Published November 20, 2014

Concentration of metabolizable energy and digestibility of energy, phosphorus, and amino acids in lemna protein concentrate fed to growing pigs[1]

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ABSTRACT: Lemna protein concentrate (LPC; 68.0% CP) is produced by extracting protein from de-oiled and dehydrated biomaterials from plants of the *Lemnaceae* family and may be used as a protein source for animals. There are, however, no published data on the nutritional value of LPC fed to pigs. Three experiments were, therefore, conducted to determine the concentration of ME, the standardized total tract digestibility (STTD) of P, and the standardized ileal digestibility (SID) of AA in LPC and to compare these values to values for fish meal and soybean meal (SBM). Experiment 1 was conducted to determine the ME of LPC, fish meal, SBM, and corn. Thirty-two barrows (initial BW: 16.8 ± 2.8 kg) were placed in metabolism cages and allotted to a randomized complete block design with 4 diets and 8 replicate pigs per diet. A corn-based diet and 3 diets that contained corn and LPC, fish meal, or SBM were formulated. Feces and urine were collected for 5 d after a 5-d adaptation period, and all samples were analyzed for GE. Results indicated that the concentration of ME was not different among corn, fish meal, and SBM (3,855, 3,904, and 4,184 kcal/kg DM, respectively), but there was a tendency (P = 0.08) for a reduced ME in LPC (3,804 kcal/kg DM) compared with SBM. In Exp. 2, 24 barrows (initial BW: 12.5 ± 2.5 kg) were allotted to a randomized complete block design with 3 diets and 8 replicate pigs per diet and used to determine the STTD of P in LPC, fish meal, and SBM. Three diets that each contained 1 of the 3 test ingredients as the sole source of P were formulated. Pigs were placed in metabolism cages, and feces were collected for 5 d after a 5-d adaptation period. The STTD of P in LPC (72.8%) was not different from the STTD of P in fish meal (65.6%), but tended (P = 0.07) to be greater than in SBM (62.8%). The SID of AA in LPC, SBM, and fish meal was determined in Exp. 3. Eight barrows (initial BW: 21.4 ± 4.0 kg) were equipped with a T-cannula in the distal ileum and randomly allotted to a replicated 4 × 4 Latin square design. A N-free diet and 3 cornstarch-based diets in which SBM, SBM and LPC or SBM and fish meal were the only sources of AA were formulated. The SID of most indispensable AA was greater (P < 0.05) in fish meal than in LPC, but the overall SID of AA was not different between fish meal and LPC. In conclusion, the ME and the STTD of P are not different between LPC and fish meal, but there is a tendency for greater ME in SBM than in LPC, whereas the STTD of P tends to be greater in LPC than in SBM. The SID of the most indispensable AA is greater in fish meal than in LPC.

Key words: amino acids, digestibility, lemna protein concentrate, metabolizable energy, phosphorus, pigs

 J. Anim. Sci. 2014.92:5222–5229
doi:10.2527/jas2014-8146

INTRODUCTION

Lemnaceae is a floating aquatic plant that grows rapidly on the surface of water and is commonly known as duckweed. The *Lemnaceae* family has been used as a source of energy and nutrients by humans and animals and to identify or test the toxicity in aquatic environments (Radić et al., 2011). Commercial production of *Lemnaceae* takes place in tropical climates, and dehydrated and de-oiled biomass of the Lemna plant, called Lemna meal, may be included in poultry and fish diets (Haustein et al., 1994; Bairagi et al., 2002). Lemna meal contains 35 to 45% CP and 7 to 10% crude fiber (Olorunfemi et al., 2006; Hasan and Chakrabarti, 2009).

A new technology developed by Parabel Inc. (Melbourne, FL) allows for extraction of CP and AA from lemna, which results in production of a lemna protein concentrate (**LPC**) that contains approximately 68% CP. It is possible that LPC can be used as a replacement for

[1]Financial support for this research was provided by Parabel Inc., Melbourne, FL.
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Received June 5, 2014.
Accepted August 26, 2014.

traditional protein sources in diets fed to pigs, but at this point, no data on the nutritional value of LPC fed to pigs are available. Therefore, the objectives of the present experiments were to determine the DE and ME, the standardized total tract digestibility (**STTD**) of P, and the standardized ileal digestibility (**SID**) of CP and AA in LPC and to compare these values to soybean meal (**SBM**) and fish meal.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for 3 experiments. Pigs used in all experiments were the offspring of G-performer boars mated to F-25 females (Genetiporc, Alexandria, MN). Ingredients that were included in the experiments included LPC, fish meal, and SBM (Table 1), and the same batches of these ingredients were used in all 3 experiments. The LPC that was used (Parabel Select LPC) was sourced from Parabel Inc. (Melbourne, FL), which produces LPC from microcrop aquatic Lemna plants. The fish meal was prepared from menhaden fish (Menhaden Select; Omega Protein, Houston, TX), and a conventional de-hulled solvent extracted and toasted source of SBM was obtained from Rose Acre Farms (Seymour, IN).

