tyrosine	54	6.0	1.3	3	8.4	2.5

and defatted rice bran can be included in maize-SBM based diets fed to weanling pigs from 2 weeks post-weaning without negative effects on pig growth performance (University of Illinois, Unpublished).

4. Pulse crops

4.1. Field peas

Global annual production of field peas is close to 12 million tons (Clansey, 2014) with Canada being the dominant producer with an annual production exceeding 6 million tons. Historically, field peas have been produced mainly for human consumption, but during the last 50 years, the industry has also found markets for field peas in livestock feeding. In Canada, Australia, and Western Europe, the use of field peas in diets fed to pigs has increased during this period because field peas may be grown in areas where other protein sources cannot be grown (Jezierny et al., 2010; Masey O' Neill et al., 2012; White et al., 2015). In feeding of pigs, only peas that are harvested at maturity are used. Field peas may have white or green seeds, but this does not influence the nutritional value of the peas.

Field peas contain less starch, but more CP and AA, than cereal grains (Table 13). The concentration of fiber is relatively low and anti-nutritional factors in the form of trypsin and chymotrypsin inhibitors are present at relatively low concentrations.

Pea protein has a relatively high concentration of lysine, but low concentration of methionine, cysteine, and tryptophan compared with soybean protein. The SID of most AA in field peas is comparable to the SID of AA in SBM (Table 14) with the exception that the digestibility of methionine, cysteine, and tryptophan in field peas is less than in SBM, and the SID of threonine tends to be less than in SBM (Stein et al., 2004; Petersen et al., 2014). The reason for these observations may be that albumin, which has a relatively high concentration of methionine, threonine, and tryptophan, is less digestible than other proteins in the seed (Le Guen et al., 1995). Some variability in digestibility of AA among different varieties of field peas has also been reported (Leterme et al., 1990; Fan and Sauer, 1999; Mariscal-Landiín et al., 2002). However, the SID of AA may be improved if field peas are heat treated (O'Doherty and Keady, 2000; Owusu-Asiedu et al., 2002; Stein and Bohlke, 2007), which is likely due to inactivation of trypsin inhibitors or possibly heat-induced conformational changes in the pea protein, which may enhance the access of proteolytic enzymes to the proteins (Owusu-Asiedu et al., 2002).

The carbohydrates in field peas include sucrose (3–4%), alpha-galactosides (3–4%), starch (40–45%), and non-starch polysaccharides (15–20%), whereas the concentration of lignin is less than 1% (Bengala Freire et al., 1991; Canibe and Bach

Table 14
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in pulse crops.

Item	Ingredients					
	Field pea			Faba beans		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Digestible energy, MJ/kg	14	13.4	1.1	1	12.3	–
Metabolizable energy, MJ/kg	5	13.3	1.5	1	12.2	–
Net energy, MJ/kg	1	10.0	–	1	8.6	–
SID indispensable amino acids						
Arginine	43	0.900	0.032	18	0.900	0.031
Histidine	49	0.820	0.038	20	0.790	0.081
Isoleucine	49	0.810	0.035	25	0.810	0.053
Leucine	49	0.810	0.041	25	0.820	0.049
Lysine	49	0.850	0.028	25	0.850	0.043
Methionine	42	0.780	0.038	23	0.730	0.117
Phenylalanine	49	0.810	0.038	20	0.800	0.059
Threonine	49	0.760	0.058	25	0.780	0.063
Tryptophan	28	0.710	0.059	14	0.640	0.112
Valine	49	0.780	0.045	25	0.780	0.049
SID, dispensable amino acids						
Alanine	43	0.770	0.041	18	0.780	0.056
Aspartic acid	43	0.820	0.032	18	0.850	0.042
Cysteine	40	0.670	0.039	22	0.620	0.109
Glutamic acid	43	0.860	0.034	18	0.880	0.031
Glycine	43	0.790	0.059	18	0.760	0.092
Proline	35	0.930	0.203	11	0.870	0.209
Serine	43	0.790	0.046	18	0.830	0.055
Tyrosine	35	0.790	0.049	9	0.820	0.068
STTD, phosphorus	9	0.540	0.084	1	0.360	–

Knudsen, 1997; Jezierny et al., 2010). In raw field peas, the apparent ileal digestibility of starch is approximately 90%, but this value is increased to approximately 95% if the field peas are extruded at 115–155 °C (Stein and Bohlke, 2007). The alpha-galactosides (i.e., raffinose, stachyose, and verbascose) require the enzyme alpha-galactosidase for digestion. This enzyme is not synthesized by mammals, but there is some intrinsic alpha-galactosidase present in field peas. Intestinal microbes also synthesize alpha-galactosidase and alpha-galactosides are, therefore, relatively easy to ferment and have an apparent ileal digestibility of 78% (Bengala Freire et al., 1991). However, alpha-galactosides may result in development of diarrhea in pigs if peas are fed in high concentrations (Jezierny et al., 2010).

The total tract digestibility of non-starch polysaccharides in peas is between 80 and 87% in both raw and extruded field peas (Canibe and Bach Knudsen, 1997; Stein and Bohlke, 2007). The digestibility of energy and the concentration of digestible and metabolizable energy in field peas are not different from values observed for maize (Grosjean et al., 1998; Stein et al., 2004). However, energy digestibility in field peas may be increased if the peas are extruded or otherwise heat treated because of increased ileal digestibility of starch (Bengala Freire et al., 1991; Stein and Bohlke, 2007). Energy digestibility is also improved by grinding field peas to a smaller particle size or by micronization (Nyachoti et al., 2006; Montoya and Leterme, 2011), which may also be a result of increased starch digestibility in finely ground particles.

Field peas contain approximately 0.4% phosphorus (NRC, 2012; Stein et al., 2006a). Of the total concentration of phosphorus, 45–52% is bound in the phytate complex, and therefore, has a low digestibility by pigs. However, the unbound phosphorus is highly digestible and the overall digestibility of phosphorus in field peas fed to growing pigs is 50–55% (Jongbloed and Kemme, 1990; Helander et al., 1996; Stein et al., 2006a). However, the digestibility of phosphorus can be improved by 10–15 percentage units if microbial phytase is added to diets containing field peas (Helander et al., 1996; Stein et al., 2006a).

Field peas are generally well tolerated by pigs and inclusion of field peas in diets usually has no negative influence on palatability. Results of several experiments have indicated that field peas may be included in diets fed to weanling pigs by 18–35% without negative impact on pig growth performance (Jondreville et al., 1992; Owusu-Asiedu et al., 2002; Stein et al., 2004) although negative effects of feeding field peas to pigs also have been observed (Friesen et al., 2006). In contrast, improvements in average daily gain, average daily feed intake and average gain to feed ratio for pigs fed diets containing 20% field peas has also been reported (Brooks et al., 2009). It has also been demonstrated that diets containing 40% field peas and fed to pigs from 1 week post-weaning or 49% field peas fed from two weeks post-weaning can be used without negative effects on pig growth performance (Stein et al., 2010; Landero et al., 2014).

Field peas may be included in diets fed to growing-finishing pigs by at least 36% in maize-based diets without any negative effects on pig growth performance or carcass characteristics (Stein et al., 2004). However, at this inclusion level, some SBM was needed to supply additional AA in the growing period. To investigate if SBM can be completely replaced by field peas in diets for growing-finishing pigs, an experiment in which field peas were included in the grower period (25–50 kg) at 66%, in the early finisher period (50–85 kg) at 48%, and during the late finishing period (85–125 kg) at 36% was conducted (Stein et al., 2006b). At these inclusion levels, all SBM in the diets was replaced by field peas. Growth performance of pigs fed these diets were compared to that of pigs fed a corn-soybean meal-based control diet or diets containing corn, soybean meal, and 36% field peas in all three phases. Results of this experiment demonstrated that pig performance was not influenced by the inclusion of field peas in the diets. Likewise, no negative effects of field peas were observed on carcass composition, carcass quality, or the palatability of pork chops or ground pork patties from pigs fed these diets. More recently, it was reported that inclusion of 30% of field peas in wheat-barley based diets that also contained 7% 00-rapeseed meal had no negative effects on pig growth performance, dressing percentage or carcass characteristics (White et al., 2015). It is, therefore, concluded that field peas may be included in diets fed to growing-finishing pigs at levels necessary to provide all AA needed by the pigs.

There are limited published data from experiments in which field peas were included in diets fed to sows. However, inclusion of 16% field peas in diets for gestating sows and 24% in diets for lactating diets had no negative effects on sow or pig performance (Gatel et al., 1988). It also was reported that if field peas are included in diets fed to gestating and lactating sows at levels of 10 or 20% there is no impact on sow or pig performance, but if the inclusion level was 30%, sow performance was reduced (von Leitgeb et al., 1994). Based on the above results, it is concluded that field peas may be used in diets fed to gestating and lactating sows at an inclusion level of up to 20%.

4.2. Faba beans

Faba beans have been cultivated for human consumption for almost 5000 years with the earliest use taking place in China, Egypt, and Mesopotamia (Singh et al., 2013b). Faba beans are also known as horse beans or field beans (Jezierny et al., 2010) and global production is approximately 4 million tons per year (Singh et al., 2013b). China accounts for approximately 50% of total production with Ethiopia, Egypt, and Australia being other major producers (Singh et al., 2013b).

The chemical composition of faba beans is close to that of field peas with approximately 22–28% of CP and between 400 and 500 g/kg of starch. However, faba beans contain several antinutritional factors including condensed tannins, trypsin inhibitors, alpha-galactosides, and vicine and convicine (Jansman et al., 1993; Jezierny et al., 2010). Concentrations of trypsin inhibitors in faba beans are close to those observed in field peas (Leterme et al., 1990). Condensed tannins reduce AA digestibility (Jansman, 1993; Mariscal-Landıín et al., 2002), but newer varieties of faba beans that contain less than 1% tannins are now available (Zijlstra et al., 2008; Kiarie et al., 2013). These varieties are white flowered instead of colored flowered and referred to as “zero-tannin faba beans”. The SID of AA in the zero-tannin beans is greater than in conventional faba beans (Mariscal-Landıín et al., 2002). In general, the SID of AA in conventional faba beans appears to be close to values reported for field peas (NRC, 2012).

The concentration of metabolizable energy in faba beans is less than in field peas (NRC, 2012; Kiarie et al., 2013), but it is possible that the concentration of metabolizable energy can be increased by extrusion as has been demonstrated for broiler chickens (Hejdysz et al., 2016), which may be a result of increased starch digestibility (Wierenga et al., 2008).

Inclusion of faba beans in diets based on barley and 00-rapeseed meal fed to growing-finishing pigs resulted in a quadratic reduction of pig growth performance and a recommendation that faba beans be included by no more than 20% in diets for growing-finishing pigs (Partanen et al., 2003). However, subsequent experiments in which zero-tannin faba beans were used indicated that up to 30% of faba beans may be included in diets based on wheat and barley (Zijlstra et al., 2008; Smith et al., 2013; White et al., 2015). It also appears that inclusion of faba beans at up to 30% in diets that are balanced for indispensable AA will have no impact on carcass characteristics or protein balance of pigs (Smith et al., 2013; White et al., 2015).

We are not aware of reports from experiments in which faba beans were included in diets fed to weanling pigs or gestating or lactating sows. However, provided the similarity in composition and antinutritional factors between field peas and faba beans, it is possible that the recommendations for inclusion of field peas in diets for weanling pigs and sows can also be used as a guide for inclusion of zero-tannin faba beans in diets for these categories of pigs.

5. Oilseed meals

5.1. Soybean products

Soybeans is the most widely used protein in the world and the global production of soybeans is increasing faster than that of any other agricultural crop (Goldsmith, 2008; USDA, 2016). Global annual production of soybeans is close to 320 million tons, which results in production of more than 200 million tons of SBM (Soy and Oilseed Blue Book, 2015). The global supply of SBM is, therefore, much greater than that of any other oilseed meal.

Most soybean products are fed to pigs in the form of SBM or derivatives of SBM, whereas use of full fat soybeans in diets fed to pigs is limited. Full fat soybeans contain several components that are undesirable for pigs, most notably trypsin inhibitors. To inactivate the trypsin inhibitors, all soybean products have to be heat treated or toasted prior to use in diets fed to pigs. However, if soybeans are properly heat treated the negative effects of trypsin inhibitors on AA digestibility is negated (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Goebel and Stein, 2011a; Yoon and Stein, 2013), and heat treated full fat soybeans can, therefore, be included in diets fed to all categories of pigs without any negative implications. Soybean meal is produced from defatted whole or dehulled soybeans (Stein et al., 2008). Dehulled SBM contains approximately 48% CP on an as-fed basis, and is sometimes referred to as high-protein SBM (Tables 15–18). Non-dehulled SBM contains approximately

Table 15
Composition of high protein soybean meal, low protein soybean meal, and soybean expellers.

Item	Ingredient								
	High protein soybean meal			Low protein soybean meal			Soybean expellers		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Gross energy, MJ/kg	96	17.7	0.7	25	17.3	0.8	5	19.6	0.2
Dry matter, g/kg	251	899.0	21.0	57	893.0	16.0	16	929.0	29.0
Crude protein, g/kg	287	481.0	21.0	71	434.0	22.0	20	444.0	19.0
Acid hydrolyzed ether extract, g/kg	25	16.0	11.0	2	12.0	11.0	3	80.0	33.0
Ash, g/kg	165	63.0	1.0	43	62.0	7.0	6	59.0	7.0
Starch, g/kg	12	24.0	22.0	12	22.0	12.0	–	–	–
Acid detergent fiber, g/kg	102	58.0	29.0	35	58.0	37.0	6	69.0	15.0
Neutral detergent fiber, g/kg	115	89.0	28.0	37	119.0	37.0	6	159.0	69.0
Total dietary fiber, g/kg	33	183.0	28.0	1	175.0	–	–	–	–
Calcium, g/kg	122	3.4	1.3	19	3.6	0.9	2	2.8	–
Phosphorus, g/kg	127	6.9	0.9	22	6.1	1.1	2	6.6	–
Indispensable amino acids, g/kg									
Arginine	190	35.4	6.1	54	31.5	3.3	13	30.3	3.8
Histidine	186	13.1	2.6	53	12.3	1.4	13	11.5	1.2
Isoleucine	196	22.1	3.9	56	19.8	1.8	13	18.9	2.5
Leucine	189	37.5	6.3	56	33.2	2.7	13	32.2	3.3
Lysine	212	30.1	4.8	55	27.5	2.0	13	27.2	3.4
Methionine	197	9.8	43.7	52	6.1	0.7	13	5.8	0.8
Phenylalanine	185	24.5	4.8	56	22.3	1.6	13	21.3	1.9
Threonine	205	18.4	3.1	55	17.5	2.1	13	16.9	0.9
Tryptophan	159	6.8	1.3	46	6.0	1.7	6	6.5	0.7
Valine	197	22.8	5.0	56	20.0	2.8	13	20.3	2.7
Dispensable amino acids, g/kg									
Alanine	150	21.5	5.7	49	19.1	1.7	11	18.0	2.4
Aspartic acid	150	54.8	10.5	49	48.8	4.9	11	45.5	8.8
Cysteine	175	7.1	1.4	49	6.4	1.4	9	6.8	0.5
Glutamic acid	150	85.8	18.5	49	77.6	8.7	11	72.3	10.8
Glycine	147	20.3	4.3	49	18.7	1.5	11	17.9	2.7
Proline	130	25.0	5.5	39	23.8	3.5	10	20.6	2.8
Serine	150	23.4	4.9	49	21.2	2.6	11	20.3	2.5
Tyrosine	132	17.0	3.8	46	15.6	1.5	10	14.0	2.8

43% CP and is sometimes referred to as low-protein soybean meal. Conventional toasted SBM is produced by extracting the fat from soy flour with a solvent, usually hexane, with a subsequent toasting step to remove residual hexane and to deactivate trypsin inhibitors and lectins. However, the oil from soybeans may also be extracted by mechanical extraction, which results in production of the co-product known as soybean expellers, which may also be fed to pigs. However, to inactivate trypsin inhibitors in soybean expellers, it is necessary that they be roasted or extruded prior to oil expelling (Wang and Johnson, 2001). Because mechanical extraction is less efficient in de-oiling soybeans than chemical extraction, the residual oil in soybean expellers is greater than in SBM and soybean expellers usually contains 4–6% ether extract, whereas SBM contains less than 3% ether extract. In contrast, soybean expellers usually contain less CP and AA than SBM because of the greater concentration of ether extract.

The concentration of CP and AA in soybeans and SBM may vary according to the area where the soybeans were produced (Hurburgh et al., 1987; Grieshop et al., 2003; Karr-Lilienthal et al., 2004; Goldflus et al., 2006). The SID of AA in SBM is greater than in most other plant based feed ingredients, and usually, SBM is used as the standard that other protein sources are measured against (González-Vega and Stein, 2012). Most AA has an SID value that is close to or above 90% (Cervantes-Pahm and Stein, 2008; Baker and Stein, 2009; Goebel and Stein, 2011a,b), and there is relatively little variability in SID values among SBM sourced from different areas of the United States (Sotak-Peper et al., 2016). In addition, the profile of indispensable AA in SBM is more favorable than that of other oilseed meals because of high concentrations of lysine and tryptophan (Stein et al., 2008). Because the concentration of these AA is relatively low in most cereal grains, and specifically in maize, SBM and cereal grains complement each other to provide a more balanced profile of AA than if any other oilseed meal is used in diets fed to pigs (Stein et al., 2008).

