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Energy concentration and phosphorus digestibility in yeast products produced from the ethanol industry, and in brewers' yeast, fish meal, and soybean meal fed to growing pigs[1]

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ABSTRACT: Two experiments were conducted to determine the DE, ME, and standardized total tract digestibility (STTD) of P in 2 novel sources of yeast (C-yeast and S-yeast) and in brewers' yeast, fish meal, and soybean meal fed to growing pigs. The 2 new sources of yeast are coproducts from the dry-grind ethanol industry. The concentrations of DM, GE, and P were 94.8%, 5,103 kcal/kg, and 1.07% in C-yeast; 94.4%, 4,926 kcal/kg, and 2.01% in S-yeast; 93.6%, 4,524 kcal/kg, and 1.40% in brewers' yeast; 91.4%, 4,461 kcal/kg, and 3.26% in fish meal; and 87.7%, 4,136 kcal/kg, and 0.70% in soybean meal, respectively. The DE and ME in each of the ingredients were determined using 42 growing barrows (28.9 ± 2.18 kg BW). A corn-based basal diet and 5 diets containing corn and 24% to 40% of each test ingredient were formulated. The total collection method was used to collect feces and urine, and the difference procedure was used to calculate values for DE and ME in each ingredient. The concentrations of DE in corn, C-yeast, S-yeast, brewers' yeast, fish meal, and soybean meal were 4,004, 4,344, 4,537, 4,290, 4,544, and 4,362 kcal/kg DM (SEM = 57), respectively, and the ME values were 3,879, 3,952, 4,255, 3,771, 4,224, and 4,007 kcal/kg DM (SEM = 76), respectively. The ME in S-yeast and fish meal were greater ($P < 0.05$) than the ME in corn and brewers' yeast, whereas the ME in C-yeast and soybean meal were not different from those of any of the other ingredients. The STTD of P in the 5 ingredients was determined using 42 barrows (28.3 ± 7.21 kg BW) that were placed in metabolism cages. Five diets were formulated to contain each test ingredient as the sole source of P, and a P-free diet was used to estimate the basal endogenous loss of P. Feces were collected for 5 d using the marker to marker method after a 5-d adaptation period. The STTD of P in brewers' yeast (85.2%) was greater ($P < 0.05$) than the STTD of P in all the other ingredients except S-yeast (75.7%). The STTD of P in C-yeast (73.9%) was not different from the STTD of P in S-yeast and fish meal (67.3%) but was greater ($P < 0.05$) than the STTD of P in soybean meal (56.7%). In conclusion, the 2 novel sources of yeast contain similar or greater concentrations of energy compared with brewers' yeast, corn, fish meal, and soybean meal, and the STTD of P in the 2 yeast products is not different from the STTD of P in fish meal.

Key words: digestibility, energy, phosphorus, pigs, yeast products

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INTRODUCTION

Soybean meal is the most commonly used plant protein in swine diets in the United States, and diets fed to pigs account for 25% of total soybean meal consumption (Stein et al., 2008; American Soybean Association, 2012). However, because of the antigens and the oligosaccharides in soybean meal, weanling pigs tolerate only limited quantities of soybean meal in their diets (NRC, 2012). Feed ingredients of animal origin such as fish meal are therefore often used in diets fed to weanling pigs instead of soybean meal (Stoner et al., 1990; Kim and Easter, 2001). However, brewers' yeast or single-cell yeast protein may also be used in diets fed to weanling pigs (White et al., 2002; Zhang et al., 2013). Single-cell yeast protein may be produced using different technologies (Øverland and Skrede, 2012). In the dry-grind ethanol production process, solubles and the wet grains are separated after centrifugation of the fermentation biomass. The solubles are then added to the distillers grains and dried, and the final product, distillers dried grains with solubles, is

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produced (Erickson et al., 2005). A new technology developed by ICM Inc. (Colwich, KS) allows for utilization of the solubles as the growth medium for yeast production. In this procedure, yeast is added to the solubles, and along with residual yeast that is already present in the solubles, added yeast will grow aerobically using the carbohydrates in the solubles as the growth medium, which will result in production of more yeast. Two novel sources of yeast have been generated using this technology, and it is expected that both products will be approved for use in animal feed within the near future. There are, however, no data on the nutritional value of these 2 new sources of yeast. Thus, the objectives of the present experiments were to determine the DE and ME and the digestibility of P in the 2 novel sources of yeast and to compare these values to values obtained in brewers' yeast, fish meal, and soybean meal.