Experiment 1: Energy Concentration

Diets, Animals, and Experimental Design. Experiment 1 was designed to determine the apparent total tract digestibility (**ATTD**) of GE and the concentration of DE and ME in LPC, fish meal, and SBM. Thirty-two barrows (initial BW of 16.8 ± 2.8 kg) were placed in metabolism cages equipped with a feeder and a nipple drinker in a randomized complete block design with 4 diets and 8 replicate pigs per diet.

Four corn-based diets were formulated (Table 2). The basal diet contained 96.4% corn (as-fed basis). The LPC diet contained 73.4% corn and 25.0% LPC (as-fed basis). The fish meal diet contained 74.3% corn and 25.0% fish meal (as-fed basis), and the SBM diet contained 61.2% corn and 35.0% SBM (as-fed basis). The reason for the increased concentration of SBM compared with the concentration of fish meal or LPC is the reduced concentration of CP in SBM compared with the other ingredients. Vitamins and minerals were included in the diets to meet or exceed requirements for weanling pigs (NRC, 1998).

Feeding and Sample Collection. Feed was supplied in a daily amount of 2.5 times the maintenance energy requirement (i.e., 106 kcal of ME/kg of $BW^{0.75}$; NRC, 1998) of the smallest pig in each replicate. The daily amount of feed was divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times.

Pigs were fed the experimental diets for 12 d. The initial 5 d were considered an adaptation period to the diet. Fecal markers were fed on d 6 (chromic oxide) and on d 11 (ferric oxide), and fecal collections were initiated when chromic oxide appeared in the feces and ceased when ferric oxide appeared (Adeola, 2001). Feces were collected twice daily and stored at −20°C immediately after collection. Urine was also collected twice daily and urine collections started on d 6 at 1700 h and ceased on d 11 at 1700 h. Urine buckets were placed under the metabolism cages to permit total collection. They were emptied in the morning and afternoon, and a preservative of 50 mL of sulfuric acid was added to each bucket when

Table 1. Analyzed nutrient composition of corn, lemna protein concentrate (LPC), fish meal, and conventional soybean meal (SBM), as-fed basis

	Ingredient			
Item	Corn	LPC	Fish meal	SBM
GE, kcal/kg	3,930	5,731	4,423	4,350
DM, %	86.44	93.87	89.90	89.41
CP, %	6.57	67.99	63.16	48.00
Ca, %	0.04	0.45	5.26	0.38
P, %	0.24	0.51	3.09	0.62
AEE[1], %	3.35	2.18	8.28	2.11
NDF, %	7.25	1.10	–	9.04
ADF, %	2.03	0.14	–	5.01
Ash, %	1.00	4.93	19.81	5.93
Phytate, %	–	0.15	–	1.51
Phytate bound P, %[2]	–	0.04	–	0.42
Phytate bound P, % of total P	–	8.29	–	68.68
Non-phytate P, %[3]	–	0.47	–	0.19
Non-phytate bound P, % of total P	–	91.70	–	31.32
Indispensable AA, %				
Arg	0.66	4.11	3.82	3.54
His	0.41	1.59	1.41	1.41
Ile	0.54	3.09	2.57	2.35
Leu	1.36	5.95	4.49	3.84
Lys	0.64	3.50	4.81	3.18
Met	0.23	1.38	1.77	0.69
Phe	0.60	3.92	2.47	2.45
Thr	0.69	2.88	2.59	1.88
Trp	0.05	1.16	0.65	0.75
Val	0.75	3.89	3.12	2.47
Dispensable AA, %				
Ala	1.02	4.08	3.97	2.12
Asp	1.00	5.62	5.65	5.53
Cys	0.27	0.73	0.57	0.65
Glu	2.10	6.69	8.53	8.70
Gly	0.67	3.69	4.68	2.06
Pro	1.14	2.83	2.94	2.54
Ser	0.50	2.46	2.35	1.99
Tyr	0.40	2.98	2.02	1.71
Total AA	13.03	60.55	58.41	47.97

[1]AEE = acid hydrolyzed ether extract.