The concentration of metabolizable and net energy in soybean meal is close to that of maize and relatively constant among different sources of SBM (Sotak-Peper et al., 2015) and greater than in other oilseed meals (Rodriguez et al., 2013). Soybean meal contains approximately 0.7% phosphorus and the majority of the phosphorus is bound to phytate as is the case for most other plant ingredients (NRC, 2012). However, addition of microbial phyase to the diets will increase the digestibility of phosphorus to between 60 and 70% and SBM is, therefore, an attractive source of digestible phosphorus in diets fed to pigs (Goebel and Stein, 2011b; Rojas and Stein, 2012; Rodriguez et al., 2013).

Because of the favorable nutritional value of SBM, animal performance is usually not improved if SBM is removed from the diets and other protein sources are used, although performance obtained on diets containing other protein sources sometimes may be equal to the performance obtained on SBM-based diets (Shelton et al., 2001). As a consequence, there

Table 16
Composition of soy protein concentrate, fermented soybean meal, soy protein isolate, and enzyme treated soybean meal.

Item	Ingredient											
	Soy protein concentrate			Fermented soybean meal			Soy protein isolate			Enzyme treated soybean meal		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	3	19.0	0.7	4	18.7	0.4	1	22.6	–	7	18.8	0.4
Dry matter, g/kg	17	922.0	21.0	10	827.0	276.0	4	938.0	14.0	17	913.0	17.0
Crude protein, g/kg	25	649.0	40.0	11	515.0	72.0	8	839.0	45.0	17	545.0	33.0
Acid hydrolyzed ether extract, g/kg	3	6.0	4.0	4	16.0	2.0	1	12.0	–	7	12.0	3.0
Ash, g/kg	13	60.0	8.0	5	69.0	2.0	2	42.0	7.0	14	65.0	4.0
Starch, g/kg	1	14.0	–	1	9.0	–	1	19.0	–	–	–	–
Acid detergent fiber, g/kg	1	44.0	–	4	51.0	4.0	–	–	–	9	59.0	23.0
Neutral detergent fiber, g/kg	4	84.0	11.0	4	84.0	4.0	1	1.9	–	8	121.0	34.0
Total dietary fiber, g/kg	3	188.0	22.0	–	–	–	–	–	–	–	–	–
Calcium, g/kg	6	3.2	0.4	7	3.2	0.4	5	1.7	0.3	11	3.0	0.4
Phosphorus, g/kg	6	8.2	0.6	7	7.9	0.3	5	7.4	0.2	11	7.5	0.3
Indispensable amino acids, g/kg												
Arginine	21	47.2	2.1	10	34.4	5.9	11	61.8	5.1	15	40.9	6.1
Histidine	21	17.8	2.5	10	13.1	2.5	11	21.5	1.5	15	14.5	1.5
Isoleucine	21	29.6	2.1	10	22.9	4.4	11	38.3	3.0	15	6.3	2.0
Leucine	21	50.7	3.1	10	38.9	7.0	8	66.4	5.0	15	43.8	5.2
Lysine	22	40.9	2.9	11	30.2	3.9	10	51.4	2.7	15	34.9	6.0
Methionine	22	8.2	1.7	11	7.1	1.0	11	11.1	1.8	15	7.6	1.4
Phenylalanine	21	33.3	2.5	10	25.7	4.3	11	43.4	2.8	15	29.0	2.9
Threonine	22	24.6	3.4	11	19.8	3.3	11	30.6	2.6	15	21.6	3.0
Tryptophan	16	7.8	2.7	11	6.8	1.0	7	11.0	0.7	14	7.6	0.5
Valine	21	30.7	4.1	10	24.9	4.2	11	40.1	1.9	14	26.9	1.8
Dispensable amino acids, g/kg												
Alanine	18	26.8	5.5	10	22.2	3.5	7	35.7	3.6	15	24.8	2.9
Aspartic acid	17	74.8	4.8	9	54.5	9.3	7	92.7	8.5	15	63.4	8.2
Cysteine	18	9.0	1.3	10	7.6	1.1	9	9.8	0.6	15	7.3	0.5
Glutamic acid	17	119.0	6.5	9	86.5	14.6	7	164.0	25.2	14	88.7	25.1
Glycine	18	26.6	3.0	10	21.3	3.5	7	35.7	3.8	15	23.8	2.5
Proline	16	35.7	3.8	9	25.9	5.7	7	44.4	6.6	14	28.3	7.0
Serine	17	33.0	2.6	10	23.2	3.6	7	42.9	7.5	15	25.8	6.1
Tyrosine	14	22.2	1.7	9	17.3	4.1	6	30.4	2.0	12	20.7	2.4

Table 17
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in high protein soybean meal, low protein soybean meal, and soybean expellers.

Item	High protein soybean meal			Low protein soybean meal			Soybean expellers		
	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	19	15.7	1.1	3	15.5	1.4	4	15.8	1.0
Metabolizable energy, MJ/kg	19	14.5	0.9	8	13.8	0.8	3	15.0	1.1
Net energy, MJ/kg	2	9.2	2.7	1	10.7	–	–	–	–
SID, indispensable amino acids									
Arginine	120	0.930	0.033	27	0.930	0.035	7	0.890	0.125
Histidine	119	0.880	0.053	28	0.880	0.046	7	0.890	0.025
Isoleucine	119	0.870	0.091	28	0.880	0.043	7	0.880	0.039
Leucine	119	0.860	0.089	28	0.870	0.038	7	0.870	0.042
Lysine	119	0.870	0.089	28	0.880	0.032	7	0.890	0.024
Methionine	113	0.880	0.096	24	0.900	0.043	7	0.860	0.056
Phenylalanine	118	0.870	0.088	28	0.870	0.032	7	0.870	0.059
Threonine	119	0.820	0.099	28	0.840	0.053	7	0.820	0.046
Tryptophan	95	0.860	0.121	19	0.890	0.035	4	0.860	0.089
Valine	119	0.850	0.092	28	0.850	0.033	7	0.860	0.044
SID, dispensable amino acids									
Alanine	94	0.830	0.104	23	0.860	0.048	6	0.870	0.019
Aspartic acid	93	0.850	0.107	23	0.860	0.035	6	0.870	0.023
Cysteine	106	0.780	0.139	18	0.820	0.052	5	0.840	0.039
Glutamic acid	94	0.860	0.103	23	0.880	0.029	6	0.890	0.031
Glycine	94	0.820	0.115	23	0.830	0.066	6	0.880	0.054
Proline	82	0.980	0.207	20	1.000	0.171	6	1.240	0.173
Serine	94	0.860	0.106	23	0.890	0.051	6	0.870	0.035
Tyrosine	70	0.870	0.114	24	0.870	0.094	6	0.860	0.056
STTD, phosphorus	36	0.521	0.099	12	0.489	0.082	–	–	–

Table 18
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in soy protein concentrate, fermented soybean meal, soy protein isolate, and enzyme treated soybean meal.

Item	Ingredient											
	Soy protein concentrate			Fermented soybean meal			Soy protein isolate			Enzyme treated soybean meal		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Digestible energy, MJ/kg	2	14.9	4.1	2	16.5	0.2	1	17.4	–	4	16.4	0.1
Metabolizable energy, MJ/kg	1	14.7	–	2	14.5	0.06	1	15.0	–	4	14.9	0.1
Net energy, MJ/kg	1	12.2	–	1	10.3	–	1	9.2	–	–	–	–
SID, indispensable amino acids												
Arginine	15	0.960	0.018	4	0.930	0.037	7	0.950	0.041	8	0.960	0.026
Histidine	15	0.910	0.027	4	0.860	0.055	7	0.890	0.064	8	0.900	0.043
Isoleucine	15	0.910	0.026	4	0.860	0.054	7	0.880	0.089	8	0.890	0.035
Leucine	15	0.900	0.025	4	0.850	0.053	7	0.890	0.056	8	0.890	0.040
Lysine	15	0.910	0.027	4	0.800	0.071	7	0.920	0.037	8	0.850	0.046
Methionine	14	0.920	0.030	4	0.900	0.028	6	0.870	0.112	7	0.910	0.025
Phenylalanine	15	0.900	0.032	4	0.850	0.081	7	0.890	0.059	8	0.880	0.067
Threonine	15	0.860	0.039	4	0.800	0.085	7	0.830	0.079	8	0.830	0.054
Tryptophan	12	0.890	0.034	4	0.850	0.092	3	0.880	0.024	7	0.850	0.051
Valine	15	0.890	0.028	4	0.840	0.060	7	0.870	0.095	8	0.890	0.046
SID, dispensable amino acids												
Alanine	14	0.890	0.026	4	0.820	0.044	6	0.900	0.038	7	0.860	0.035
Aspartic acid	14	0.870	0.044	4	0.830	0.065	6	0.920	0.027	7	0.860	0.029
Cysteine	14	0.790	0.056	4	0.710	0.108	4	0.810	0.107	7	0.760	0.096
Glutamic acid	14	0.910	0.033	4	0.810	0.062	6	0.940	0.032	7	0.890	0.049
Glycine	14	0.880	0.029	4	0.790	0.042	6	0.900	0.032	7	0.870	0.069
Proline	12	1.040	0.089	3	1.060	0.228	5	1.210	0.321	6	1.210	0.240
Serine	14	0.910	0.031	4	0.580	0.058	6	0.930	0.029	7	0.870	0.038
Tyrosine	9	0.930	0.034	3	0.900	0.029	5	0.890	0.103	4	0.910	0.028
STTD, phosphorus	3	0.504	0.066	2	0.655	–	1	0.480	–	1	0.663	–

are few restrictions on the use of SBM in diets fed to growing-finishing pigs or gestating or lactating sows, and SBM can, therefore, be used as the sole source of additional AA in grain based diets fed to these groups of pigs. However, for pigs that are less than 20 kg, SBM is usually not included as the sole source of supplemental AA. The reason for this is that in addition to trypsin inhibitors, soybeans also contain lectins, antigens and oligosaccharides (Cervantes-Pahm and Stein, 2010). These components are not a problem for pigs greater than 20 kg because the developed digestive tract of older animals is efficient in fermenting the oligosaccharides and the lectins and antigens cause no harm to the older pigs. However, for pigs less than 20 kg, the antigens and the oligosaccharides result in reduced efficiency of digestion and inclusion of conventional soybean meal is, therefore, limited in diets fed to these pigs (Li et al., 1990; Liying et al., 2003). To alleviate this problem, the antigens and the oligosaccharides may be removed from SBM, which can be accomplished via fermentation, enzyme treatment, or alcohol extraction. Fermentation is usually accomplished by inclusion of one or several stains of microbes such as *aspergillus oryzae*; Bifidobacterium lactis, lactobacillus subtilis, or other microbes (Feng et al., 2007; Song et al., 2010; Rojas and Stein, 2013). In contrast, enzyme treated SBM is produced by inclusion of proprietary enzymes and yeast during fermentation for approximately 10 h (Cervantes-Pahm and Stein, 2010). Both fermentation and enzyme treatment results in removal of oligosaccharides and sucrose from SBM and enzyme treatment also removes most of the antigens (Cervantes-Pahm and Stein, 2010). Fermentation may also reduce the size of the peptides in the SBM, which is believed to result in increased SID of AA (Hong et al., 2004), but the peptide size is not always reduced in fermented SBM (Cervantes-Pahm and Stein, 2010), and the SID of AA in fermented SBM and enzyme treated SBM has not been demonstrated to be greater than in conventional SBM (Cervantes-Pahm and Stein, 2010; Rojas and Stein, 2013). In contrast, the standardized total tract digestibility of phosphorus is greater in fermented SBM than in conventional SBM is no microbial phytase is used in the diet (Rojas and Stein, 2012). The concentration of metabolizable energy in fermented or enzyme treated SBM is within the range of values reported for conventional SBM, but slightly greater than in fish meal (Goebel and Stein, 2011b; Rojas and Stein, 2013).

Because of the removal of oligosaccharides, fermented SBM may be included in diets fed to weanling pigs by up to approximately 10% without causing any negative effects (Jones et al., 2010; Kim et al., 2010; Rojas and Stein, 2015a). Fermented SBM may be used in place of animal protein sources such as fish meal or poultry by product meal, and the need for adding animal proteins to diets fed to weanling pigs may, therefore, be reduced if fermented or enzyme treated SBM is used.

Soy protein concentrate is produced by acid leaching at a pH of around 4.5 followed by extraction of water-soluble carbohydrates from defatted SBM by ethanol (60–90%), and denaturing of the protein with moist heat and extraction with water (Endres, 2001). The soluble carbohydrates that are removed during the ethanol extraction include the oligosaccharides that are harmful to young pigs, but the majority of the fiber in SBM is insoluble fiber and remains in soy protein concentrate. Soy protein concentrate must contain at least 65% CP on a dry matter basis (Deak et al., 2008), but functional differences among different sources of soy protein concentrate may be observed due to differences in the production process (Li et al., 1991; Endres, 2001; Wang and Johnston, 2001).

Soy protein isolate is the most concentrated form of soy protein that is available and it is produced by solubilizing the protein in SBM with water and precipitating the protein from the solution. This process removes the fat and carbohydrate components from the product (Cromwell, 2000); therefore, soy protein isolate contains at least 90% CP on a DM basis (Endres, 2001; Deak et al., 2008). The allergenic proteins glycinin and β-conglycinin are deactivated when soy protein concentrate and soy protein isolate are produced by extraction at temperatures greater than 50 °C (Sissons et al., 1982) and both products are well tolerated by weanling pigs (Li et al., 1991). However, because of the high costs involved in producing soy protein isolate, this product is usually not used in the feeding of pigs.

5.2. Canola and 00-rapeseed meal and canola and 00-rapeseed expellers

The development of rapeseeds with reduced concentrations of glucosinolates and erucic acid in the 1970'ties resulted in increased usage of rapeseed products in diets fed to pigs (Daun, 2011). These new varieties are called canola in North America and Australia, and double-low rapeseeds or 00-rapeseeds in other countries in the world. The oil from 00-rapeseed and canola is mainly used for human consumption or for biodiesel production, but the meal or expellers that are the co-products that are left after crushing of the seeds, may be used in diets fed to pigs. The global production of canola and rapeseed is approximately 71 million tons, which results in production of close to 40 million tons of canola meal or 00-rapeseed meal (Soy and Oilseed Blue Book, 2015).

The concentration of CP in 00-rapeseed meal and canola meal is usually between 35 and 40%, whereas the concentrations in expellers is between 32 and 36% (Newkirk, 2011; Table 19 and 20), but there are no differences between canola meal and 00-rapeseed meal in terms of nutrient composition (Maison and Stein, 2014). Unlike the situation for SBM, it is not common practice to de-hull rapeseed and canola seeds before feeding to pigs, and the concentration of fiber is, therefore, greater in canola and 00-rapeseed meal than in SBM with total dietary fiber values often being between 20 and 30%. The majority of the fibers are pectic polysaccharides that are very complex and difficult to ferment, and the apparent total tract digestibility of fiber is, therefore, relatively low (Maison et al., 2015a). As a consequence, the energy value in canola and 00-rapeseed meal is less than in SBM, but greater than in sunflower meal (Adeola and Kong, 2014; Liu et al., 2014b, 2016; Berrocoso et al., 2015). There is, however, no difference in ME between 00-rapeseed meal and canola meal (Maison et al., 2015a), but there is a greater concentration of ME in 00-rapeseed expellers compared with 00-rapeseed meal, which is due to the greater concentration of residual oil in the expellers compared with the meal (Maison et al., 2015a). Likewise, there is a greater concentration of metabolizable energy in canola expellers compared with canola meal (Woyengo et al., 2010).

The concentration of lysine is less in 00-rapeseed and canola meal compared with SBM, but the concentration of the sulfur containing AA is greater in 00-rapeseed and canola protein than in soy protein (NRC, 2012). There is no difference in the digestibility of AA between canola meal and 00-rapeseed meal, but 00-rapeseed expellers have AA digestibility that is slightly greater than in 00-rapeseed meal (Woyengo et al., 2010; Maison and Stein, 2014). However, the digestibility of AA in canola meal is approximately 10 percentage units less than in SBM (Li et al., 2002; Liu et al., 2014b; Berrocoso et al., 2015), which may be a result of the high concentration of fiber in canola and rapeseed protein because there is an inverse relationship between the digestibility of AA in canola meal and the concentration of neutral detergent fiber (Fan et al., 1996). There is also more variability in the SID values for AA that have been determined for 00-rapeseed meal, 00-rapeseed expellers and canola meal compared with SBM (Fan et al., 1996; Li et al., 2015a, 2015b). Some of this variability may be a result of some crushing plants overheating the meals during processing (Messerschmidt et al., 2014) because increased heat treatment of canola or 00-rapeseed meal results in reduced SID of AA (Newkirk et al., 2003; Almeida et al., 2014a; Eklund et al., 2015). Correct processing temperature is, therefore, important in the processing of 00-rapeseeds and canola seeds.

Concentrations of calcium and phosphorus in 00-rapeseed and canola meal are greater than in SBM, and the digestibility of P in canola meal is relatively low (Adhikari et al., 2015), but there is no difference in the digestibility of P between canola meal and 00-rapeseed meal or between 00-rapeseed meal and 00-rapeseed expellers (Maison et al., 2015b). However, if microbial phytase is added to the diets, the digestibility of phosphorus is between 50 and 70% in canola meal as well as 00-rapeseed meal and 00-rapeseed expellers (Maison et al., 2015b). The concentration of calcium in canola meal and 00-rapeseed meal is greater than in most other plant ingredients (Table 19). The true total tract digestibility of calcium in canola meal is approximately 46%, but this value will increase to around 70% if microbial phytase is added to the diet (Gonzalez-Vega et al., 2013).