MATERIALS AND METHODS

Two digestibility experiments were conducted in an environmentally controlled room (21°C–24°C) at the University of Illinois at Urbana-Champaign. The protocol for both experiments was approved by the Institutional Animal Care and Use Committee at the University of Illinois. All pigs used in the experiments were the offspring of Landrace boars mated to Yorkshire-Duroc females (Pig Improvement Company, Hendersonville, TN).

Two sources of yeast were obtained from ICM Inc. These sources were produced by adding yeast to the solubles from ethanol production. The solubles contain both carbohydrates that can serve as energy sources for yeast and also residual yeast from the fermentation resulting in ethanol production. After 96 h of incubation, the yeast was separated from the solubles via centrifugation and was dried. One of the sources of yeast generated is genetically modified *Saccharomyces cerevisiae* yeast, and the other source is wild-type *Pichia stipitis* yeast, which is also used in the production of many food additives. These 2 sources of yeast resulted in the production of the 2 different yeast products (C-yeast and S-yeast, respectively) that were used in the present experiments (Table 1).

Brewers' yeast (Brewtech) was sourced from International Ingredient Corp. (St. Louis, MO), and fish meal (Select Menhaden) was sourced from Omega Protein (Houston, TX). Dehulled soybean meal (Solae LLC, Gibson City, IL) was also procured, and a local source of yellow dent corn was obtained from the University of Illinois feed mill (Champaign, IL). The same batches of C-yeast, S-yeast, brewers' yeast, fish meal, and soybean meal were used in both experiments.

Table 1. Analyzed composition of corn, C-yeast, S-yeast, brewers' yeast, fish meal, and soybean meal (as-fed basis)[1]

	Ingredient[2]					
Item	Corn	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal
DM, %	86.5	94.8	94.4	93.6	91.4	87.7
GE, kcal/kg	3,977	5,103	4,926	4,524	4,461	4,136
CP, %	—	43.9	36.4	50.4	63.9	45.4
Acid hydrolyzed ether extract, %	2.03	5.58	4.39	0.58	9.17	0.85
Ash, %	—	5.95	9.35	6.35	18.68	5.59
ADF, %	—	8.23	13.77	2.17	—	8.32
NDF, %	—	21.64	25.56	0.40	—	10.38
Starch, %	—	0.77	1.84	4.72	—	1.62
Glucose, %	—	0.28	0.13	ND	—	0.09
Sucrose, %	—	ND	ND	ND	—	6.21
Raffinose, %	—	ND	ND	0.06	—	1.09
Stachyose, %	—	ND	ND	0.00	—	4.50
Arabinose, %	—	0.01	0.13	0.03	—	ND
Mannose, %	—	0.02	0.02	ND	—	0.04
Ca, %	—	0.02	0.02	0.18	5.01	0.36
Total P, %	—	1.07	2.01	1.40	3.26	0.70
Phytic acid, %	—	1.55	2.23	1.03	0.33	2.50
Phytate P,[3] %	—	0.44	0.63	0.29	0.09	0.71
Nonphytate P,[4] %	—	0.63	1.38	1.11	3.17	0.28
Indispensable AA, %						
Arg	—	2.10	1.74	2.48	3.87	3.17
His	—	1.06	0.85	1.09	1.55	1.16
Ile	—	1.91	1.52	2.22	2.69	2.04
Leu	—	3.61	2.82	3.34	4.60	3.37
Lys	—	2.72	2.08	3.33	5.06	2.82
Met	—	0.78	0.60	0.85	1.88	0.67
Phe	—	1.99	1.62	2.08	2.57	2.25
Thr	—	1.96	1.61	2.09	2.59	1.66
Trp	—	0.31	0.40	0.59	0.62	0.60
Val	—	2.44	1.95	2.64	3.12	2.17
Total	—	18.88	15.19	20.71	28.55	19.91
Dispensable AA, %						
Ala	—	2.81	2.34	3.76	3.96	1.90
Asp	—	3.45	2.77	4.22	5.83	4.93
Cys	—	0.64	0.50	0.58	0.55	0.57
Glu	—	5.17	4.14	5.77	8.27	7.81
Gly	—	1.92	1.53	2.23	4.48	1.86
Pro	—	1.87	1.51	1.73	2.78	2.04
Ser	—	1.81	1.49	2.16	2.25	1.91
Tyr	—	1.64	1.33	1.53	2.05	1.61
Total	—	19.31	15.61	21.98	30.17	22.63
All AA, %	—	38.19	30.80	42.69	58.72	42.54

[1]C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

[2]ND = not detectable.