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

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

Table 2. Composition of experimental diets containing corn, lemna protein concentrate (LPC), fish meal, or soybean meal (SBM), as-fed basis, Exp. 1

	Diet			
Item	Corn	LPC	Fish meal	SBM
Ingredients, %				
Ground corn	96.40	73.40	74.30	61.20
Lemna protein concentrate	–	25.00	–	–
Fish meal	–	–	25.00	–
Soybean meal, 48% CP	–	–	–	35.00
Monocalcium phosphate	1.70	–	–	2.00
Ground limestone	1.20	0.90	–	1.10
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin mineral premix[1]	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00
Analyzed composition				
GE, kcal/kg	3,719	4,283	3,964	3,891
DM, %	86.88	88.48	87.68	88.20
CP, %	6.38	22.06	21.06	18.75
ADF, %	1.95	1.68	1.77	2.97
NDF, %	9.99	8.48	11.81	8.26
AEE[2], %	3.61	4.17	4.34	3.29
Ash, %	3.65	3.03	6.33	4.02

[1]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[2]AEE = acid hydrolyzed ether extract.

they were emptied. The weight of the collected urine was recorded, and a 10% subsample was stored at −20°C.

Sample Analysis. After completing sample collections, urine samples were thawed and mixed within animal and diet, and a subsample was collected for analysis. Fecal samples were dried at 65°C in a forced-air oven and ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) before analyses. Urine samples were prepared and lyophilized before energy analysis as previously described (Kim et al., 2009). All samples were analyzed in duplicate.

Diets and ingredients were analyzed for DM (method 930.15; AOAC, 2007), CP by combustion (method 999.03; AOAC, 2007) using a Rapid N cube apparatus (Elementar Americas Inc., Mt. Laurel, NJ), ADF (method 973.18; AOAC, 2007), NDF (Holst, 1973), ash (method 942.05; AOAC, 2007), and acid hydrolyzed ether extract (**AEE**), which was determined by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (method 2003.06; AOAC, 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN). Diets, ingredients, fecal samples, and urine samples were also analyzed for GE using bomb calorimetry (Model 6300; Parr Instruments, Moline, IL). Ingredients were analyzed for AA (Method 982.30 E [a, b, c]; AOAC, 2007), and P and Ca were analyzed by inductively coupled plasma spectroscopy after wet ash sample preparation (method 975.03; AOAC, 2007).

Calculations and Statistical Analysis. The ATTD of GE was calculated in all diets and in each ingredient using the direct procedure and the difference procedure, respectively (Adeola, 2001). The DE and ME concentrations were also calculated for each diet by subtracting the GE in the feces and in the feces and urine, respectively, from the intake of GE (Adeola, 2001). The DE and ME in the corn diet were divided by 0.964 to calculate the DE and ME in corn. The contributions of DE and ME from corn to the diets containing LPC, fish meal, and SBM were then calculated and subtracted from the total DE and ME of these diets, and the concentrations of DE and ME in LPC, fish meal, and SBM were calculated by the difference (Adeola, 2001).

Data were analyzed by ANOVA using the Mixed Procedure of SAS (SAS Inst. Inc., Cary, NC). Homogeneity of the variances among treatments was confirmed using the HOVTEST = BF procedure in SAS. The Univariate procedure was also used to identify outliers, but no outliers were detected. Diet was the fixed effect, and pig and replicate were random effects. The LSMEANS statement was used to calculate treatment means, and the PDIFF option was used to separate means if differences were detected. The pig was the experimental unit for all analyses and an α level of 0.05 was used to assess significance among means.

Experiment 2: P Digestibility

Diets, Animals, and Experimental Design. Experiment 2 was designed to determine the ATTD and STTD of P in LPC, fish meal, and SBM. Twenty-four barrows (initial BW of 12.5 ± 2.5 kg) were placed in metabolism cages in a randomized complete block design with 3 diets and 8 replicate pigs per diet. The 3 diets were formulated (Table 3) by mixing cornstarch and sugar with LPC, fish meal, or SBM. Vitamins and minerals, except P, were included in the diets to meet or exceed requirements for weanling pigs (NRC, 1998). The only sources of P in the diets were the test ingredients.

Feeding and Sample Collection. Feed was supplied in a daily amount of 3 times the maintenance energy requirement of the smallest pig in each replicate and divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times.

Pigs were fed their experimental diets for 12 d. The initial 5 d were considered an adaptation period to the

Table 3. Composition of experimental diets containing lemna protein concentrate (LPC), fish meal, or soybean meal (SBM), as-fed basis, Exp. 2

	Diet		
Item	LPC	Fish meal	SBM
Ingredients, %			
Lemna protein concentrate	25.00	–	–
Fish meal	–	15.00	–
Soybean meal, 48% CP	–	–	40.00
Soybean oil	4.00	2.50	4.00
Ground limestone	0.70	–	1.00
Sucrose	15.00	15.00	15.00
Cornstarch	54.60	66.80	39.30
Sodium chloride	0.40	0.40	0.40
Vitamin mineral premix[1]	0.30	0.30	0.30
Total	100.00	100.00	100.00
Analyzed composition			
DM, %	93.12	91.72	92.63
Ca, %	0.48	0.89	0.37
P, %	0.14	0.49	0.26
ADF, %	–	–	2.48
NDF, %	0.73	–	3.96
Ash, %	2.64	3.33	3.71