New varieties of canola seeds with increased concentrations of CP have recently been introduced to the market and crushing of these seeds results in production of high protein canola meal that contains 45–48% crude protein (Jia et al., 2012; Slominski et al., 2012; Trindade Neto et al., 2012; Liu et al., 2014b). The concentration of ME in high protein canola meal is comparable to that in conventional canola meal and the same is the case for the digestibility of AA (Trindade Neto et al., 2012; Berrocoso et al., 2015; Liu et al., 2014b, 2016).

Although the concentration in glucosinolates in canola meal and 00-rapeseed meal is much less than in old type rapeseed meal, the concentration of glucosinolates may vary between less than 5 micromol per gram to more than 20 micromol per gram and it is assumed that the degree of heating during processing may to some degree impact the concentration of glucosinolates in the meal (Messerschmidt et al., 2014). Glucosinolates in canola meal or 00-rapeseed meal may affect iodine metabolism (Tripathi and Mishra, 2007), which may result in increased size of the thyroid gland and reduced plasma concentrations of thyroid hormones (i.e., thyroxine and trioiodothyronine) if canola meal or 00-rapeseedd meal is included in the diets (Mullan et al., 2000; Parr et al., 2015).

Table 19
Composition of canola meal, canola expellers, sunflower meal (dehulled), cottonseed meal, and peanut meal.

Item	Ingredient														
	Canola meal			Canola expellers			Sunflower meal, dehulled			Cottonseed meal			Peanut meal		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	45	17.9	0.5	15	19.7	1.2	4	18.1	0.4	20	17.8	0.8	1	19.4	–
Dry matter, g/kg	96	908.0	21.0	17	928.0	19.0	10	915.0	9.0	44	909.0	21.0	6	918.0	11.5
Crude protein, g/kg	130	373.0	27.0	20	358.0	36.0	11	387.0	46.0	52	369.0	79.0	11	467.0	46.0
Acid hydrolyzed ether extract, g/kg	21	37.0	4.0	–	–	–	2	21.0	–	6	22.0	15.0	–	–	–
Ash, g/kg	64	70.0	11.0	17	68.0	4.0	9	69.0	8.0	37	63.0	6.0	5	60.0	18.0
Starch, g/kg	9	32.0	25.0	2	39.0	34.0	2	21.0	10.0	4	19.0	5.0	1	67.0	–
Acid detergent fiber, g/kg	58	184.0	32.0	13	201.0	70.0	5	219.0	20.0	32	234.0	94.0	1	125.0	–
Neutral detergent fiber, g/kg	74	271.0	51.0	20	279.0	89.0	5	307.0	9.0	23	284.0	66.0	1	162.0	–
Total dietary fiber, g/kg	4	297.0	25.0	1	258.0	–	–	–	–	–	–	–	–	–	–
Calcium, g/kg	47	7.1	1.4	11	6.8	1.0	2	3.8	0.2	8	3.0	1.0	2	3.9	1.6
Phosphorus, g/kg	48	10.6	0.8	12	1.5	1.4	2	12.2	0.8	18	7.9	3.4	2	5.8	0.3
Indispensable amino acids, g/kg															
Arginine	102	22.1	2.5	19	19.0	2.9	8	32.7	3.4	18	44.1	15.5	8	52.2	5.6
Histidine	93	10.4	1.6	19	9.1	2.7	8	9.4	0.9	22	16.1	18.7	8	10.0	1.5
Isoleucine	101	14.5	1.3	19	15.7	4.5	8	15.6	1.8	22	13.2	4.6	8	14.3	1.5
Leucine	101	25.1	2.5	19	21.7	3.8	8	24.5	1.2	22	23.9	8.5	8	26.3	2.3
Lysine	102	20.7	2.3	19	17.4	3.4	8	14.2	1.1	24	16.2	5.7	8	14.8	1.4
Methionine	80	7.1	1.5	19	6.2	1.3	7	7.9	1.5	18	5.8	2.8	6	5.0	1.6
Phenylalanine	95	14.8	2.1	19	14.6	3.9	8	16.5	2.1	22	21.6	6.5	8	20.2	1.9
Threonine	102	15.5	3.3	19	13.3	2.2	8	13.6	0.8	22	13.3	4.5	8	12.4	2.0
Tryptophan	60	4.3	1.0	8	4.8	2.2	3	4.6	0.4	15	5.7	2.5	6	3.8	0.5
Valine	101	18.2	1.9	19	17.1	3.2	8	18.3	2.6	22	17.6	6.7	8	16.3	2.5
Dispensable amino acids, g/kg															
Alanine	71	16.0	1.5	14	13.5	4.0	5	16.4	1.2	14	15.3	3.0	4	18.7	3.0
Aspartic acid	69	25.9	3.3	14	21.6	6.8	5	35.1	3.5	15	33.2	7.8	4	44.9	14.0
Cysteine	72	8.5	0.9	16	8.4	1.2	6	5.3	1.9	14	8.8	3.6	4	5.4	0.5
Glutamic acid	69	62.2	6.7	14	56.3	17.8	5	77.1	10.2	15	70.2	15.5	4	75.1	24.2
Glycine	71	18.0	1.8	14	16.1	4.9	5	21.2	1.9	15	5.9	3.1	4	27.3	4.0
Proline	69	21.8	4.1	9	15.3	9.7	5	18.2	5.1	12	14.9	4.2	4	15.2	8.2
Serine	71	14.1	2.2	14	10.8	4.4	5	15.5	2.2	15	17.9	6.0	4	21.3	2.6
Tyrosine	68	10.6	1.8	15	1.9	1.9	5	8.8	1.9	17	11.0	5.0	5	14.2	1.3

Table 20
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in canola meal, canola expellers, sunflower meal (dehulled), cottonseed meal, and peanut meal.

Item	Ingredient														
	Canola meal			Canola expellers			Sunflower Meal, dehulled			Cottonseed meal			Peanut meal		
	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD	N	$\bar{X}$	SD
Digestible energy, MJ/kg	33	12.9	1.6	11	14.9	3.3	1	11.9	–	11	9.1	1.4	1	14.3	–
Metabolizable energy, MJ/kg	15	11.6	1.3	4	11.9	2.5	3	10.7	0.5	17	9.0	1.1	1	13.0	–
Net energy, MJ/kg	1	6.2	–	5	11.5	2.6	1	8.2	–	1	6.2	–	–	–	–
SID, indispensable amino acids															
Arginine	57	0.850	0.054	10	0.840	0.054	6	0.920	0.037	21	0.880	0.034	6	0.930	0.037
Histidine	51	0.790	0.099	10	0.800	0.034	6	0.830	0.070	21	0.740	0.083	6	0.810	0.081
Isoleucine	57	0.760	0.079	10	0.750	0.079	6	0.790	0.058	21	0.700	0.091	6	0.810	0.069
Leucine	57	0.780	0.069	10	0.800	0.042	6	0.790	0.051	21	0.730	0.072	6	0.800	0.073
Lysine	57	0.730	0.093	10	0.710	0.119	6	0.760	0.065	21	0.630	0.105	6	0.770	0.079
Methionine	55	0.830	0.066	10	0.840	0.035	5	0.850	0.031	17	0.730	0.133	4	0.830	0.044
Phenylalanine	51	0.770	0.076	9	0.790	0.079	6	0.800	0.066	21	0.810	0.052	6	0.870	0.047
Threonine	57	0.710	0.086	10	0.690	0.104	6	0.760	0.082	21	0.690	0.092	6	0.750	0.103
Tryptophan	34	0.760	0.098	6	0.700	0.148	3	0.790	0.072	12	0.720	0.099	4	0.750	0.045
Valine	57	0.730	0.089	10	0.700	0.099	6	0.780	0.075	21	0.730	0.078	6	0.770	0.081
SID, dispensable amino acids															
Alanine	42	0.760	0.061	9	0.740	0.080	4	0.720	0.030	18	0.700	0.086	2	0.820	0.086
Aspartic acid	42	0.740	0.069	9	0.710	0.136	4	0.750	0.035	18	0.760	0.061	2	0.910	0.011
Cysteine	47	0.740	0.065	7	0.710	0.081	4	0.790	0.072	8	0.750	0.091	1	0.810	–
Glutamic acid	42	0.830	0.064	9	0.840	0.051	4	0.850	0.019	17	0.840	0.047	2	0.920	0.017
Glycine	42	0.770	0.069	9	0.750	0.116	4	0.670	0.064	18	0.770	0.094	2	0.860	0.008
Proline	33	0.920	0.142	7	0.940	0.209	4	0.870	0.151	15	0.860	0.171	2	0.990	0.293
Serine	42	0.740	0.076	9	0.740	0.108	4	0.740	0.051	18	0.750	0.069	2	0.880	0.016
Tyrosine	37	0.760	0.084	9	0.760	0.099	4	0.760	0.055	15	0.760	0.059	1	0.920	–
STTD, phosphorus	17	0.415	0.095	1	0.262	–	2	0.393	0.152	6	0.374	0.089	–	–	–

Because of the difference in glucosinolate concentration among different sources of canola meal or 00-rapeseed meal, pig responses to inclusion of canola meal or 00-rapeseed meal in the diets may be somewhat variable. However, it appears that in diets for weanling pigs, at least 20–25% high protein or conventional canola meal may be used without reducing pig performance (King et al., 2001; Landero et al., 2011, 2012b, 2013; Sanjayan et al., 2014) and inclusion of up to 40% may be possible if canola meal with low concentrations of glucosinolates is used (Parr et al., 2015). Likewise, inclusion of up to 24% canola expellers in diets fed to weanling pigs has no or minimal impact on pig growth performance (Seneviratne et al., 2011; Landero et al., 2012a; Le et al., 2014).

For growing-finishing pigs, numerous experiments have indicated that between 10 and 30% canola meal or 00-rapeseed meal may be used without detrimental effects on pig growth performance (Mullan et al., 2000; King et al., 2001; Kim et al., 2015a). However, increasing the inclusion of canola expellers from 0 to 22.5% or canola meal from 10 to 30% in diets that also contained 15 or 20% DDGS resulted in a linear reduction in pig growth performance and carcass weight (Seneviratne et al., 2010; Smit et al., 2014a, 2014b). Complete replacement of SBM in diets fed to growing-finishing pigs resulted in a reduction in average daily gain and in the gain to feed ratio during the growing phase, but not during the early finishing and late finishing phases (Shelton et al., 2001). In contrast, results of recent research indicate that conventional and high protein canola meal may fully replace SBM in corn-based diets fed to growing-finishing pigs without any negative impacts on pig growth performance or carcass quality if diets are fortified with sufficient levels of crystalline AA (Little et al., 2015). Thus it appears that if canola meal is included in well balanced diets for growing-finishing pigs that do not contain other high-fiber ingredients, there are few limitations to the inclusion rate, but if diets contain other high-fiber ingredients such as DDGS, or if diets are not balanced for indispensable AA, a negative response may be observed.

There is less information about inclusion of canola meal in diets fed to sows than in diets fed to weanling pigs or growing-finishing pigs. However, inclusion of 10–20% 00-rapeseed meal in diets fed to sows has been reported not to impact sow or litter performance (King et al., 2001; Schone et al., 2001; Opalka et al., 2003). Recent results from our laboratory indicate that conventional or high protein canola meal may replace all SBM in diets fed to gestating as well as lactating sows without negatively impacting sow or pig performance (University of Illinois, unpublished).

5.3. Sunflower meal

Global production of sunflower seeds is approximately 40 million tons with Russia, Ukraine, and the European Union being the major producers (Jocic and Miladinovic, 2015). The oil concentration in sunflower seeds is greater than 50%, which is greater than in any of the other oil seeds. As a consequence, only around 16 million tons of sunflower meal is produced on an annual basis (Soya and Oilseed Blue Book, 2015).

Sunflower meal contains 30–33% CP and 40–55% neutral detergent fiber (Rodriguez et al., 2013; Liu et al., 2015a). However, due to the high fiber concentration of the hulls, sunflower meal is often fed to pigs only if the seeds were partially de-hulled prior to crushing, resulting in a meal that contains approximately 38% CP and 30% neutral detergent fiber (NRC, 2012; Rodriguez et al., 2013). The concentration of lysine in sunflower protein is low, but the concentration of the sulfur containing AA is greater than in soybean meal (NRC, 2012). The SID of AA in sunflower meal is less than in canola meal and SBM (González-Vega and Stein, 2012; Nørgaard et al., 2012) although if concentrations of NDF is less than 30%, the SID of AA can be close to values usually obtained in soybean meal (Almeida et al., 2014b). Significant differences among sources of sunflower meal in terms of the SID of AA have been reported (Liu et al., 2015a), and this is likely a result of the relatively large differences in neutral detergent fiber among sources. Thus, it appears that the digestibility of AA in sunflower meal is reduced if the fiber concentration is increased. The relatively high concentration of fiber also reduces energy digestibility and the concentration of ME of partially dehulled sunflower meal is much less than in SBM and also less than in canola meal (Rodriguez et al., 2013; Adeola and Kong, 2014).

More than 80% of the phosphorus in sunflower meal is bound to phytate resulting in a reduced digestibility of phosphorus in sunflower meal compared with soybean meal and canola meal (Rodriguez et al., 2013). However, supplementation of diets containing sunflower meal with microbial phytase increases the digestibility of phosphorus to more than 50% (Rodriguez et al., 2013).

Sunflower meal has low concentrations of anti-nutritional factors, but results from experiments in which sunflower meal was included in diets fed to weanling, growing, or reproducing swine have been highly variable (Dinussen, 1990). Full replacement of SBM with sunflower meal during the entire growing-finishing period resulted in a reduction in average daily gain and gain to feed ratio (Shelton et al., 2001). However, because diets were not balanced for metabolizable energy, diets containing sunflower meal contained less metabolizable energy than diets containing SBM, which may have been the reason for this observation (Shelton et al., 2001). It is also possible that most of the negative effects that have been reported when sunflower meal was used are a result of the low concentrations of lysine, threonine, and tryptophan in sunflower meal and the negative effects may, therefore, be alleviated if diets are properly balanced for AA. Indeed, partially de-hulled sunflower meal may replace SBM in diets fed to weanling or growing-finishing pigs if diets are balanced for indispensable AA (Wahlstrom et al., 1985; Dinussen, 1990). However, the high concentrations of fiber in sunflower meal may sometimes restrict inclusion rates to less than 15 or 20% (Chiba, 2001). Sunflower meal may also be used as the main protein source in diets fed to gestating and lactating sows if diets are balanced for AA (Dinussen, 1990).

5.4. Cottonseed meal

Cotton seeds are produced in many countries in the world and annual global production is approximately 44 million tons (Soy and Oilseed Bluebook, 2015). After removal of oil, lint and hulls, approximately 45% of the seed remains and is used as cottonseed meal, and global production of cotton seed meal is approximately 15 million tons per year (Soy and Oilseed Bluebook, 2015). The concentration of CP in cotton seed meal is between 37 and 45%, which is similar to that in canola meal and the concentration of neutral detergent fiber is between 25 and 30%, which is also similar to canola meal, but much greater than in SBM. The concentration of lysine and most other indispensable AA is less in cottonseed meal than in canola meal, but greater than in sunflower meal (González-Vega and Stein, 2012). However, the SID of most indispensable AA is less in cottonseed meal than in other oilseed meals (Tanksley et al., 1981; Prawirodigdo et al., 1998; González-Vega and Stein, 2012; NRC, 2012). The concentration of metabolizable energy in cotton seed meal has been recently determined to be 11.3 mega joule per kg (Rodriguez et al., 2013), which is less than in most other oil seed meals. However, in a different source of cottonseed meal, the concentration of metabolizable energy was approximately 13.1 mega joule per kg (Adeola and Kong, 2014).

Cottonseed meal contains more than 1% phosphorus, which is more than in most other oilseed meals (Rodriguez et al., 2013). The majority of the phosphorus is bound to phytate and the standardized total tract digestibility of phosphorus, therefore, is only 45% if no microbial phytase is used, but if microbial phytase is added to the diet, the digestibility of phosphorus increases to 60% (Rodriguez et al., 2013).

The major limitation to the use of cottonseed meal in diets for pigs is the concentration of the anti-nutritional factor gossypol, which may be present in by up to 5% or more in cottonseed meal. Gossypol may be either free or bound, and the bound gossypol is not toxic to pigs, whereas free gossypol is toxic (Tanksley, 1990). During heat processing, gossypol binds to lysine, which reduces the concentration of free gossypol, but also results in low digestibility of lysine (Yu et al., 1996). Gossypol also binds to iron salts and addition of iron sulfate in excess of what is needed by the pigs will reduce binding of gossypol to lysine and results in greater digestibility of lysine (Clawson et al., 1975). It is, therefore, recommended that iron sulfate be added to diets that contain cottonseed meal in the same quantities as the quantities of free gossypol in the diet, which will eliminate the toxic effects of gossypol (Knabe et al., 1979; Tanksley, 1990). There are also so-called glandless cottonseed varieties on the market and cotton seed meal from these varieties does not contain gossypol, and the SID of indispensable AA in glandless cottonseed meal is equivalent to that of SBM (Tanksley et al., 1981; LaRue et al., 1985). Unfortunately, production of glandless cottonseed is not common and the majority of the meal on the market is from conventional sources of cotton seed.