[1]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 4. Composition of experimental diets containing lemna protein concentrate (LPC), fish meal, or soybean meal (SBM), as-fed basis, Exp. 3

	Diet			
Item	LPC	Fish meal	SBM	N-Free[1]
Lemna protein concentrate	20.00	–	–	–
Fish meal	–	15.00	–	–
Soybean meal, 48% CP	20.00	20.00	40.00	–
Soybean oil	–	–	3.00	4.00
Solka floc	–	–	–	4.00
Monocalcium phosphate	–	–	1.30	2.40
Ground limestone	1.10	–	1.30	0.50
Sucrose	15.00	15.00	15.00	15.00
Lactose	10.00	10.00	10.00	10.00
Chromic oxide	0.40	0.40	0.40	0.40
Cornstarch	32.80	38.90	28.30	62.50
Magnesium oxide	–	–	–	0.10
Potassium carbonate	–	–	–	0.40
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin mineral premix[2]	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00

[1]N-free = nitrogen-free diet.

[2]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

diet. Fecal markers were fed as described for Exp. 1, and feces were collected twice daily for 5 d. All fecal samples were stored at −20°C immediately after collection.

Sample Analysis. At the conclusion of the experiment, fecal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analyses. All diets and fecal samples were analyzed in duplicate for DM, Ca, and P as described for Exp. 1. Diet samples were also analyzed for ADF, NDF, and ash as described for Exp. 1.

Calculations and Statistical Analysis. Values for ATTD of P in each ingredient were calculated (Almeida and Stein, 2010), and those values were corrected for basal endogenous losses of P to calculate STTD of P. Basal endogenous P loss (**EPL**) were assumed to be 199 mg/kg DM (Almeida and Stein, 2010). Data were analyzed as explained for Exp. 1.

Experiment 3: AA Digestibility

Diets, Animals, and Experimental Design. Experiment 3 was designed to determine the apparent ileal digestibility (**AID**) and the SID of CP and AA in LPC and fish meal. Eight growing barrows (initial BW of 21.4 ± 4.0 kg) were equipped with a T-cannula in the distal ileum according to procedures adapted from Stein et al. (1998). Pigs were allotted to a replicated 4 × 4 Latin square design with 4 periods and 4 diets in each square. Pigs were housed individually in pens (1.2 × 1.5 m) in an environmentally controlled room. A feeder and a nipple drinker were installed in each pen.

Four diets were prepared (Tables 4 and 5). One diet contained SBM as the sole source of AA. Two additional diets contained SBM and LPC or SBM and fish meal and the last diet was a N-free diet. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 1998). All diets also contained 0.4% chromic oxide as an indigestible marker.

Feeding and Sample Collection. All pigs were fed at a level of 2.5 times the maintenance energy requirement and water was available at all times throughout the experiment. Pig weights were recorded at the beginning and at the end of each period, and the amount of feed supplied each day was also recorded. The initial 5 d of each period was considered an adaptation period to the diet, and ileal digesta were collected for 8 h on d 6 and 7 as described by Cervantes-Pahm and Stein (2010).

Table 5. Analyzed nutrient composition of experimental diets containing lemna protein concentrate (LPC), fish meal, or soybean meal (SBM), as-fed basis, Exp. 3

	Diet			
Item	LPC	Fish meal	SBM	N-Free[1]
GE, kcal/kg	4,178	3,970	4,001	3,805
DM, %	93.19	92.39	92.69	93.32
CP, %	23.91	19.84	17.63	0.28
Ash, %	4.49	4.80	5.47	3.30
Indispensable AA, %				
Arg	1.42	1.00	1.11	0.01
His	0.55	0.37	0.41	0.00
Ile	1.09	0.67	0.75	0.01
Leu	1.87	1.16	1.24	0.02
Lys	1.24	1.06	0.95	0.01
Met	0.37	0.31	0.22	0.00
Phe	1.23	0.70	0.81	0.01
Thr	0.86	0.61	0.59	0.01
Trp	0.36	0.20	0.22	0.04
Val	1.26	0.79	0.79	0.01
Dispensable AA, %				
Ala	1.17	0.83	0.69	0.02
Asp	2.10	1.53	1.72	0.02
Cys	0.27	0.16	0.22	0.01
Glu	3.05	2.44	2.88	0.04
Gly	1.10	0.92	0.69	0.01
Pro	1.00	0.74	0.79	0.01
Ser	0.80	0.61	0.64	0.01
Tyr	0.79	0.47	0.52	0.01
Total AA	20.53	14.57	15.24	0.21

[1]N-free = nitrogen-free diet.

Sample Analysis. At the conclusion of the experiment, ileal samples were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. All ileal digesta samples were lyophilized and finely ground. All samples of digesta and diets were analyzed in duplicate for DM, CP, and AA, as described for Exp. 1, and for chromium (Fenton and Fenton, 1979). All diet samples were also analyzed for GE and ash as described for Exp. 1.

Calculations and Statistical Analysis. Values for AID and SID of CP and AA were calculated for the 3 diets containing CP (Stein et al., 2007). Basal endogenous losses were calculated from pigs fed the N-free diet, and by correcting the AID of CP and AA for the basal endogenous losses, the SID of CP and AA were calculated. The contribution of AA from SBM to diets containing SBM and LPC or SBM and fish meal was calculated from the SBM diet, which allowed for the calculation of AID and SID of CP and AA in LPC and fish meal by difference (Mosenthin et al., 2007). Data were analyzed by ANOVA using the MIXED procedure of SAS as described for Exp. 1.

Table 6. Concentration of digestible and metabolizable energy and apparent total tract digestibility (ATTD) of energy in corn, lemna protein concentrate (LPC), fish meal, and soybean meal (SBM), as-fed basis, Exp. 1[1]

Item	Corn	LPC	Fish meal	SBM	SEM	*P*-value
Diet						
GE intake, kcal	2,308^{c}	2,654^{a}	2,488^{b}	2,418^{b}	62.3	< 0.01
GE in feces, kcal	269.2^{bc}	471.9^{a}	290.1^{b}	242.4^{c}	14.8	< 0.01
GE in urine, kcal	36.3^{b}	112.5^{a}	92.4^{a}	95.7^{a}	12.7	< 0.01
ATTD of GE, %	88.4^{b}	82.2^{c}	88.3^{b}	90.0^{a}	0.5	< 0.01
DE kcal/kg	3,286^{b}	3,521^{a}	3,502^{a}	3,501^{a}	20.0	< 0.01
ME kcal/kg	3,212^{b}	3,338^{a}	3,353^{a}	3,349^{a}	29.3	0.05
Ingredient						
ATTD of GE, %	88.3^{a}	69.6^{b}	88.5^{a}	92.5^{a}	1.5	< 0.01
DE, kcal/kg	3,408^{c}	4,076^{a}	3,878^{b}	4,044^{ab}	64.5	< 0.01
DE, kcal/kg DM	3,943^{c}	4,342^{ab}	4,314^{b}	4,523^{a}	70.0	< 0.01
ME, kcal/kg	3,332^{b}	3,571^{ab}	3,510^{ab}	3,743^{a}	92.9	0.03
ME, kcal/kg DM	3,855	3,804	3,904	4,184	106.2	0.08

$^{a–c}$Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment.

RESULTS

Experiment 1: Energy Concentration

Gross energy intake was less ($P < 0.05$) for pigs fed the corn diet than for pigs fed the LPC, fish meal, or SBM diets, but the GE intake was greater ($P < 0.05$) for pigs fed the LPC diet than for pigs fed fish meal or SBM diets (Table 6). The fecal excretion of GE was greater ($P < 0.05$) for pigs fed the LPC diet than for pigs fed the other diets, but pigs fed the fish meal diet excreted more ($P < 0.05$) GE than pigs fed the SBM diet. Pigs fed the corn diet had less ($P < 0.05$) excretion of GE in urine than pigs fed the other diets, but no differences in urine excretion of GE were observed among pigs fed the LPC, fish meal, or SBM diets. The ATTD of GE was greater ($P < 0.05$) in pigs fed the SBM diet than in pigs fed the other diets, but the ATTD of GE was less ($P < 0.05$) in pigs fed the LPC diet than in pigs fed the corn or fish meal diets. There were no differences among LPC, fish meal, and SBM diets in DE and ME values, but all of those diets contained more ($P < 0.05$) DE and ME than the corn diet.

Corn had less ($P < 0.05$) DE (as-fed and DM basis) than LPC, fish meal, and SBM and the DE concentration was greater ($P < 0.05$) in LPC than in fish meal, if calculated on an as-fed basis, but that was not the case when calculated on a DM basis. However, the DE calculated on a DM basis was greater ($P < 0.05$) in SBM than in fish meal, but not different from the DE in LPC. Soybean meal contained more ($P < 0.05$) ME (as-fed basis) than corn, but there were no differences in concentrations of ME (as-fed basis) among LPC, fish meal, and SBM. However, when ME was calculated on

Table 7. Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in lemna protein concentrate (LPC), fish meal, and soybean meal (SBM), Exp. 2[1]

Item	LPC	Fish meal	SBM	SEM	*P*-value
Feed intake, g DM/d	437.5	417.7	450.1	17.29	0.08
P intake, g/d	0.7[c]	2.2[a]	1.3[b]	0.06	< 0.01
P in feces, %	0.5[c]	3.8[a]	2.9[b]	0.09	< 0.01
P output, g/d	0.3[c]	0.9[a]	0.6[b]	0.07	< 0.01
Absorbed P, g/d	0.4[c]	1.4[a]	0.7[b]	0.04	< 0.01
ATTD of P, %	59.5	61.9	55.7	2.99	0.33
Basal EPL,[2] mg/d	87.5	83.5	90.0	3.46	0.08
STTD of P,[3] %	72.8	65.6	62.8	2.99	0.07

[a–c]Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment.