Inclusion of cottonseed meal in diets fed to pigs has not been extensively researched. However, based on data available in the literature, it was concluded that cottonseed meal may substitute up to 50% of the soybean meal in diets fed to growing-finishing pigs and gestating sows and 25% in diets for lactating sows (Tanksley, 1990). There are very limited data for inclusion of cottonseed meal in diets for weanling pigs, but data from one experiment indicate that up to 40% of the SBM in diets for weanling pigs may be replaced by glandless cottonseed meal (LaRue et al., 1985).

5.5. Peanut meal

Peanuts (also known as “ground nuts”) are believed to originate in Northern Argentina, but cultivation has spread throughout the world where peanuts are grown in tropical and sub-tropical areas. Global annual production of peanuts is approximately 40 million tons with more than 40% of world production taking place in China (Soy and Oilseed Bluebook, 2015). Other countries with a notable production of peanuts include India, Nigeria, and the United States (Soy and Oilseed Bluebook, 2015). The majority of peanuts are consumed by humans but approximately 7 million tons of de-oiled peanut meal is available for animal feeding (Soy and Oilseed Bluebook, 2015).

The oil from peanuts may be extracted using mechanical extraction, and the resulting peanut expellers contain 5–10% ether extract (Chiba, 2001). However, if the oil is solvent extracted, the concentration of ether extract in the resulting peanut meal is less than 2% (Chiba, 2001; Batal et al., 2005; Li et al., 2014). Peanut meal contains approximately 45% CP (Batal et al., 2005; Li et al., 2014). The concentration of indispensable AA in peanut meal is less than in SBM and canola meal, but the digestibility of most AA is close to that observed in sunflower meal. The relative bioavailability of threonine and tryptophan in peanut meal was estimated at 72–76% and 76–92%, respectively (Adeola, 2009). However, some variability in nutritional composition among sources of peanut meal has been reported (Batal et al., 2005). The concentration of metabolizable energy was recently determined to vary from 12.7 to 15.5 mega joule per kg dry matter with an average of 13.9 mega joule per kg dry matter (Li et al., 2014). Peanut meal is generally free of anti-nutritional factors, but there is a risk of peanut meal containing aflatoxins (Chiba, 2001; Batal et al., 2005).

Feeding diets containing peanut meal to weanling or growing pigs resulted in a reduction in growth performance, which may have been caused by imbalances of indispensable AA (Combs and Wallace, 1962; Orok et al., 1975). However, growing and finishing pigs fed diets containing 10–20% peanut meal as well as 3–4% blood meal had growth performance that was not different from that of pigs fed diets based on SBM (Ilori et al., 1984). Likewise, replacement of SBM by peanut meal in diets for growing and finishing pigs and inclusion of crystalline AA to balance concentrations of indispensable AA among diets resulted in no reductions in growth performance or carcass characteristics (Shelton et al., 2001). These observations indicate that the reason for the poor performance observed in early studies with peanut meal may be a consequence of

Table 21
Composition of tropical oilseed meals.

Item	Ingredient											
	Coprameal			Copraexpellers			Palm kernelmeal			Palm kernelexpellers		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Gross energy, MJ/kg	2	18.2	0.6	4	18.2	1.2	4	17.4	1.5	8	18.0	1.2
Dry matter, g/kg	3	907.0	21.0	3	912.0	28.0	8	915.0	23.0	7	912.0	19.0
Crude protein, g/kg	3	217.0	6.0	4	202.0	3.0	8	150.0	14.0	7	152.0	12.0
Acid hydrolyzed ether extract, g/kg	1	19.0	–	–	–	–	1	13.0	–	2	68.0	8.0
Ash, g/kg	3	62.0	4.0	3	57.0	5.0	8	35.0	6.0	7	39.0	3.0
Starch, g/kg	–	26.0	–	1	94.0	–	1	10.0	–	2	26.0	5.0
Acid detergent fiber, g/kg	3	271.0	3.0	1	228.0	–	8	397.0	74.0	7	411.0	33.0
Neutral detergent fiber, g/kg	3	547.0	2.0	1	414.0	–	8	666.0	83.0	7	667.0	81.0
Calcium, g/kg	2	0.8	0.5	1	0.4	–	4	2.2	0.4	4	3.1	0.6
Phosphorus, g/kg	2	5.4	0.2	1	5.2	–	4	5.8	0.6	4	5.2	0.1
Indispensable amino acids, g/kg												
Arginine	1	20.8	–	1	21.7	–	5	31.2	38.4	2	15.3	11.6
Histidine	1	3.5	–	1	3.9	–	5	7.6	11.8	2	2.0	–
Isoleucine	1	6.6	–	1	6.2	–	5	13.7	19.1	2	4.7	0.1
Leucine	1	12.0	–	1	11.9	–	5	21.5	29.0	2	8.2	0.4
Lysine	1	4.2	–	1	5.4	–	6	9.0	12.6	2	3.7	0.4
Methionine	1	2.7	–	1	2.8	–	6	7.9	14.2	2	2.5	0.1
Phenylalanine	1	7.9	–	1	8.3	–	5	13.8	18.9	2	5.3	0.3
Threonine	1	5.5	–	1	6.1	–	6	10.7	15.5	2	3.7	0.1
Tryptophan	1	1.5	–	1	2.8	–	5	2.9	4.5	2	1.2	–
Valine	1	9.7	–	1	9.6	–	5	18.1	23.4	2	6.5	0.3
Dispensable amino acids, g/kg												
Alanine	1	8.5	–	1	8.1	–	5	14.1	19.0	2	5.3	0.2
Aspartic acid	1	15.0	–	1	15.5	–	5	27.6	36.4	2	10.0	0.4
Cysteine	1	2.8	–	1	2.6	–	5	4.1	5.3	2	1.7	0.1
Glutamic acid	1	33.4	–	1	34.9	–	5	51.9	59.8	2	22.9	1.0
Glycine	1	8.2	–	1	8.4	–	5	14.4	18.3	2	5.8	0.1
Proline	1	6.0	–	1	7.0	–	5	10.2	14.1	2	4.0	0.1
Serine	1	7.1	–	1	8.9	–	5	13.7	14.1	2	5.0	0.2
Tyrosine	1	4.1	–	1	4.2	–	5	10.9	17.1	2	2.9	0.1

inadequate supply of indispensable AA. However, it appears that if indispensable AA are supplied in the quantities needed by the animals, peanut meal may be included in diets fed to growing or finishing pigs.

5.6. Palm kernel meal and palm kernel expellers

Palm kernel meal and palm kernel expellers are the co-products from crushing of the oil palm kernel and are produced primarily in Southeast Asia, Africa, and Latin America. Global production of palm kernel meal and palm kernel expellers is approximately 8.5 million tons per year (Soy and Oilseed Bluebook, 2015). Mechanical extraction of the oil from the palm kernel is most common, which results in production of palm kernel expellers that have a concentration of ether extract of 6–8% (Tables 21 and 22). However, solvent extraction may also be used to remove the oil, which results in production of palm kernel meal that contains less than 2% ether extract. The species of the oil palm and the amount of shells from the kernel that is included in the meal also may influence nutrient composition. However, on average, palm kernel meal and palm kernel expellers contain 15–18% CP and 3–4% ash. Compared with other oilseed meals, the concentration of neutral detergent fiber is very high in palm kernel products and often exceeds 60%. The fiber is characterized by having a relatively large concentration of beta (1–4) D-mannans and a high amount of lignin.

The nutritional value of palm kernel meal and palm kernel expellers was recently reviewed (Stein et al., 2015). The concentration of indispensable AA is less than in other oilseed meals, but the SID of AA is generally less than in SBM although some sources of palm kernel expellers may have SID of AA that is close to that in SBM (Sulabo et al., 2013). However, a very low SID of lysine has been reported for palm kernel expellers indicating that heat damage may sometimes take place during the de-oiling process (Son et al., 2014). Protein from palm kernel ingredients is also characterized by having a very high concentration of arginine and the arginine to lysine ratio is approximately 4–1 (Stein et al., 2015). However, because pigs are efficient in metabolizing arginine, this is not believed to result in any metabolic problems.

The digestibility of energy in palm kernel meal and palm kernel expellers is also less than in SBM because of the high concentration of fiber and values for metabolizable energy of less than 12 Megajoule per kg have been reported for palm kernel meal (Sulabo et al., 2013), whereas palm kernel expellers may contain approximately 13 megajoule per kg (Agunbiade et al., 1999; Sulabo et al., 2013). However, it is possible that addition of the enzyme mannanase may increase the digestibility of energy in palm kernel expellers (Mok et al., 2013), although that is not always the case (Kwon and Kim, 2015; Mok et al., 2015).

Table 22
Concentration of digestible, metabolizable, and net energy, coefficient of standardized ileal digestibility (SID) of amino acids, and coefficient of standardized total tract digestibility (STTD) of phosphorus in tropical oilseed meals.

Item	Ingredient											
	Copra meal			Copra expellers			Palm kernel meal			Palm kernel expellers		
	N	X̄	SD	N	X̄	SD	N	X̄	SD	N	X̄	SD
Digestible energy, MJ/kg	1	12.6	–	1	15.7	–	3	12.4	1.2	5	12.8	0.8
Metabolizable energy, MJ/kg	1	11.9	–	4	13.1	1.3	3	11.9	1.3	7	12.2	0.7
Net energy, MJ/kg	1	7.3	–	1	10.9	–	1	8.5	–	1	8.9	–
SID, indispensable amino acids												
Arginine	1	0.910	–	1	0.580	–	4	0.810	0.097	2	0.900	0.030
Histidine	1	0.830	–	1	0.580	–	4	0.610	0.205	2	0.840	0.026
Isoleucine	1	0.820	–	1	0.580	–	4	0.620	0.168	1	0.430	0.602
Leucine	1	0.820	–	1	0.580	–	4	0.660	0.175	1	0.420	0.596
Lysine	1	0.730	–	1	0.580	–	4	0.460	0.229	1	0.390	0.557
Methionine	1	0.860	–	1	0.580	–	4	0.680	0.138	1	0.440	0.515
Phenylalanine	1	0.850	–	1	0.580	–	4	0.690	0.166	1	0.430	0.608
Threonine	1	0.770	–	1	0.580	–	4	0.600	0.188	1	0.390	0.553
Tryptophan	1	0.880	–	1	0.580	–	1	0.880	–	1	0.450	0.636
Valine	1	0.790	–	1	0.580	–	4	0.670	0.125	1	0.410	0.586
SID, dispensable amino acids												
Alanine	1	0.780	–	1	0.580	–	4	0.610	0.176	1	0.410	0.578
Aspartic acid	1	0.790	–	1	0.580	–	4	0.530	0.174	1	0.390	0.554
Cysteine	1	0.680	–	1	0.580	–	4	0.460	0.214	1	0.390	0.548
Glutamic acid	1	0.800	–	1	0.580	–	4	0.680	0.106	1	0.420	0.596
Glycine	1	0.760	–	1	0.580	–	4	0.570	0.169	1	0.420	0.592
Proline	1	1.290	–	1	0.580	–	3	0.880	0.291	1	0.690	0.968
Serine	1	0.820	–	1	0.580	–	4	0.750	0.057	1	0.410	0.585
Tyrosine	1	0.830	–	1	0.580	–	4	0.530	0.262	1	0.420	0.592
STTD, phosphorus	1	0.706	–	1	0.717	–	2	0.579	–	4	0.447	0.055

The concentration of P in palm kernel meal and palm kernel expellers is between 0.5 and 0.6 and approximately 60% of the P is bound to phytate (Almaguer et al., 2014). As a consequence, the standardized total tract digestibility of P in palm kernel expellers and palm kernel meal is increased from 35 to 50% to approximately 70% if microbial phytase is added to the diet (Son et al., 2013; Almaguer et al., 2014; Mok et al., 2015).

Because of the low energy value in palm kernel meal and palm kernel expellers, these ingredients are usually not included in diets fed to weanling, growing, or reproducing pigs in quantities greater than around 20% (Stein et al., 2015). However, if diets are balanced for metabolizable energy and SID AA, up to 15% of palm kernel meal may be included in diets fed to weanling pigs from two weeks post-weaning without reducing animal growth performance (Jaworski et al., 2014), whereas inclusion of 15% palm kernel expellers reduced growth performance. For finishing pigs, inclusion of 5% palm kernel meal had no effect on animal growth performance if diets were also fortified with a carbohydrase enzyme complex (Ao et al., 2011) and diets for lactating sows may contain at least 20% palm kernel expellers without negative impacts on sow or litter performance (Kim et al., 2015b).

5.7. Copra meal and copra expellers

The production of copra meal and copra expellers is less than that of any other oilseed meal and annual global production is estimated at less than two million tons (Soy and Oilseed Bluebook, 2015). Yet, in some areas of Southeast Asia and Africa, copra products are the main protein sources available to the local swine industry (Stein et al., 2015). The nutritional composition of copra meal and copra expellers is somewhat similar to that of palm kernel meal and palm kernel expellers with a relatively low concentration of CP (20–22%) and a high concentration of fiber. The concentration of arginine in copra meal and copra expellers is approximately 10% of CP and the arginine to lysine ratio is close to 5–1 (Stein et al., 2015). In general, the quality of copra protein is relatively low, and diets containing copra expellers or copra meal need to be supplemented with synthetic AA. However, the SID of most AA in copra meal and copra expellers is greater than in palm kernel meal and palm kernel expellers (Sulabo et al., 2013; Son et al., 2014). The concentration of metabolizable energy in copra meal is greater than in palm kernel meal (Sulabo et al., 2013), but the concentration of metabolizable energy in copra expellers is not greater than in palm kernel expellers (Kwon and Kim, 2015). The concentration of phytate in copra meal is less than in palm kernel meal and the digestibility of phosphorus is, therefore, greater in copra meal and copra expellers than in most other oilseed meals (Son et al., 2013; Almaguer et al., 2014).

Because a large proportion of the fiber in copra is soluble, inclusion of copra meal or copra expellers in diets fed to pigs will increase diet water binding capacity and diet bulk (Jaworski et al., 2014), which may be the main limiting factor in utilization of copra products in diets fed to pigs (Stein et al., 2015). There are very few recent reports on effects of adding copra meal or copra expellers to diets fed to growing-finishing pigs, and it is, therefore, not possible to know how modern lean pigs with a limited capacity for feed intake respond to copra meal or copra expellers. It is possible that modern high lean pigs will be more negatively affected by the high water binding capacity of diets containing copra products than older genotypes, and inclusion of copra meal in diets for weanling pigs should, therefore, be limited to less than 10% because greater inclusion rates will reduce pig growth performance (Jaworski et al., 2014).

References

Abelilla, J.J., Sulabo, R.C., Stein, H.H., Acda, S.P., Angeles, A.A., Oliveros, M.C.R., Merca, F.E., 2015. Effect of microbial phytase on the standardized total tract digestibility and in vitro release of phosphorus in corn, soybean meal, and rice bran fed to growing pigs. J. Anim. Sci. 93 (Suppl. 2), 55 (Abstr.).

Adeola, O., Kong, C., 2014. Energy value of distillers dried grains with solubles and oilseed meals for pigs. J. Anim. Sci. 92, 164–170.

Adeola, O., Ragland, D., 2012. Ileal digestibility of amino acids in coproducts of corn processing into ethanol for pigs. J. Anim. Sci. 90, 86–88.

Adeola, O., Young, L.G., McMillan, E.G., Moran, E.T., 1986. Comparative protein and energy value of OAC Wintri triticale and corn for pigs. J. Anim. Sci. 63, 1854–1861.

Adeola, O., 2009. Bioavailability of threonine and tryptophan in peanut meal for starter pigs using slope-ratio assay. Animal 3, 677–684.

Adhikari, P.A., Heo, J.M., Nyachoti, C.M., 2015. True and standardized total tract phosphorus digestibility in canola meals from *Brassica napus* black and Brassica juncea yellow fed to growing pigs. J. Anim. Sci. 93, 209–216.

Agunbiade, J.A., Wiseman, J., Cole, D.J.A., 1999. Energy and nutrient use of palm kernels, palm kernel meal and palm kernel oil in diets for growing pigs. Anim. Feed Sci. Technol. 80, 165–181.

Almaguer, B.L., Sulabo, R.C., Liu, Y., Stein, H.H., 2014. Standardized total tract digestibility of phosphorus in copra meal, palm kernel expellers, palm kernel meal, and soybean meal fed to growing pigs. J. Anim. Sci. 92, 2473–2480.

Almeida, F.N., Stein, H.H., 2010. Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus. J. Anim. Sci. 88, 2968–2977.

Almeida, F.N., Stein, H.H., 2012. Effects of graded levels of microbial phytase on the standardized total tract digestibility of phosphorus in corn and corn co-products. J. Anim. Sci. 90, 1262–1269.

Almeida, F.N., Petersen, G.I., Stein, H.H., 2011. Digestibility of amino acids in corn, corn coproducts, and bakery meal fed to growing pigs. J. Anim. Sci. 89, 4109–4115.

Almeida, F.N., Htoo, J.K., Thomson, J., Stein, H.H., 2014a. Effects of heat treatment on apparent and standardized ileal digestibility of amino acids in canola meal fed to growing pigs. Anim. Feed Sci. Technol. 187, 44–52.