[2]EPL = basal endogenous P loss. This value was measured in pigs fed a P-free diet and determined to be 199 mg/kg DMI (Almeida and Stein, 2010). The daily basal EPL was calculated by multiplying daily DMI by 199 mg/kg DMI.

[3]Values for STTD were calculated by correcting values for ATTD for basal EPL.

a DM basis, no differences among corn, LPC, fish meal, and SBM were observed, but there was a tendency ($P = 0.08$) for a greater ME in SBM than in LPC.

Experiment 2: P Digestibility

The ADFI was not different among pigs fed diets containing LPC, fish meal, or SBM (Table 7). Daily P intake and P concentration in feces were greater ($P < 0.05$) in pigs fed the fish meal diet than in pigs fed LPC or SBM diets, and these values were also greater ($P < 0.05$) for pigs fed the SBM diet than for pigs fed the LPC diet. Phosphorus output and daily absorption of P were less ($P < 0.05$) in pigs fed the LPC diet than for pigs fed fish meal or SBM diets, and P output and daily absorption of P were greater ($P < 0.05$) for pigs fed the fish meal diet than for pigs fed the SBM diet. The basal EPL, ATTD of P, and STTD of P were, however, not different among LPC, fish meal, and SBM, although there was a tendency ($P = 0.07$) for the STTD of P to be greater in LPC than in SBM.

Experiment 3: AA Digestibility

The AID of CP, Arg, His, Ile, Phe, Thr, and Val was not different between LPC and fish meal (Table 8). The AID of Lys and Met was greater ($P < 0.01$) in fish meal than in LPC, but the AID of Trp was greater ($P < 0.01$) in LPC than in fish meal. The AID of Ala, Cys, Glu, Gly, Pro, and Tyr was not different between LPC and fish meal. The AID of Asp was greater ($P < 0.01$) in LPC than in fish meal, but the AID of Ser was greater ($P < 0.01$) in fish meal than in LPC.

The SID of CP and most of the indispensable AA except for Arg, His, and Val was greater ($P < 0.05$) in fish meal than in LPC. The SID of Trp was greater ($P < 0.01$) in LPC than in fish meal. The SID of Ala, Cys, and Ser was greater ($P < 0.01$) in fish meal than in LPC, but the SID of Asp was greater ($P < 0.01$) in LPC than in fish meal. The SID of Glu, Gly, Pro, and Tyr was not different between LPC and fish meal.

DISCUSSION

Experiment 1: Energy Concentration

The concentration of GE, DE, and ME in corn and the ATTD of GE in corn were in agreement with values reported by Widmer et al. (2007) and Goebel and Stein (2011). The DE, ME, and ATTD of GE that were determined for SBM were also in close agreement with values reported by Goebel and Stein (2011). Values for DE and ME in fish meal were close to the values reported by NRC (2012).

The GE concentration was much greater in LPC than in fish meal and SBM, but because the ATTD of GE in LPC was less than in fish meal and SBM, the ME in LPC was not greater than in fish meal. The greater GE in LPC than in fish meal is likely a result of the greater concentration of CP and the much lower concentration of ash than in fish meal. It is not clear why the GE in LPC is not as well digested as in fish meal and SBM. However, the nutrients analyzed in LPC did not add up to 100%, indicating that there are additional components in LPC that were not analyzed. Therefore, more research is needed to elucidate the reason for the low ATTD of GE in LPC. Nevertheless, the fact that the DE and ME in LPC are close to values obtained for fish meal indicates that the ME of a diet will not change if LPC is used instead of fish meal.

Experiment 2: P Digestibility

The concentration of P in fish meal and SBM is in agreement with values reported by NRC (2012). Results of the present experiment indicate that pigs fed the fish meal diet had a greater absorption of P than pigs fed the LPC and SBM diets, which is due to the greater concentration of P in fish meal than in LPC and SBM. However, the lack of differences among ingredients in the ATTD of P indicated that the P in LPC, fish meal, and SBM is equally well digested. The ATTD of P in fish meal obtained in this experiment is slightly less than values reported by Sauvant et al. (2004). The concentration of ash in whole menhaden fish is approximately 5.5% (Deegan, 1986). The fact that the ash concentration for the fish meal used in this experiment is much greater than the concentration in whole fish indicates that a large proportion of the fish meal used in this experiment may have been fish bones from the fish filet industry. For meat and bones meal, it has been demonstrated that the ATTD of P is reduced if