Almeida, F.N., Htoo, J.K., Thomson, J., Stein, H.H., 2014b. Amino acid digestibility in heat damaged sunflower meal and cottonseed meal fed to growing pigs. J. Anim. Sci. 92, 585–593.

Ammar, K., Mergoum, M., Rajaram, S., 2004. The history and evolution of triticale. In: Mergoum, M., Gomez-Macpherson, H. (Eds.), Triticale Improvement and Production. Food and Agriculture Production of the United Nations, Rome, Italy, pp. 1–9.

Anderson, P.V., Kerr, B.J., Weber, T.E., Ziemer, C.J., Shurson, G.C., 2012. Determination and prediction of digestible and metabolizable energy from chemical analysis of corn coproducts fed to finishing pigs. J. Anim. Sci. 90, 1242–1254.

Ao, X., Zhou, T.X., Meng, Q.W., Lee, J.H., Jang, H.D., Cho, J.H., Kim, I.H., 2011. Effects of a carbohydrase cocktail supplementation on the growth performance nutrient digestibility, blood profiles and meat quality in finishing pigs fed palm kernel meal. Livest. Sci. 137, 238–243.

Arosemena, A., DePeters, E.J., Fadel, J.G., 1995. Extent of variability in nutrient composition within selected by-product feedstuffs. Anim. Feed Sci. Technol. 54, 103–120.

Bach Knudsen, K.E., 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Anim. Feed Sci. Technol. 67, 319–338.

Bach-Knudsen, K.E., Munck, L., 1985. Dietary fibre contents and compositions of sorghum and sorghum-based foods. J. Cereal Sci. 3, 153–164.

Baker, K.M., Stein, H.H., 2009. Amino acid digestibility and concentration of digestible and metabolizable energy in soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans and fed to growing pigs. J. Anim. Sci. 87, 2282–2290.

Baker, K.M., Kim, B.G., Stein, H.H., 2010. Amino acid digestibility in conventional high protein, or low oligosaccharide varieties of full-fat soybeans and in soybean meal by weanling pigs. Anim. Feed Sci. Technol. 162, 66–73.

Barrera, M., Cervantes, M., Sauer, W.C., Araiza, A.B., Torrentera, N., Cervantes, M., 2004. Ileal amino acid digestibility and performance of growing pigs fed wheat-based diets supplemented with xylanase. J. Anim. Sci. 82, 1997–2003.

Batal, A., Dale, N., Café, M., 2005. Nutrient composition of peanut meal. J. Appl. Poult. Res. 14, 254–257.

Batterham, E.S., Saini, H.S., Baigent, D.R., 1990. The effect of rate of feeding on the nutritional value of three triticale cultivars for growing pigs. Anim. Feed Sci. Technol. 27, 317–325.

Bengala Freire, J., Aumaitre, A., Peiniau, J., 1991. Effects of feeding raw and extruded peas on ileal digetibility, pancreatic enzymes and plasma glucose and insulin in early weaned pigs. J. Anim. Phys. Anim. Nutr. 65, 154–164.

Benz, J.M., Linneen, S.K., Tokach, M.D., Dritz, S.S., Nelssen, J.L., DeRouchey, J.M., Goodband, R.D., Sulabo, R.C., Prusa, K.J., 2010. Effects of dried distillers grains with solubles on carcass fat quality of finishing pigs. J. Anim. Sci. 88, 3666–3682.

Benz, J.M., Tokach, M.D., Dritz, S.S., Nelssen, J.L., DeRouchey, J.M., Sulabo, R.C., Goodband, R.D., 2011. Effects of increasing choice white grease in corn- and sorghum-based diets on growth performance, carcass characteristics, and fat quality characteristics of finishing pigs. J. Anim. Sci. 89, 773–782.

Berrocoso, J.D., Rojas, O.J., Liu, Y., Shoulders, J., Gonzalez-Vega, J.C., Stein, H.H., 2015. Energy concentration and amino acid digestibility in high protein canola meal, conventional canola meal, and in soybean meal fed to growing pigs. J. Anim. Sci. 93, 2208–2217.

Bolarinwa, O.A., Adeola, O., 2016. Regression and direct methods do not give different estimates of digestible and metabolizable energy values of barley, sorghum, and wheat for pigs. J. Anim. Sci. 94, 102527/jas2015-9766.

Brazle, F.K., Coffey, K.P., 1990. Rice Mill Feed as a Feed for Growing Cattle. Southeast Kansas Branch Stn., Manhattan, KS, Report of Progress No. 599.

Brestenský, M., Nitrayová, S., Patráš, P., Heger, J., 2013. Standardized ileal digestibilities of amino acids and nitrogen in rye barley, soybean meal, malt sprouts, sorghum, wheat germ and broken rice fed to growing pigs. Anim. Feed Sci. Technol. 186, 120–124.

Brooks, K.R., Wiegand, B.R., Meteer, A.L., Petersen, G.I., Spencer, J.D., Winter, J.R., Robb, J.A., 2009. Inclusion of yellow field peas and carbohydrase enzyme in nursery pig diets to improve growth performance. Prof. Anim. Sci. 25, 17–25.

Canibe, N., Bach Knudsen, K.E., 1997. Digestibility of dried and toasted peas in pigs: 1. Ileal and total tract digestibilities of carbohydrates. Anim. Feed Sci. Technol. 64, 293–310.

Carr, S.N., Rincker, P.J., Killefer, J., Baker, D.H., Ellis, M., McKeith, F.K., 2005. Effects of different cereal grains and ractopamine hydrochloride on performance, carcass characteristics, and fat quality in late-finishing pigs. J. Anim. Sci. 83, 223–230.

Casas, G.A., Stein, H.H., 2015. Effects of microbial phytase on the apparent and standardized total tract digestibility of phosphorus in rice co-products fed to growing pigs. J. Anim. Sci. 93, 3441–3448.

Casas, G.A., Stein, H.H., 2016. Effects of microbial xylanase on digestibility of dry matter, organic matter, neutral detergent fiber, and energy and the concentrations of digestible and metabolizable energy in rice co-products fed to weanling pigs. J. Anim. Sci. 94, 1933–1939.

Casas, G.A., Almeida, J.A.S., Stein, H.H., 2015. Amino acid digestibility in rice co-products fed to growing pigs. Anim. Feed. Sci. Technol 207, 150–158.

Cervantes, M., Gómez, R., Fierro, S., Barrera, M.A., Morales, A., Araiza, B.A., Zijlstra, R.T., Sánchez, J.E., Sauer, W.C., 2011. Ileal digestibility of amino acids, phosphorus, phytate and energy in pigs fed sorghum-based diets supplemented with phytase and Pancreatin®. J. Physiol. Anim. Nutr. 95, 179–186.

Cervantes-Pahm, S.K., Stein, H.H., 2008. Effect of dietary soybean oil and soybean protein concentrate on the concentration of digestible amino acids in soybean products fed to growing pigs. J. Anim. Sci. 86, 1841–1849.

Cervantes-Pahm, S.K., Stein, H.H., 2010. Ileal digestibility of amino acids in conventional, fermented, and enzyme-treated soybean meal and in soy protein isolate, fish meal, and casein fed to weanling pigs. J. Anim. Sci. 88, 2674–2683.

Cervantes-Pahm, S.K., Liu, Y., Stein, H.H., 2014a. Comparative digestibility of energy and nutrients and fermentability of dietary fiber in eight cereal grains fed to pigs. J. Sci. Food. Agric. 94, 841–849.
Cervantes-Pahm, S.K., Liu, Y., Stein, H.H., 2014b. Digestible indispensable amino acid score (DIAAS) and digestible amino acids in eight cereal grains. Br. J. Nutr. 111, 1663–1672.
Che, T.M., Perez, V.G., Song, M., Pettigrew, J.E., 2012. Effect of rice and other cereal grains on growth performance, pig removal, and antibiotic treatment of weaned pigs under commercial conditions. J. Anim. Sci. 90, 4916–4924.
Chiba, L.I., 2001. Protein supplements. In: Austin, A.J., Southern, L.L. (Eds.), Swine Nutrition. , 2nd ed. CRC Press LLC, Boca Raton, Florida, USA, pp. 803–837.
Clansey, B., 2014. Global Pulses Conclave – 2014, Available at: http://www.slideshare.net/ipga/stat-global-pulses-conclave (accessed 24.01.16).
Clawson, A.J., Maner, J.H., Gomez, G., Flores, Z., Buitrago, J., 1975. Unextracted cottonseed in diets for monogastric animals. II. The effect of boiling and oven vs sun drying following pretreatment with a ferrous sulfate solution. J. Anim. Sci. 40, 648–654.
Combs, G.E., Wallace, H.D., 1962. Peanut meal as a source of protein in pig starter and grower rations. J. Anim. Sci. 21, 95–97.
Cozannet, P., Primot, Y., Gady, C., Métayer, J.P., Callu, P., Lessire, M., Skiba, F., Noblet, J., 2010a. Ileal digestibility of amino acids in wheat distillers dried grains with solubles for pigs. Anim. Feed Sci. Technol. 158, 177–186.
Cozannet, P., Primot, Y., Gady, C., Métayer, J.P., Lessire, M., Skiba, F., Noblet, J., 2010b. Energy value of wheat distillers grains with solubles for growing pigs and adult sows. J. Anim. Sci. 88, 2382–2392.
Cozannet, P., Preynat, A., Noblet, J., 2012. Digestible energy values of feed ingredients with or without addition of enzymes complex in growing pigs. J. Anim. Sci. 90, 209–211.
Cromwell, G.L., Azain, M.J., Adeola, O., Baidoo, S.K., Carter, S.D., Crenshaw, T.D., Kim, S.W., Mahan, D.C., Miller, P.S., Shannon, M.C., 2011. Corn distillers dried grains with solubles in diets for growing-finishing pigs: a cooperative study. J. Anim. Sci. 89, 2801–2811.
Cromwell, G.L., 2000. Utilization of soy products in swine diets. In: Drackley, J.K. (Ed.), Soy in Animal Nutrition. Federation of Animal Sciences Societies, Savoy, IL, pp. 258–282.
Daun, J.K., 2011. Origin, distribution, and production. In: Daun, J.K., Eskin, N.A.M., Hickling, D. (Eds.), Canola, Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, Illinois, United States, pp. 1–27.
Deak, N.A., Johnson, L.A., Lusas, E.W., Rhee, K.C., 2008. Soy protein products, processing, and utilization. In: Johnson, L.A., White, P.J., Galloway, R. (Eds.), Soybeans, Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, IL, pp. 661–724.
Deb, U.K., Bantilan, M.C.S., Roy, A.D., Parthasarathy, R.P., 2004. Global sorghum production scenario. In: Bantilan, M.C.S., Deb, U.K., Gowda, C.L.L., Reddy, B.V.S., Obilana, A.B., Evenson, R.E. (Eds.), Sorghum Genetic Enhancement: Research Process, Dissemination and Impacts. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India, pp. 21–38.
Delcuour, J.A., Hoseney, R.C., 2010. Principles of Cereal Science and Technology, 3rd ed. AACC International, Inc., St. Paul, MN (p. 12).
Dinussen, W.E., 1990. Sunflower meal. In: Thacker, P.A., Kirkwood, R.N. (Eds.), Nontraditional Feed Sources for Use in Swine Production. Butterworths, Stoneham, Massachusetts, USA, pp. 465–472.
Eklund, M., Rademacher, M., Sauer, W.C., Blank, R., Mosenthin, R., 2014. Standardized ileal digestibility of amino acids in alfalfa meal, sugar beet pulp, and wheat bran compared to wheat and protein ingredients for growing pigs. J. Anim. Sci. 92, 1037–1043.
Eklund, M., Sauer, N., Schöne, F., Messerschmidt, U., Rosenfelder, P., Htoo, J.K., Mosenthin, R., 2015. Effect of processing of rapeseed under defined conditions in a pilot plant on chemical composition and standardized ileal amino acid digestibility in rapeseed meal for pigs. J. Anim. Sci. 93, 2813–2825.
Emiola, I.A., Opapeju, F.O., Slominski, B.A., Nyachoti, C.M., 2009. Growth performance and nutrient digestibility in pigs fed wheat distillers dried grains with solubles-based diets supplemented with a multicarbohydrase enzyme. J. Anim. Sci. 87, 2315–2322.
Endres, J.G., 2001. Soy Protein Products Characteristics, Nutritional Aspects, and Utilization. AOCS Press, Urbana, Illinois, USA.
Fairbairn, S.L., Patience, J.F., Classen, H.L., Zijlstra, R.T., 1999. The energy content of barley fed to growing pigs: characterizing the nature of its variability and developing prediction equations for its estimation. J. Anim. Sci. 77, 1502–1512.
Fan, M.Z., Sauer, W.C., 1999. Variability of apparent ileal amino acid digestibility in different pea samples for growing-finishing pigs. Can. J. Anim. Sci 79, 67–475.
Fan, M.Z., Sauer, W.C., Gabert, V.M., 1996. Variability of apparent ileal amino acid digestibility in canola meal for growing-finishing pigs. Can. J. Anim. Sci. 76, 563–569.
Farrell, D.J., Chan, C., McCrae, F., McKenzie, R.J., 1983. A nutritional evaluation of triticale with pigs. Anim. Feed Sci. Technol. 9, 49–62.
Feng, J., Liu, X., Xu, Z.R., Lu, Y.P., Liu, Y.Y., 2007. The effect of *Aspergillus oryzae* 3.042 fermented soybean meal on growth performance: digestibility of dietary components and activities of intestinal enzymes in weaned piglets. Anim. Feed Sci. Technol. 134, 295–303.
Fioli, C., Hancock, J.D., Monge, C., Gugle, T.L., Carter, S.D., Cole, N.A., 2007. Effects of corn and sorghum-based distillers dried grains with solubles on growth performance and carcass characteristics in finishing pigs. J. Anim. Sci. 85 (Suppl. 2), 95 (Abstr.).
Friesen, M.J., Kiarie, E., Nyachoti, C.M., 2006. Response of nursery pigs to diets with increasing levels of raw peas. Can. J. Anim. Sci. 86, 531–533.
Garcia, H., Wang, L.F., Landero, J.L., Beltranena, E., Cervantes, M., Morales, A., Zijlstra, R.T., 2015. Effect of feeding wheat millrun on diet nutrient digestibility and growth performance in starter pigs. Anim. Feed Sci. Technol. 207, 283–288.
Gatel, F., Grosjean, F., Leuillet, M., 1988. Utilization of white-flowered smooth-seeded spring peas (*Pisum sativum hortense:* CV Amino) by the breeding sow. Anim. Feed Sci. Technol. 22, 91–104.
Goebel, K.P., Stein, H.H., 2011a. Ileal digestibility of amino acids in conventional and low-Kunitz soybean products fed to weanling pigs. Asian Australas. J. Anim. Sci. 24, 88–95.
Goebel, K.P., Stein, H.H., 2011b. Phosphorus digestibility and energy concentration of enzyme-treated and conventional soybean meal fed to weanling pigs. J. Anim. Sci. 89, 764–772.
Goldflus, F., Ceccantini, M., Santos, W., 2006. Amino acid content of soybean samples collected in different Brazilian states-harvest 2003/2004. Braz. J. Poult. Sci. 8, 105–111.
Goldsmith, P.D., 2008. Economics of soybean production, marketing and utilization. In: Johnson, L.A., White, P.J., Galloway, R. (Eds.), Soybeans, Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, Illinois, United States, pp. 117–150.
González-Vega, J.C., Stein, H.H., 2012. Amino acid digestibility in canola, cottonseed, and sunflower products fed to finishing pigs. J. Anim. Sci. 90, 4391–4400.
Gonzalez-Vega, J.C., Walk, C.L., Liu, Y., Stein, H.H., 2013. Endogenous losses of calcium and true total tract digestibility of calcium in canola meal fed to growing pigs. J. Anim. Sci. 92, 4807–4816.
Gonzalez-Vega, J.C., Walk, C.L., Stein, H.H., 2015. Effect of microbial phytase, fiber, and soybean oil on calculated values for apparent and standardized total tract digestibility of calcium in fish meal. J. Anim. Sci. 93, 4808–4818.
Goodband, R.D., Hines, R.H., 1988. An evaluation of barley in starter diets for swine. J. Anim. Sci. 66, 3086–3093.
Greiner, L., Neill, C., Allee, G.L., Wang, X., Connor, J., Touchette, K., Usry, J.L., 2015. The feeding of dried distillers' grains with solubles to lactating sows. J. Anim. Sci. 93, 5718–5724.
Grieshop, C.M., Kadzere, C.T., Clapper, G.M., Flickinger, E.A., Bauer, L.L., Frazier, R.L., Fahey, G.C., 2003. Chemical and nutritional characteristics of United States soybeans and soybean meals. J. Agric. Food Chem. 51, 7684–7691.
Grosjean, F., Bastianelli, D., Bourdillon, A., Cerneau, P., Jondreville, C., Peyronnet, C., 1998. Feeding value of pea (*Pisum Sativum* L.) 2. Nutritional value in the pig. Anim. Sci. 7, 621–625.
Guo, P.P., Li, P.L., Li, Z.C., Stein, H.H., Liu, L., Xia, T., Yang, Y.Y., Ma, Y.X., 2015. Effects of post-harvest storage duration and variety on nutrient digestibility and energy content in wheat in finishing pigs. Asian Australasian J. Anim. Sci 28, 1488–1495.

Hargrove Jr., K.L., 1994. Processing and utilization of rice bran in the United States. In: Marshall, W.E., Wadsworth, J.I. (Eds.), Rice, Science and Technology. Marcel Dekker, Inc New Orleans, LA, pp. 381–404.
Hejdysz, M., Kaczmarek, S.A., Rutkowski, A., 2016. Extrusion cooking improves the metabolisable energy of faba beans and the amino acid digestibility in broilers. Anim. Feed Sci. Technol. 212, 100–111.
Helander, E., Nasi, M., Partanen, K., 1996. Effects of supplementary *Aspergillus niger* phytase on the availability of plant phosphorus, other minerals, and nutrients in growing pigs fed on high pea-diets. J. Anim. Phys. Anim. Nutr. 76, 66–79.
Herfel, T., Jacobi, S., Lin, X., Van Heugten, E., Fellner, V., Odle, J., 2013. Stabilized rice bran improves weaning pig performance via a prebiotic mechanism. J. Anim. Sci. 91, 907–913.
Heuzé, V., Tran, G., 2011. Rice Bran and Other Rice By-products Feedipedia.org. A Programme by INRA, CIRAD, AFZ and FAO (accessed 06.15) http://www.feedipedia.org/node/750.
Hong, K.J., Lee, C.H., Kim, S.W., 2004. *Aspergillus oryzae* GB-107 fermentation improves nutritional quality of food soybeans and feed soybean meals. J. Med. Food. 7, 430–435.
Hongtrakul, K., Goodband, R.D., Behnke, K.C., Nelssen, J.L., Tokach, M.D., Bergström, J.R., Nessmith, W.B., Kim, I.H., 1998. The effects of extrusion processing of carbohydrate sources on weanling pig performance. J. Anim. Sci. 76, 3034–3042.
Huang, Q., Piao, X.S., Ren, P., Li, D.F., 2012. Prediction of digestible and metabolizable energy content and standardized ileal amino acid digestibility in wheat shorts and red dog for growing pigs. Asian Australas. J. Anim. Sci. 25 (12), 1748–1758.
Huang, Q., Shi, C.X., Su, Y.B., Liu, Z.Y., Li, D.F., Liu, L., Huang, C.F., Piao, X.S., Lai, C.H., 2014. Prediction of the digestible and metabolizable energy content of wheat milling by-products for growing pigs from chemical composition. Anim. Feed Sci. Technol. 196, 107–116.
Hurburgh Jr., C.R., Paynter, L.N., Schmitt, S.G., 1987. Quality characteristics of Midwestern soybeans. Appl. Eng. Agric. 3, 159–165.
Ilori, J.O., Miller, E.R., Ullrey, D.E., Ku, P.K., Hogberg, M.G., 1984. Combinations of peanut meal and blood meal as substitutes for soybean meal in corn-based, growing-finishing pig diets. J. Anim. Sci. 59, 2.
Jansman, A.J.M., Huisman, J., van der Poel, A.F.B., 1993. Ileal and faecal digestibility in piglets of field beans (*Vicia faba* L:) varying in tannin content. Anim. Feed Sci. Technol. 42, 83–96.
Jansman, A.J.M., 1993. Tannins in feedstuffs for simple-stomached animals. Nut. Res. Rev. 6, 209–236.
Jaworski, N.W., Shoulders, J., Gonzalez-Vega, J.C., Stein, H.H., 2014. Effects of using copra meal palm kernel expellers, or palm kernel meal in diets for weanling pigs. Prof. Anim. Sci. 30, 243–251.
Jaworski, N.W., Lærke, H.N., Bach Knudsen, K.E., Stein, H.H., 2015. Carbohydrate composition and in vitro digestibility of dry matter and non-starch polysaccharides in corn, sorghum, and wheat and co-products from these grains. J. Anim. Sci. 93, 1103–1113.
Jezierny, D., Mosenthin, R., Bauer, E., 2010. The use of grain legumes as a protein source in pig nutrition. Rev. Anim. Feed Sci. Technol. 157, 111–128.
Ji, Y., Zuo, L., Wang, F., Li, D., Lai, C., 2012. Nutritional value of 15 corn gluten meals for growing pigs: chemical composition: energy content and amino acid digestibility. Arch. Anim. Nutr. 66, 283–302.
Jia, W., Mikulski, D., Rogiewicz, A., Zdunczyk, Z., Jankowski, J., Slominski, B.A., 2012. Low-fiber canola. Part II: nutritive value of the meal. J. Agric. Food Chem. 60, 12231–12237.
Jocic, S., Miladinovic, D., 2015. Breeding and genetics of sunflower. In: Force, E.M., Dunford, N.T., Salas, J.J. (Eds.), Sunflower, Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, Illinois, United States, pp. 1–25.
Jondreville, C., Grosjean, F.C., Buron, G., Peyronnet, C., Beneytout, J.L., 1992. Comparison of four pea varieties in pig feeding through digestibility and growth performance results. J. Anim.Physiol. Anim. Nutr. 68, 113–122.
Jones, C.K., DeRouchey, J.M., Nelssen, J.L., Tokach, M.D., Dritz, S.S., Goodband, R.D., 2010. Effects of fermented soybean meal and specialty animal protein sources on nursery pig performance. J. Anim. Sci. 88, 1725–1732.
Jongbloed, A.W., Kemme, P.A., 1990. Apparent digestible phosphorus in the feeding of pigs in relation to availability: requirement and environment. 1. Digestible phosphorus in feedstuffs from plant and animal origin. Neth. J. Agric. Sci. 38, 567–575.
Karr-Lilienthal, L.K., Grieshop, C.M., Merchen, N.R., Mahan, D.C., Fahey Jr., G.C., 2004. Chemical composition and protein quality comparisons of soybeans and soybean meals from five leading soybean-producing countries. J. Agric. Food Chem. 52, 6193–6199.
Kaufmann, C., Sauer, W.C., Cervantes, M., Zhang, Y., Rademacher, J.H.M., Htoo, J.K., 2005. Amino acid and energy digestibility in different sources of rice bran for growing pigs. Can. J. Anim. Sci. 85, 355–363.
Kerr, B.J., Dozier, W.A., Shurson, G.C., 2013. Effects of reduced-oil corn distillers dried grains with solubles composition on digestible and metabolizable energy value and prediction in growing pigs. J. Anim. Sci. 91, 3231–6252.
Kiarie, E., Lopez, P., Furedi, C., Nyachoti, C.M., 2013. Amino acids and energy utilization in zero-tannin faba bean and co-fermented wheat and corn dried distillers grains with solubles fed to growing pigs. J. Anim. Sci. 91, 1728–1735.
Kil, D.Y., Sauber, T.E., Jones, D.B., Stein, H.H., 2010. Effect of the form of dietary fat and the concentration of dietary neutral detergent fiber on ileal and total tract endogenous losses and apparent and true digestibility of fat by growing pigs. J. Anim. Sci. 88, 2959–2967.
Kim, J.C., Simmins, P.H., Mullan, B.P., Pluske, J.R., 2005. The digestible energy value of wheat for pigs: with special reference to the post-weaned animal [Review]. Anim. Feed Sci. Technol. 122, 257–287.
Kim, B.G., Petersen, G.I., Hinson, R.B., Allee, G.L., Stein, H.H., 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87, 4013–4021.
Kim, S.W., van Heugten, E., Ji, F., Lee, C.H., Mateo, R.D., 2010. Fermented soybean meal as a vegetable protein source for nursery pigs: I: effects on growth performance of nursery pigs. J. Anim. Sci. 88, 214–224.
Kim, B.G., Kil, D.Y., Zhang, Y., Stein, H.H., 2012. Concentrations of analyzed or reactive lysine, but not crude protein, may predict the concentration of digestible lysine in distillers dried grains with solubles fed to pigs. J. Anim. Sci. 90, 3798–3808.
Kim, B.G., Kil, D.Y., Stein, H.H., 2013. In growing pigs, the true ileal and total tract digestibility of acid hydrolyzed ether extract in extracted corn oil is greater than in intact sources of corn or soybean oil. J. Anim. Sci. 91, 755–763.
Kim, B.G., Wulf, D.M., Maddock, R.J., Peters, D.N., Pedersen, C., Liu, Y., Stein, H.H., 2014. Effects of dietary barley on growth performance carcass traits, and pork quality in finishing pigs. Rev. Colomb. Cienc. Pecu. 27, 102–113.
Kim, K., Goel, A., Lee, S., Choi, Y., Chae, B., 2015a. Comparative ileal amino acid digestibility and growth performance in growing pigs fed different level of canola meal. J. Anim. Sci. Technol. 57, 21.
Kim, J., Seo, J., Kim, W., Yun, H.M., Kim, S.C., Jang, Y., Jang, K., Kim, K., Kim, B., Park, S., Park, I., Kim, M.K., Seo, K.S., Kim, H.B., Kim, I.H., Seo, S., Song, M., 2015b. Effects of palm kernel expellers on productive performance nutrient digestibility, and white blood cells of lactating sows. Asian Australas. J. Anim. Sci. 28, 1150–1154.
King, R.H., Eason, P.E., Kerton, D.K., Dunshea, F.R., 2001. Evaluation of solvent-extracted canola meal for growing pigs and lactating sows. Aust. J. Agric. Res. 52, 1033–1041.
Knabe, D.A., Tanksley Jr., T.D., Hesby, J.H., 1979. Effect of lysine, crude fiber and free gossypol in cottonseed meal on the performance of growing pigs. J. Anim. Sci. 49, 134–142.
Kwon, W.B., Kim, B.G., 2015. Effects of supplemental beta-mannanase on digestible energy and metabolizable energy contents of copra expellers and palm kernel expellers fed to pigs. Asian Australas. J. Anim. Sci. 28, 1014–1019.
l'Anson, K.A., Choct, M., Brooks, P.H., 2013. Effect of xylanase supplementation of wheat-based liquid diets for weaner pigs, steeped for 1 or 24 h before feeding. Anim. Prod. Sci. 53, 540–547.
LaRue, D.C., Knabe, D.A., Tanskley, T.D., 1985. Commercially processed glandless cottonseed meal for starter, grower and finisher swine. J. Anim. Sci. 60, 2.
Landero, J.L., Beltranena, E., Cervantes, M., Morales, A., Zijlstra, R.T., 2011. The effect of feeding solvent-extracted canola meal on growth performance and diet nutrient digestibility in weaned pigs. Anim. Feed Sci. Technol. 170, 136–140.

Landero, J.L., Beltranena, E., Cervantes, M., Araiza, A.B., Zijlstra, R.T., 2012a. The effect of feeding expeller-pressed canola meal on growth performance and diet nutrient digestibility in weaned pigs. Anim. Feed Sci. Technol. 171, 240–245.
Landero, J.L., Beltranena, E., Zijlstra, R.T., 2012b. Growth performance and preference studies to evaluate solvent-extracted Brassica napus or *Brassica juncea* canola meal fed to weaned pig. J. Anim. Sci. 90, 406–408.
Landero, J.L., Beltranena, E., Zijlstra, R.T., 2013. Diet nutrient digestibility and growth performance of weaned pigs fed solvent-extracted *Brassica juncea* canola meal. Anim. Feed Sci. Technol. 180, 64–72.
Landero, J.L., Wang, L.F., Beltranena, E., Zijlstra, R.T., 2014. Diet nutrient digestibility and growth performance of weaned pigs fed field pea. Anim. Feed Sci. Technol. 198, 295–303.
Le Guen, M.P., Huisman, J., Verstegen, M.W.A., 1995. Partition of the amino acids in ileal digesta from piglets fed pea protein diets. Livest. Prod. Sci. 44, 169–178.
Le, M.H.A., Landero, J.L., Beltranena, E., Zijlstra, R.T., 2014. The effect of feeding increasing inclusion of extruded *Brassica juncea* canola expeller on growth performance and nutrient digestibility in weaned pigs. Anim. Feed Sci. Technol. 192, 73–80.
Lee, J.W., McKeith, F.K., Stein, H.H., 2012. Up to 30% corn germ may be included in diets fed to growing-finishing pigs without affecting pig growth performance, carcass composition, or pork fat quality. J. Anim. Sci. 90, 4933–4942.
Leick, C.M., Puls, C.L., Ellis, M., Killefer, J., Carr, T.R., Scramlin, S.M., England, M.B., Gaines, A.M., Wolter, B.F., Carr, S.N., McKeith, F.K., 2010. Effect of distillers dried grains with solubles and ractopamine (Paylean) on quality and shelf-life of fresh pork and bacon. J. Anim. Sci. 88, 2751–2766.
Leterme, P., Beckers, Y., Thewis, A., 1990. Trypsin inhibitors in peas: varietal effect and influence on digestibility of crude protein by growing pigs. Anim. Feed. Sci. Technol. 29, 45–55.
Leterme, P., Tahon, F., Thewis, A., 1991. Nutritive value of triticale cultivars in pigs as a function of their chemical composition. Anim. Feed Sci. Technol. 35, 94–53.
Li, D.F., Nelssen, J.L., Reddy, P.G., Blecha, F., Hancock, J.D., Allee, G.L., Goodband, R.D., Klemm, R.D., 1990. Transient hypersensitivity to soybean meal in the early-weaned pig. J. Anim. Sci. 68, 1790–1799.
Li, D.F., Nelssen, J.L., Reddy, P.G., Blecha, F., Klemm, R.D., Giesting, D.W., Hancock, J.D., Allee, G.L., Goodband, R.D., 1991. Measuring suitability of soybean products for early-weaned pigs with immunological criteria. J. Anim. Sci. 69, 3299–3307.
Li, D., Pengbin, X., Liming, G., Shijun, F., Canghai, H., 2002. Determination of apparent ileal amino acid digestibility in rapeseed meal and cake processed at different temperatures using the direct and difference method with growing pigs. Arch. Anim. Nutr. 56, 339–349.
Li, Q., Piao, X., Liu, J., Zeng, Z., Zhang, S., Lei, X., 2014. Determination and prediction of the energy content and amino acid digestibility of peanut meals fed to growing pigs. Arch. Anim. Nutr. 68 (3), 196–210.
Li, P., Wang, F., Wu, F., Wang, J., Liu, L., Lai, C., 2015a. Chemical composition, energy and amino acid digestibility in double-low rapeseed meal fed to growing pigs. J. Anim. Sci. Technol. 6, 37.
Li, P.L., Wu, F., Chen, Y.F., Wang, J.R., Guo, P.P., Li, Z.C., Liu, L., Lai, C.H., 2015b. Determination of the energy content and amino acid digestibility of double-low rapeseed cakes fed to growing pigs. Anim. Feed. Sci. Technol. 210, 243–253.
Little, K.M., Bohrer, B.M., Maison, T., Liu, Y., Stein, H.H., Boler, D.D., 2015. Effects of feeding canola meal from high protein or conventional varieties of canola seeds on growth performance, carcass characteristics, and cutability of pigs. J. Anim. Sci. 93, 1284–1297.
Liu, P., Souza, L.W.O., Baidoo, S.K., Shurson, G.C., 2012. Impact of distillers dried grains with solubles particle size on nutrient digestibility, DE and ME content, and flowability in diets for growing pigs. J. Anim. Sci. 90, 4925–4932.
Liu, Y., Song, M., Almeida, F.N., Tilton, S.L., Cecava, M.J., Stein, H.H., 2014a. Energy concentration and amino acid digestibility in corn and corn co-products from the wet-milling industry fed to growing pigs. J. Anim. Sci. 92, 4547–4556.
Liu, Y., Song, M., Maison, T., Stein, H.H., 2014b. Effects of protein concentration and heat treatment on concentration of digestible and metabolizable energy and on amino acid digestibility in four sources of canola meal fed to growing pigs. J. Anim. Sci. 92, 4466–4477.
Liu, J.D., Li, Q.Y., Zeng, Z.K., Li, P., Xu, X., Wang, H.L., Zhang, S., Piao, X.S., 2015a. Determination and prediction of the amino acid digestibility of sunflower seed meals in growing pigs. Asian Australas. J. Anim. Sci. 28, 86–94.
Liu, Y., Rojas, O.J., Stein, H.H., 2015b. Effects of extrusion of corn and oats on the digestibility of energy and nutrients in diets fed to pigs. J. Anim. Sci. 93 (Suppl. 2), 134–135 (Abstr.).
Liu, Y., Jaworski, N.W., Rojas, O.J., Stein, H.H., 2016. Energy concentration and amino acid digestibility in high protein canola meal conventional canola meal, and in soybean meal fed to growing pigs. Anim. Feed Sci. Technol. 212, 52–62.
Liying, Z., Li, D., Qiao, S., Johnson, E.W., Li, B., Thacker, P.A., Han, I.K., 2003. Effects of stachyose on performance: diarrhea incidence and intestinal bacteria in weanling pigs. Arch. Anim. Nutr. 57, 1–10.
Lowell, J.E., Liu, Y., Stein, H.H., 2015. Comparative digestibility of energy and nutrients in feed ingredients fed to sows and growing pigs. Arch. Anim. Nutr. 69, 79–97.
Mahan, D.C., Newton, E.A., 1993. Evaluation of feed grains with dried skim milk and added carbohydrate sources on weanling pig performance. J. Anim. Sci. 71, 3376–3382.
Maison, T., Stein, H.H., 2014. Digestibility by growing pigs of amino acids in canola meal from North America and 00-rapeseed meal and 00-rapeseed expellers from Europe. J. Anim. Sci. 92, 3502–3514.
Maison, T., Liu, Y., Stein, H.H., 2015a. Digestibility of energy and detergent fiber and concentration of digestible and metabolizable energy in canola meal, 00-rapeseed meal, and 00-rapeseed expellers fed to growing pigs. J. Anim. Sci. 93, 652–660.
Maison, T., Liu, Y., Stein, H.H., 2015b. Digestible phosphorous in canola meal from North America and 00-rapeseed meal and 00-rapeseed expellers from Europe without and with microbial phytase fed to growing pigs. J. Anim. Sci. 93, 3494–3502.
Mariscal-Landín, G., Avellaneda, J.H., Reis de Souza, T.C., Aguilera, A., Borbolla, G.A., Mar, B., 2004. Effect of tannins in sorghum on amino acid ileal digestibility and on trypsin (E.C.2.4.21.4) and chymotrypsin (E.C.2.4.21.1) activity of growing pigs. Anim. Feed Sci. Technol. 117, 245–264.
Mariscal-Landıín, G., Lebreton, Y., Sève, B., 2002. Apparent and standardised true ileal digestibility of protein and amino acids from faba bean lupin and pea, provided as whole seeds, dehulled or extruded in pig diets. Anim. Feed Sci. Technol. 97, 183–198.
Masey O' Neill, H.V., Rademacher, M., Mueller-Harvey, I., Stringano, E., Kightley, S., Wiseman, J., 2012. Standardised ileal digestibility of crude protein and amino acids of UK-grown peas and faba beans by broilers. Anim. Feed Sci. Technol. 175, 158–167.
Mateos, G.G., López, E., Latorre, M.A., Vicente, B., Lázaro, R.P., 2007. The effect of inclusion of oat hulls in piglet diets based on raw or cooked rice and maize. Anim. Feed Sci. Technol. 135, 100–112.
McDowell, 2013. Vitamin History. The Early Years, 1st ed. Design and Publishing Inc., Sarasota, FL.
Medel, P., Salado, S., de Blas, J.C., Mateos, G.G., 1999. Processed cereals in diets for early-weaned piglets. Anim. Feed Sci. Technol. 82, 145–156.
Medel, P., Garcıía, M., Lázaro, R., de Blas, C., Mateos, G.G., 2000. Particle size and heat treatment of barley in diets for early-weaned piglets. Anim. Feed Sci. Technol. 84, 13–21.
Medel, P., Baucells, F., Gracia, M.I., de Blas, C., Mateos, G.G., 2002. Processing of barley and enzyme supplementation in diets for young pigs. Anim. Feed Sci. Technol. 95, 113–122.
Messerschmidt, U., Eklund, M., Sauer, N., Rist, V.T.S., Rosenfelder, P., Spindler, H.K., Htoo, J.K., Schöne, F., Mosenthin, R., 2014. Chemical composition and standardized ileal amino acid digestibility in rapeseed meals sourced from German oil mills for growing pigs. Anim. Feed Sci. Technol. 187, 68–76.
Mok, C.H., Lee, J.H., Kim, B.G., 2013. Effects of exogenous phytase and β-mannanase on ileal and total tract digestibility of energy and nutrient in palm kernel expeller-containing diets fed to growing pigs. Anim. Feed Sci. Technol. 186, 209–213.
Mok, C.H., Kong, C., Kim, B.G., 2015. Combination of phytase and β-mannanase supplementation on energy and nutrient digestibility in pig diets containing palm kernel expellers. Anim. Feed Sci. Technol. 205, 116–121.