Table 8. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of CP and AA in lemna protein concentrate (LPC) and fish meal by growing pigs, Exp. 3[1,2]

	AID				SID			
	Ingredient				Ingredient			
Item, %	LPC	Fish meal	SEM	*P*-value	LPC	Fish meal	SEM	*P*-value
CP	72.35	74.40	1.25	0.27	78.12	82.34	1.25	0.03
Indispensable AA								
Arg	86.29	86.45	1.52	0.92	88.28	91.49	1.52	0.09
His	78.32	77.42	1.50	0.61	80.23	82.29	1.50	0.26
Ile	78.03	80.20	1.34	0.14	79.36	84.48	1.34	< 0.01
Leu	78.62	81.66	1.31	0.06	80.11	85.72	1.31	< 0.01
Lys	78.60	83.08	1.24	< 0.01	81.19	86.48	1.24	< 0.01
Met	77.68	85.30	0.87	< 0.01	80.05	88.30	0.87	< 0.01
Phe	80.29	81.63	1.40	0.38	81.08	84.87	1.40	0.03
Thr	70.23	72.05	1.22	0.24	75.01	81.13	1.22	< 0.01
Trp	89.68	78.25	1.51	< 0.01	90.31	81.67	1.51	< 0.01
Val	77.33	78.03	1.53	0.69	79.22	82.97	1.53	0.06
Mean	78.94	80.62	1.20	0.27	81.03	85.45	1.20	0.03
Dispensable AA								
Ala	73.87	75.66	1.09	0.19	78.36	83.40	1.09	< 0.01
Asp	80.97	71.68	1.92	< 0.01	82.49	75.60	1.92	0.02
Cys	64.99	68.58	2.31	0.31	64.26	74.35	2.31	0.02
Glu	86.14	85.07	1.95	0.62	86.93	87.51	1.95	0.79
Gly	62.80	63.30	2.96	0.91	78.40	83.63	2.96	0.23
Pro	62.86	39.34	21.28	0.41	100.57	117.63	21.28	0.55
Ser	71.25	79.12	1.27	< 0.01	74.52	85.21	1.27	< 0.01
Tyr	81.93	82.80	1.32	0.56	83.00	86.42	1.32	0.06
Mean	72.92	72.47	3.23	0.92	79.45	85.47	3.23	0.21
All AA	75.85	76.15	1.93	0.91	80.25	85.56	1.93	0.07

[1]Data are least squares means of 8 observations.

[2]Values for SID were calculated by correcting the values for AID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DMI) as CP, 19.64; Arg, 0.70; His, 0.20; Ile, 0.33; Leu, 0.56; Lys, 0.36; Met, 0.09; Phe, 0.34; Thr, 0.61; Trp, 0.12; Val, 0.46; Ala, 0.64; Asp, 0.85; Cys, 0.21; Glu, 1.02; Gly, 1.91; Pro, 7.16; Ser, 0.54; Tyr, 0.28.

the concentration of bones increases (Hua et al., 2005). It is, therefore, possible that the reason for the relatively poor ATTD of P in fish meal is the high concentration of bone. The ATTD of P in SBM obtained in this experiment is within the range of values previously reported (Bohlke et al., 2005; Almeida and Stein, 2010; Goebel and Stein, 2011; Rojas and Stein, 2012). The tendency for a greater STTD of P in LPC than in SBM, demonstrates that P in LCP is well digested by pigs. This is likely a result of the low concentration of phytate in LPC because phytate in feed ingredients reduces the digestibility of P due to the lack endogenous phytase in the small intestine of pigs (Eeckhout and De Paepe, 1994; Yi and Kornegay, 1996).

Experiment 3: AA Digestibility

The AA composition of fish meal was in agreement with previous values (Cervantes-Pahm and Stein, 2010; NRC, 2012). The AID and SID of CP and AA in fish meal obtained in this experiment are also in agreement with previous values (Cervantes-Pahm and Stein, 2010). To our knowledge, this is the first time the AA composition of LPC has been reported, and also the first time the AID and SID of AA in LPC have been determined. However, results of this experiment indicate that the AA in LPC are relatively well digested by pigs. This indicates that if LPC is included in diets for pigs, AA digestibility will not be compromised.

Conclusions

Results of these experiments indicate that the ME in LPC is not different from the ME in corn or fish meal, but there was a tendency for a greater ME in SBM than in LPC. The concentration of ME will, therefore, not be changed if LPC is included in diets fed to pigs at the expense of fish meal, but it may be slightly reduced if LPC replaces SBM. The STTD of P had a tendency to be greater in LPC than in SBM, which is likely a consequence of the low phytate concentration in LPC compared with SBM. The AA in LPC are relatively well digested by young pigs. For the overall SID of AA, there was no difference between fish meal and LCP, but the SID of some indispensable AA was greater in fish meal than in LPC.