Montagne, L., Pluske, J.R., Hampson, D.J., 2003. A review of interations between dietary fibre and the intestinal mucosa: and their consequences on digestive health in young non-ruminant animals. Anim. Feed. Sci. Technol. 108, 95–117.
Montoya, Carlos A., Leterme, Pascal, 2011. Effect of particle size on the digestible energy content of field pea (*Pisum sativum* L.) in growing pigs. Anim. Feed. Sci. Technol. 169, 113–120.
Mullan, B.P., Pluske, J.R., Allen, J., Harris, D.J., 2000. Evaluation of Western Australian canola meal for growing pigs. Aust. J. Agric. Res. 51, 547–553.
Myer, R.O., Combs, G.E., 1991. Fat supplementation of diets containing a high level of oats for growing-finishing swine. J. Anim. Sci. 69, 4665–4669.
Myer, R.O., Barnett, R.D., Cornell, J.A., Combs, G.E., 1989. Nutritive value of diets containing triticale and varying mixtures of triticale and maize for growing-finishing swine. Anim. Feed. Sci. Technol. 22, 217–225.
Nørgaard, J.V., Fernandez, J.A., Jørgensen, H., 2012. Ileal digestibility of sunflower meal, pea, rapeseed cake, and lupine in pigs. J. Anim. Sci. 90, 203–205.
NRC, 2012. Nutrient Requirements of Swine, 11th ed. National Academy Press, Washington, DC.
Nasir, Z., Wang, L.F., Young, M.G., Swift, M.L., Beltranena, E., Zijlstra, R.T., 2015. The effect of feeding barley on diet nutrient digestibility and growth performance of starter pigs. Anim. Feed Sci. Technol. 210, 287–294.
Newkirk, R.W., Classen, H.L., Scott, T.A., Edney, M.J., 2003. The digestibility and content of amino acids in toasted and non-toasted canola meals. Can. J. Anim. Sci. 83, 131–139.
Newkirk, R., 2011. Meal nutrients composition. In: Daun, J.K., Eskin, N.A.M., Hickling, D. (Eds.), Canola: Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, IL, pp. 229–244.
Nishimuta, J.F., Sunki, G.R., Rao, D.R., 1980. Performance of pigs given diets containing different levels of triticale. Anim. Prod. 31, 177–182.
Nitrayová, S., Heger, J., Patráš, P., Kluge, H., Brož, J., 2009. Effect of xylanase on apparent ileal and total tract digestibility of nutrients and energy of rye in young pigs. Arch. Anim. Nutr. 63, 281–291.
Nortey, T.N., Patience, J.F., Sands, J.S., Trottier, N.L., Zijlstra, R.T., 2008. Effects of xylanase supplementation on the apparent digestibility and digestible content of energy, amino acids, phosphorus, and calcium in wheat and wheat by-products from dry milling fed to grower pigs. J. Anim. Sci. 86, 3450–3464.
Nyachoti, C.M., House, J.D., Slominski, B.A., Seddon, I.R., 2005. Energy and nutrient digestibilities in wheat dried distillers' grains with solubles fed to growing pigs. J. Sci. Food Agric. 85, 2581–2586.
Nyachoti, C.M., Arntfield, S.D., Guenter, W., Cenkowski, S., Opapeju, F.O., 2006. Effect of micronized pea and enzyme supplementation on nutrient utilization and manure output in growing pigs. J. Anim. Sci. 84, 2150–2156.
O'Connell, J.M., Callan, J.J., O'Doherty, J.V., 2005. The interaction between cereal type and lactose level on piglet performance and diet digestibility post weaning. J. Anim. Sci. 81, 265–269.
O'Doherty, J.V., Keady, U., 2000. The nutritive value of extruded and raw peas for growing and finishing pigs. Anim. Sci. 70, 265–274.
Ofongo, S.T., Kehraus, S., Iyayi, E.A., Sudekum, K.H., 2008. Rice mill feed: an agro-industrial by-product with potential for rural development. In: Tielkes, E. (Ed.), Tropentag 2008, Conference on International Research on Food Security. Natural Resource Management and Rural Development, Stuttgart-Hohenheim, Germany (p. 352).
Opalka, M., Tywonczuk, J., Koziorowski, M., Dusza, L., 2003. Effect of diets containing graded levels of low glucosinolate rapeseed press cake on reproductive organs and hormonal status in gilts and their female piglets. Anim. Sci. 77, 131–139.
Orok, E.J., Bowland, J.P., Briggs, C.W., 1975. Rapeseed, peanut and soybean meals as protein supplements with or without added lysine: biological performance and carcass characteristics of pigs and rats. Can. J. Anim. Sci. 55, 135–146.
Owsley, W.F., Knabe, D.A., Tanksley, T.D., 1981. Effect of sorghum particle size on digestibility of nutrients at the terminal ileum and over the total digestive tract of growing-Finishing pigs. J. Anim. Sci. 52.
Owusu-Asiedu, A., Baidoo, S.K., Nyachoti, C.M., 2002. Effect of heat processing on nutrient digestibility in pea and supplementing amylase and xylanase to raw extruded, or micronized pea-based diets on performance of early weaned pigs. Can. J. Anim. Sci. 82, 367–374.
Pahm, A.A., Pedersen, C., Stein, H.H., 2008. Application of the reactive lysine procedure to estimate lysine digestibility in distillers dried grains with solubles fed to growing pigs. J. Agric. Food Chem. 56, 9441–9446.
Parr, C.K., Liu, Y., Parsons, C.M., Stein, H.H., 2015. Effects of high protein or conventional canola meal on growth performance, organ weights, bone ash, and blood characteristics of weanling pigs. J. Anim. Sci. 93, 2165–2173.
Partanen, K., Alaviuhkola, T., Siljander-Rasi, H., Suomi, K., 2003. Faba beans in diets for growing-finishing pigs. Agric. Food Sci. Finl. 12, 35–47.
Paulicks, B.R., Roth, F.X., Kirchgessner, M., 2000. Effects of potassium diformate (Formi® LHS) in combination with different grains and energy densities in the feed on growth performance of weaned pigs. J. Anim. Physiol. Anim. Nutr. 84, 102–111.
Pedersen, C., Boersma, M.G., Stein, H.H., 2007a. Energy and nutrient digestibility in NutriDense corn and other cereal grains fed to growing pigs. J. Anim. Sci. 85, 2473–2483.
Pedersen, C., Boersma, M.G., Stein, H.H., 2007b. Digestibility of energy and phosphorus in 10 samples of distillers dried grain with solubles fed to growing pigs. J. Anim. Sci. 85, 1168–1176.
Petersen, G.I., Liu, Y., Stein, H.H., 2014. Coefficient of standardized ileal digestibility of amino acids in corn soybean meal, corn gluten meal, high-protein distillers dried grains, and field peas fed to weanling pigs. Anim. Feed Sci. Technol. 188, 145–149.
Pichardo, A., Cervantes-Ramírez, M., Cuca, M., Figueroa, J.L., Araiza, A., Torrentera, N., Maximiliano, C., 2003. Limiting amino acids in wheat for growing-finishing pigs. INCI 28, 287–291.
Pluske, J.R., Siba, P.M., Pethick, D.W., Durmic, Z., Mullan, B.P., Hampson, D.J., 1996. The incidence of swine dysentery in pigs can be reduced by feeding diets that limit the amount of fermentable substrate entering the large intestine. J. Nutr. 126, 2920–2933.
Pluske, J.R., Black, B., Pethick, D.W., Mullan, B.P., Hampson, D.J., 2003. Effects of different sources and levels of dietary fibre in diets on performance: digesta characteristics and antibiotic treatment of pigs after weaning. Anim. Feed Sci. Technol. 107, 129–142.
Prakash, J., Ramaswamy, H.S., 1996. Rice bran proteins: properties and food uses. Crit. Rev. Food. Sci. Nutr. 36, 537–552.
Prasad, M.P.R., Rao, B.D., Kalpana, K., Rao, M.V., Patil, J.V., 2014. Glycemic index and glycemic load of sorghum products. J. Sci. Food Agric. 95, 1626–1630.
Prawirodigdo, S., Gannon, N.J., van Barneveld, R.J., Kerton, D.J., Leury, B.J., Dunshea, F.R., 1998. Assessment of apparent ileal digestibility of amino acids and nitrogen in cottonseed and soyabean meals fed to pigs determined using ileal dissection under halothane anaesthesia or following carbon dioxide-stunning. Br. J. Nutr. 80, 183–191.
Rodriguez, D.A., Sulabo, R.C., Gonzalez, J.C., Stein, H.H., 2013. Energy concentration and phosphorus digestibility in canola cottonseed, and sunflower products fed to growing pigs. Can. J. Anim. Sci. 93, 493–503.
Rojas, O.J., Stein, H.H., 2012. Digestibility of phosphorus by weanling pigs of fermented and conventional soybean meal without and with microbial phytase. J. Anim. Sci. 90, 1506–1512.
Rojas, O.J., Stein, H.H., 2013. Concentration of digestible, metabolizable, and net energy and digestibility of energy and nutrients in fermented soybean meal, conventional soybean meal, and fish meal fed to weanling pigs. J. Anim. Sci. 91, 4397–4405.
Rojas, O.J., Stein, H.H., 2015a. Effects of replacing fish chicken, or poultry by-product meal with fermented soybean meal in diets fed to weanling pigs. Rev. Colomb. Cienc. Pecu. 28, 22–41.
Rojas, O.J., Stein, H.H., 2015b. Effects of reducing the particle size of corn grain on the concentration of digestible and metabolizable energy and on the digestibility of energy and nutrients in corn grain fed to growing pigs. Livest. Sci. 181, 187–193.
Rojas, O.J., Stein, H.H., 2016. Use of feed technology to improve the nutritional value of feed ingredients. Anim. Prod. Sci. (in press).
Rojas, O.J., Liu, Y., Stein, H.H., 2013. Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn co-products, and bakery meal fed to growing pigs. J. Anim. Sci. 91, 5326–5335.
Rojas, O.J., Liu, Y., Stein, H.H., 2016. Effects of particle size of yellow dent corn on physical characteristics of diets and growth performance and carcass characteristics of growing-finishing pigs. J. Anim. Sci. 94, http://dx.doi.org/10.2527/jas2015-9054.

Rosenfelder, P., Eklund, M., Mosenthin, R., 2013. Nutritive value of wheat and wheat by-products in pig nutrition: a review. Anim. Feed Sci. Technol. 185, 107–125.

Rosenfelder, P., Mosenthin, R., Spindler, H.K., Jørgensen, H., Bach Knudsen, K.E., Sauer, N., Htoo, J.K., Eklund, M., 2015. Standardized ileal digestibility of amino acids in eight genotypes of soft winter wheat fed to growing pigs. J. Anim. Sci. 93, 1133–1144.

Salyer, J.A., DeRouchey, J.M., Tokach, M.D., Dritz, S.S., Goodband, R.D., Nelssen, J.L., Petry, D.B., 2012. Effects of dietary wheat middlings, distillers dried grains with solubles, and choice white grease on growth performance, carcass characteristics, and carcass fat quality of finishing pigs. J. Anim. Sci. 90, 2620–2630.

Sanjayan, N., Heo, J.M., Nyachoti, C.M., 2014. Nutrient digestibility and growth performance of pigs fed diets with different levels of canola meal from *Brassica napus* black and *Brassica juncea* yellow. J. Anim. Sci. 92, 3895–3905.

Schone, F., Leiterer, M., Hartung, H., Jahreis, G., Tischendorf, F., 2001. Rapeseed glucosinolated and iodine in sows affect the mild iodine concentration and the iodine status of piglets. Br. J. Nutr. 85, 659–670.

Schwarz, T., Kuleta, W., Turek, A., Tuz, R., Nowicki, J., Rudzki, B., Bartlewski, P.M., 2014. Assessing the efficiency of using a modern hybrid rye cultivar for pig fattening with emphasis on production costs and carcass quality. Anim. Prod. Sci. 55, 467–473.

Seneviratne, R.W., Young, M.G., Beltranena, E., Goonewardene, L.A., Newkirk, R.W., Zijlstra, R.T., 2010. The nutritional value of expeller-pressed canola meal for grower-finisher pigs. J. Anim. Sci. 88, 2073–2083.

Seneviratne, R.W., Beltranena, E., Goonewardene, L.A., Zijlstra, R.T., 2011. Effect of crude glycerol combined with solvent-extracted or expeller-pressed canola meal on growth performance and diet nutrient digestibility of weaned pigs. Anim. Feed Sci. Technol. 170, 105–110.

Serna-Saldivar, S.R., 2010. Dry-milling operations. In: Barbosa Canovas, G.V. (Ed.), Cereal Grains: Properties, Processing and Nutritional Attributes. CRC Press, Boca Raton, FL, pp. 193–200.

Shelton, J.L., Hemann, M.D., Strode, R.M., Brashear, G.L., Ellis, M., McKeith, F.K., Bidner, T.D., Southern, L.L., 2001. Effect of different protein sources on growth and carcass traits in growing-finishing pigs. J. Anim. Sci. 79, 2428–2435.

Shelton, J.L., Matthews, J.O., Southern, L.L., Higbie, A.D., Bidner, T.D., Fernandez, J.M., Pontif, J.E., 2004. Effect of nonwaxy and waxy sorghum on growth, carcass traits, and glucose and insulin kinetics of growing-finishing barrows and gilts. J. Anim. Sci. 82, 1699–1706.

Shi, C.X., Liu, Z.Y., Shi, M., Li, P., Zeng, Z.K., Liu, L., Huang, C.F., Zhu, Z.P., Li, D.F., 2015. Prediction of digestible and metabolizable energy content of rice bran fed to growing pigs. Asian Australas. J. Anim. Sci. 28 (5), 654–661.

Singh, A.K., Bharati, R.C., Manibhushan, Chandra, Naresh, Pedpati, Anitha, 2013a. An assessment of faba bean (*Vicia faba* L.) current status and future prospect. Afr. J. Agric. Res. 8, 50.