LITERATURE CITED

Adeola, O. 2001. Digestion and balance techniques in pigs. In: A. J. Lewis and L. L. Southern, editors, Swine nutrition. 2nd ed. CRC Press, Washington, DC. p. 903–916.

AOAC. 2007. Official methods of analysis. 18th ed. rev. 2. W. Hortwitz and G. W. Latimer Jr., editors, Assoc. of Off. Agric. Chem. Int., Gaithersburg, MD.

Almeida, F. N., and H. H. Stein. 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.

Bairagi, A., K. Sarkar-Ghosh, S.K. Sen, and A.K. Ray. 2002. Duckweed (*Lemna polyrhiza*) leaf meal as a source of feedstuff in formulated diets for rohu (*Labeo rohita Ham.*) fingerlings after fermentation with a fish intestinal bacterium. Bioresour. Technol. 85:17–24.

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396–2403.

Cervantes-Pahm, S. K., and H. H. Stein. 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.

Deegan, L. A. 1986. Changes in body composition and morphology of young-of-the-year gulf menhaden, *Brevoortia patronus* goode, in Fourleague Bay, Louisina. J. Fish Biol. 29:403–415.

Eeckhout, W., and M. De Paepe. 1994. Total phosphorus, phytate-phosphorus and phytase activity in plant feedstuffs. Anim. Feed Sci. Technol. 47:19–29.

Fenton, T. W., and M. Fenton. 1979. An improved procedure for the determination of chromic oxide in feeds and feces. Can. J. Anim. Sci. 59:631–634.

Goebel, K. P., and H. H. Stein. 2011. Phosphorus digestibility and energy concentration of enzyme-treated and conventional soybean meal fed to weanling pigs. J. Anim. Sci. 89:764–772.

Hasan, M. R., and R. Chakrabarti. 2009. Floating aquatic macrophytes—Duckweeds. In: M. R. Hasan and R. Chakrabarti, editors, Use of algae and aquatic macrophytes as feed in small-scale aquaculture. Food and Agric. Organ. of the U. N., Rome. p. 29–52.

Haustein, A. T., R. H. Gilman, and P. W. Skillicorn. 1994. Performance of broiler chickens fed diets containing duckweed (*Lemna Gibba*). J. Agric. Sci. 122:285–289.

Holst, D. O. 1973. Holst filtration apparatus for Van Soest detergent fiber analysis. J. Assoc. Off. Anal. Chem. 56:1352–1356.

Hua, K., L. Liu, and D. P. Bureau. 2005. Determination of phosphorus fractions in animal protein ingredients. J. Agric. Food Chem. 53:1571–1574.

Kim, B. G., G. I. Petersen, R. B. Hinson, G. L. Allee, and H. H. Stein. 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.

Mosenthin, R., A. J. M. Jansman, and M. Eklund. 2007. Standardization of methods for the determination of ileal amino acid digestibilities in growing pigs. Livest. Sci. 109:276–281.

NRC. 1998. Nutrient requirements of swine. 10th rev. ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

Olorunfemi, T. O. S., F. M. Aderibigbe, B. K. Alese, and E. A. Fasakin. 2006. Utilization of duckweed (*Lemna paucicostata)* in least cost feed formulation for broiler starter: A linear programming analysis. Inf. Technol. J. 5:166–171.

Radić, S., D. Stipaničev, P. Cvjetko, M. Marijanović Rajčić, S. Širac, B. Pevalek-Kozlina, and M. Pavlica. 2011. Duckweed *Lemna minor* as a tool for testing toxicity and genotoxicity of surface waters. Ecotoxicol. Environ. Saf. 74:182–187.

Rojas, O. J., and H. H. Stein. 2012. Digestibility of phosphorus by growing pigs of fermented and conventional soybean meal without and with microbial phytase. J. Anim. Sci. 90:1506–1512.

Sanderson, P. 1986. A new method of analysis of feeding stuffs for the determination of crude oils and fats. In: W. Haresign and D. J. A. Cole, editors, Recent advances in animal nutrition. Butterworths, London. p. 77–81.

Sauvant, D., J. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials. 2nd ed. Wageningen Acad., Wageningen, the Netherlands.

Stein, H. H., C. F. Shipley, and R. A. Easter. 1998. Technical Note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76:1433–1436.

Stein, H. H., B. Sève, M. F. Fuller, P. J. Moughan, and C. F. M. de Lange. 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. J. Anim. Sci. 85:172–180.

Tran, G., and D. Sauvant. 2004. Chemical data and nutritional value In: Tables of composition and nutritional value of feed materials. 2nd ed. Wageningen Acad., Wageningen, the Netherlands. p. 17–24.

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

Yi, Z., and E. T. Kornegay. 1996. Sites of phytase activity in the gastrointestinal tract of young pigs. Anim. Feed Sci. Technol. 61:361–368.