Singh, A., Das, M., Bal, S., Banerjee, R., 2013b. Rice processing. In: Ferreira-Guine, R.P., dos Reis-Correa, P.M. (Eds.), Engineering Aspects of Cereals and Cereal Based Products. CRC Press, Boca Raton, FL, pp. 71–97.

Sissons, J.W., Nyrup, A., Kilshaw, P.J., Smith, R.H., 1982. Ethanol denaturation of soya bean protein antigens. J. Sci. Food Agric. 33, 706–710.

Slominski, B.A., Boros, D., Campbell, L.D., Guenter, W., Jones, O., 2004. Wheat by-products in poultry nutrition. Part I. Chemical and nutritive composition of wheat screenings, bakery by-products and wheat mill run. Can. J. Anim. Sci. 84, 421–428.

Slominski, B.A., Jia, W., Rogiewicz, A., Nyachoti, C.M., Hickling, D., 2012. Low-fiber canola. Part II. Chemical and nutritive composition of the meal. J. Agric. Food Chem. 60, 12225–12230.

Smit, M.N., Seneviratne, R.W., Young, M.G., Lanz, G., Zijlstra, R.T., Beltranena, E., 2014a. Feeding increasing inclusions of canola meal with distillers dried grains and solubles to growing-finishing barrows and gilts. Anim. Feed Sci. Technol. 189, 107–116.

Smit, M.N., Seneviratne, R.W., Young, M.G., Lanz, G., Zijlstra, R.T., Beltranena, E., 2014b. Feeding *Brassica juncea* or *Brassica napus* canola meal at increasing dietary inclusions to growing-finishing gilts and barrows. Anim. Feed Sci. Technol. 198, 176–185.

Smith, L.A., Houdijk, J.G.M., Homer, D., Kyriazakis, I., 2013. Effects of dietary inclusion of pea and faba bean as a replacement for soybean meal on grower and finisher pig performance and carcass quality. J. Anim. Sci. 91, 3733–3741.

Solà-Oriol, D., Roura, E., Torrallardona, D., 2014. Feed preference in pigs: relationship between cereal preference and nutrient composition and digestibility. J. Anim. Sci. 92, 220–228.

Son, A.R., Shin, S.Y., Kim, B.G., 2013. Standardized total tract digestibility of phosphorus in copra expellers palm kernel expellers, and cassava root fed to growing pigs. Asian Australas. J. Anim. Sci. 26, 1609–1613.

Son, A.R., Hyun, Y., Htoo, J.K., Kim, B.G., 2014. Amino acid digestibility in copra expellers and palm kernel expellers by growing pigs. Anim. Feed. Sci. Technol. 187, 91–97.

Song, Y.S., Pérez, V.G., Pettigrew, J.E., Martinez-Villaluenga, C., Gonzalez de Mejia, E., 2010. Fermentation pf soybean meal and its inclusion in diets for newly weaned pigs reduced diarrhea and measures of immunoreactivity in the plasma. Anim. Feed Sci. Technol., http://dx.doi.org/10.1016/j.anifeedsci.2010.04.011.

Sotak, K.M., Goodband, R.D., Tokach, M.D., Dritz, S.S., DeRouchey, J.M., Nelssen, J.L., 2014. Nutrient database for sorghum distillers dried grains with solubles from ethanol plants in the western plains region and their effects on nursery pig performance. J. Anim. Sci. 92, 292–302.

Sotak, K.M., Houser, T.A., Goodband, R.D., Tokach, M.D., Dritz, S.S., DeRouchey, J.M., Goehring, B.L., Skaar, G.R., Nelssen, J.L., 2015. The effects of feeding sorghum dried distillers grains with solubles on finishing pig growth performance, carcass characteristics, and fat quality. J. Anim. Sci. 93, 2904–2915.

Sotak-Peper, K.M., Gonzalez-Vega, J.C., Stein, H.H., 2015. Concentrations of digestible, metabolizable, and net energy in soybean meal produced in different areas of the United States and fed to pigs. J. Anim. Sci. 93, 5694–5701.

Sotak-Peper, K.M., Gonzalez-Vega, J.C., Stein, H.H., 2016. Amino acid digestibility in soybean meal produced in different areas of the United States and fed to pigs. J. Anim. Sci. Submitted.

Soy and Oilseed Blue Book, 2015. Annual Directory of the World Oilseed Industry Soyatech LLC. Southwest Harbor, Maine, USA, 04679.

Spindler, H.K., Mosenthin, R., Eklund, M., 2014. Evaluation through literature data on standardized ileal digestibility and basal ileal endogenous loss of amino acids associated with barley in pigs. Animal 8 (10), 1603–1611.

Statista, 2015. Global Grain Production from 2008/2009 to 2014/2015 (accessed, 29.11.15) http://www.statista.com/statistics/271943/total-world-grain-production-since-2008-2009/.

Stein, H.H., Bohlke, R.A., 2007. The effects of thermal treatment of field peas (*Pisum sativum* L.) on nutrient and energy digestibility by growing pigs. J. Anim. Sci. 85, 1424–1431.

Stein, H.H., Kil, D.Y., 2006. Reduced use of antibiotic growth promoters in diets fed to weanling pigs. Dietary tools, part 2. Anim. Biotechnol. 17, 217–231.

Stein, H.H., Shurson, G.C., 2009. Board invited review: the use and application of distillers dried grains with solubles (DDGS) in swine diets. J. Anim. Sci. 87, 1292–1303.

Stein, H.H., Kim, S.W., Nielsen, T.T., Easter, R.A., 2001. Standardized ileal protein and amino acid digestibility by growing pigs and sows. J. Anim. Sci. 79, 2113–2122.

Stein, H.H., Benzoni, G., Bohlke, R.A., Peters, D.N., 2004. Assessment of the feeding value of South Dakota grown field peas (*Pisum sativum* L.) for growing pigs. J. Anim. Sci. 82, 2568–2578.

Stein, H.H., Boersma, M.G., Pedersen, C., 2006a. Apparent and true total tract digestibility of phosphorus in field peas (*Pisum sativum* L.) by growing pigs. Can. J. Anim. Sci. 85, 523–525.

Stein, H.H., Everts, A.K.R., Sweeter, K.K., Peters, D.N., Maddock, R.J., Wulf, D.M., Pedersen, C., 2006b. Influence of dietary field peas on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 84, 3110–3117.

Stein, H.H., Berger, L.L., Drackley, J.K., Fahey Jr., G.C., Hernot, D.C., Parsons, C.M., 2008. Nutritional properties and feeding values of soybeans and their co-products. In: Johnson, L.A., White, P.J., Galloway, R. (Eds.), Soybeans, Chemistry, Production, Processing, and Utilization. AOCS Press, Urbana, IL, pp. 613–660.

Stein, H.H., Connot, S.P., Pedersen, C., 2009. Energy and nutrient digestibility in four sources of distillers dried grains with solubles produced from corn grown within a narrow geographical area and fed to growing pigs. Asian Austr. J. Anim. Sci. 22, 1016–1025.

Stein, H.H., Peters, D.N., Kim, B.G., 2010. Effects of including raw or extruded field peas (*Pisum sativum* L.) in diets fed to weanling pigs. J. Sci. Food Agric. 90, 1429–1436.

Stein, H.H., Casas, G.A., Abelilla, J.J., Liu, Y., Sulabo, R.C., 2015. Nutritional value of high fiber co-products from the copra, palm kernel, and rice industries in diets fed to pigs. J. Anim. Sci. Biotechnol. 6, 56.

Strang, E.J.P., Eklund, M., Rosenfelder, P., Spindler, H.K., Sauer, N., Htoo, J.K., Mosenthin, R., 2014. Standardized ileal amino acid digestibility in eight genotypes of rye fed to growing pigs. J. Anim. Sci. 92 (E-suppl. 2), 222 (Abstr.).

Sulabo, R.C., Ju, W.S., Stein, H.H., 2013. Amino acid digestibility and concentration of digestible and metabolizable energy in copra meal, palm kernel expellers, and palm kernel meal fed to growing pigs. J. Anim. Sci. 91, 1391–1399.

Tanksley, T.D., Knabe, D.A., Purser, Kenneth, Zebrowska, Teresa, Corley, J.R., 1981. Apparent digestibility of amino acids and nitrogen in three cottonseed meals and one soybean meal. J. Anim. Sci. 52, 4.

Tanksley, T.D., 1990. Cottonseed meal. In: Thacker, P.A., Kirkwood, R.N. (Eds.), Nontraditional Feed Sources for Use in Swine Production. Butterworths Publishers, Stoneham, Massachusetts, United States, pp. 139–151.

Thacker, P.A., 2009. Effects of supplementary threonine, canola oil or enzyme on nutrient digestibility, performance and carcass traits of growing-finishing pigs fed diets containing wheat distillers grains with solubles. Asian Australas. J. Anim. Sci. 22 (12), 1676–1685.

Thacker, P.A., 2012. Effect of wheat distillers' grains with solubles and a feed flavour on performance and carcass traits of growing-finishing pigs fed wheat and canola meal based diets. Arch. Anim. Nutr. 66, 117–130.

Tokach, M., Goodband, R., DeRouchy, J., 2012. Sorghum in Swine Production. Feeding Guide. United Sorghum Checkoff Program (accessed 14.12.15) http://sorghumcheckoff.com/wp-content/uploads/2012/06/swineguideforweb.pdf.

Trindade Neto, M.A., Opepaju, F.O., Slominski, B.A., Nyachoti, C.M., 2012. Ileal amino acid digestibility in canola meals from yellow- and black-seeded Brassica napus and *Brassica juncea* fed to growing pigs. J. Anim. Sci. 90, 3477–3484.

Tripathi, M.K., Mishra, A.S., 2007. Glucosinolates in animal nutrition: a review. Anim. Feed Sci. Technol. 132, 1–27.

Triticale-Infos, 2015. The World Market of Triticale (accessed 27.11.15) http://www.triticale-infos.eu/cultivation/market/triticale-world/index.html.

USA Rice Federation, 2011. Rice Technical Information Kit The Complete Guide for Using U.S. Rice as an Ingredient (accessed 14.08.14) https://www.usarice.com/doclib/124/5572.pdf.

USDA, 2016. Oil Crops Outlook (accessed 01.16.2016) http://www.ers.usda.gov/media/1994275/ocs-16a.pdf.

Urriola, P.E., Hoehler, D., Pedersen, C., Stein, H.H., Shurson, G.C., 2009. Amino acid digestibility of distillers dried grains with solubles, produced from sorghum, a sorghum-corn blend, and corn fed to growing pigs. J. Anim. Sci. 87, 2574–2580.

Urriola, P.E., Shurson, G.C., Stein, H.H., 2010. Digestibility of dietary fiber in distillers co-products fed to growing pigs. J. Anim. Sci. 88, 2373–2381.

Vicente, B., Valencia, D.G., Perez-Serrano, M., Lázaro, R., Mateos, G.G., 2009. Effects of feeding rice and the degree of starch gelatinization of rice on nutrient digestibility and ileal morphology of young pigs. Br. J. Nutr. 101, 1278–1281.

von Leitgeb, R., Feichtinger, K., Lafer, E., Eibensteiner, W., Lettner-F, F., 1994. Einsatz von erbsen (*Pisum sativum* L.) in der zuchtsauen- und ferkelfutterung. Bodenkultur 45, 155–161.

Wahlstrom, R.C., Reiner, L.J., Libal, G.W., 1977. Oats, dehulled oats and hulless barley as ingredients in pig starter diets. J. Anim. Sci., 5.

Wahlstrom, R.C., Libal, G.W., Thaler, R.C., 1985. Efficacy of supplemental tryptophan, treonine, isoleucine and methionine for weanling pigs fed a low-protein lysine- supplemented, corn-sunflower meal diet. J. Anim. Sci. 60, 720–724.

Wang, T., Johnson, L.A., 2001. Survey of soybean oil and meal qualities produced by different processes. J. Am. Oil. Chem. Soc. 78, 311–318.

Warren, B.E., Farrell, D.J., 1990a. The nutritive value of full-fat and defatted Australian rice bran: I. Chemical composition. Anim. Feed Sci. Technol. 27, 219–228.

Warren, B.E., Farrell, D.J., 1990b. The nutritive value of full-fat and defatted Australian rice bran. II. Growth studies with chickens rats and pigs. Anim. Feed Sci. Technol. 27, 229–246.

Warren, B.E., Farrell, D.J., 1990c. The nutritive value of full-fat and defatted Australian rice bran: III. The apparent digestible energy content of defatted rice bran in rats and pigs and the metabolisability of energy and nutrients in defatted and full-fat bran in chickens and adult cockerels. Anim. Feed Sci. Technol. 27, 247–257.

Weiss, E., Aumiller, T., Spindler, H.K., Rosenfelder, P., Eklund, M., Witzig, M., Jørgensen, H., Bach-Knudsen, K.E., Mosenthin, R., 2016. Wheat and barley differently affect porcine intestinal microbiota. J. Sci. Food Agric. 96, 2230–2239.

White, G.A., Smith, L.A., Houdijk, J.G.M., Homer, D., Kyriazakis, I., Wiseman, J., 2015. Replacement of soya bean meal with peas and faba beans in growing/finishing pig diets: effect on performance, carcass composition and nutrient excretion. Anim. Feed Sci. Technol. 209, 202–210.

Whitney, M.H., Shurson, G.C., Johnston, L.J., Wulf, D.M., Shanks, B.C., 2006. Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern Midwestern ethanol plant. J. Anim. Sci. 84, 3356–3363.

Widmer, M.R., McGinnis, L.M., Stein, H.H., 2007. Energy, amino acid, and phosphorus digestibility of high protein distillers dried grain and corn germ fed to growing pigs. J. Anim. Sci. 85, 2994–3003.

Widmer, M.R., McGinnis, L.M., Wulf, D.M., Stein, H.H., 2008. Effects of feeding distillers dried grains with solubles, high protein distillers dried grains, and corn germ to growing-finishing pigs on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 86, 1819–1831.

Widodo, A.E., Nolan, J.V., Iji, P.A., 2015. The nutritional value of new varieties of high-yielding triticale: feeding value of triticale for broiler chickens. S. Afr. J. Anim. Sci. 45 (No. 1).

Widyaratne, G.P., Zijlstra, R.T., 2007. Nutritional value of wheat and corn distiller's dried grain with solubles: digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. Can. J. Anim. Sci. 87, 103–114.

Widyaratne, G.P., Patience, J.F., Zijlstra, R.T., 2009. Effect of xylanase supplementation of diets containing wheat distiller's dried grains with solubles on energy: amino acid and phosphorus digestibility and growth performance of grower-finisher pigs. Can. J. Anim. 89, 91–95.

Wierenga, K.T., Beltranena, E., Yáñez, J.L., Zijlstra, R.T., 2008. Starch and energy digestibility in weaned pigs fed extruded zero-tannin faba bean starch and wheat as an energy source. Can. J. Anim Sci 88, 65–69.

Wondra, K.J., Hancock, J.D., Behnke, K.C., Hines, R.H., Stark, C.R., 1995. Effects of particle size and pelleting on growth performance, nutrient digestibility, and stomach morphology in finishing pigs. J. Anim. Sci. 73, 757–763.

Woyengo, T.A., Kiarie, E., Nyachoti, C.M., 2010. Energy and amino acid utilization in expeller-extracted canola meal fed to growing pigs. J. Anim. Sci. 88, 1433–1441.

Woyengo, T.A., Beltranena, E., Zijlstra, R.T., 2014. Nonruminant nutrition symposium: controlling feed cost by including alternative ingredients into pig diets: a review. J. Anim. Sci. 92, 1293–1305.

Yang, Y., Slominski, B.A., Brule-Babel, A., Nyachoti, C.M., 2010. Amino acid and fiber digestibility, intestinal bacterial profile, and enzyme activity in growing pigs fed dried distillers grains with solubles-based diets. J. Anim. Sci. 88, 3304–3312.

Yin, Y.L., McEvoy, J.D.G., Schulze, H., Hennig, U., Souffrant, W.B., McCracken, K.J., 2000. Apparent digestibility (ileal and overall) of nutrients and endogenous nitrogen losses in growing pigs fed wheat (var: soissons) or its by-products without or with xylanase supplementation. Livest. Prod. Sci 62, 119–132.

Yin, Y.L., Baidoo, S.K., Boychuk, L.L., 2001. Effect of replacing wheat or maize with micronized barley on starter, grower and finisher pig performance. Asian Australas. J. Anim. Sci. 14 (5), 668–676.

Yoon, J., Stein, H.H., 2013. Energy concentration of high protein low-oligosaccharide, and conventional full fat de-hulled soybeans fed to growing pigs. Anim. Feed Sci. Technol. 184, 105–109.

Yu, F., Moughan, P.J., Barry, T.N., McNabb, W.C., 1996. The effect of condensed tannins from heated and unheated cottonseed on the ileal digestibility of amino acids for the growing rat and pig. Br. J. Nutr. 76, 359–371.
Zijlstra, R.T., Beltranena, E., 2013. Swine converts co-products from food and biofuel industries into animal protein for food. Anim. Front. 3, 48–53.
Zijlstra, R.T., De Lange, C.F.M., Patience, J.F., 1999. Nutritional value of wheat for growing pigs: chemical composition and digestible energy content. Can. J. Anim. Sci. 79, 187–194.
Zijlstra, R.T., Lopetinsky, K., Beltranena, E., 2008. The nutritional value of zero-tannin faba bean for grower-finisher pigs. Can. J. Anim. Sci 88, 293–302.