[3]Calculated as 28.2% of phytate (Trans and Sauvant, 2004).

[4]Calculated as the difference between phytate P and total P.

Experiment 1: Energy Measurements

A total of 42 growing barrows with an initial BW of 28.9 kg (SD = 2.18) were used. Pigs were individually housed in metabolism cages equipped with a feeder and a nipple drinker. Pigs were assigned to 6 dietary treatments with 7 pigs per treatment in a randomized complete block design using the Experimental Animal Allotment Program (Kim and Lindemann, 2007).

Six experimental diets were formulated (Table 2). One diet contained corn as the sole source of energy, and vitamins, and minerals. Five additional diets were formulated by mixing corn with C-yeast (33%), S-yeast (40%), brewers' yeast (33%), fish meal (24%), or soybean meal (31%). Vitamins and all minerals were added to all diets according to requirement estimates (NRC, 1998).

The daily feed allotment was calculated as 3 times the maintenance energy requirement (i.e., 106 kcal ME per $kg^{0.75}$; NRC, 1998) and divided into 2 equal meals. The ME values for C-yeast and S-yeast were assumed to be similar to that of brewers' yeast because no specific values for these 2 ingredients were available at the time of feeding. Pigs had free access to water throughout the experiment. The initial 5 d of the experiment were considered an adaptation period to the diet. On d 6, a marker (0.5% chromic oxide) was mixed into the morning meal. Fecal samples were collected as the marker appeared in the feces. On d 11, a second marker (0.5% ferric oxide) was included in the morning meal. Fecal collection continued until the second marker appeared in the feces (Adeola, 2001; Baker and Stein, 2009). Urine collection started at 0900 h on d 6 and ceased at 0900 h on d 11. Urine was collected in urine buckets that contained 50 mL of 6 *N* HCl. All urine in the buckets was collected every day, and the total weight was recorded. A subsample of 10% of the collected urine was then stored at −20°C. Fecal samples were also stored at −20°C immediately after collection. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a subsample was collected for analysis. Fecal samples were dried in a forced-air oven, and ingredient, diet, and fecal samples were finely ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) before analysis. Ingredient samples were analyzed in duplicate for ash (method 942.05; AOAC International, 2007), CP (method 990.03; AOAC International, 2007), and AA (Method 982.30 E (a, b, c); AOAC International, 2007). To assure a complete fat extraction from the ingredients (NRC, 2012), acid hydrolyzed ether extract was determined in all ingredients using a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN; method 2003.06; AOAC International, 2007). Ingredients, diets, and feces were also analyzed in duplicate for DM (method 927.05; AOAC International, 2007). The concentration of GE in all samples of ingredients, diets, and feces was determined using bomb calorimetry (Parr Instruments, Moline, IL), with benzoic acid being the internal standard. Urine samples were lyophilized and analyzed for GE using the procedure described by Kim et al. (2009).

Table 2. Composition of experimental diets for the energy experiment (as-fed basis), Exp. 1

	Diet[1]					
Item	Corn	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal
Ingredient, %						
Ground corn	96.40	64.30	57.30	64.30	75.30	65.20
C-yeast	—	33.00	—	—	—	—
S-yeast	—	—	40.00	—	—	—
Brewers' yeast	—	—	—	33.00	—	—
Fish meal	—	—	—	—	24.00	—
Soybean meal, 48% CP	—	—	—	—	—	31.00
Monocalcium phosphate	1.70	—	—	—	—	2.00
Ground limestone	1.20	2.00	2.00	2.00	—	1.10
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30
Analyzed composition						
DM, %	86.5	94.8	94.4	93.6	91.4	87.7
GE, kcal/kg	3,773	4,197	4,232	3,987	4,012	3,842
Calculated composition						
ADF, %	2.78	4.57	7.16	2.57	3.25	4.46
NDF, %	8.78	13.00	15.44	5.99	10.25	9.16

[1]C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

[2]The vitamin-micromineral premix 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-α-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, 1.0 mg, and nicotinic acid, 43.0 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu as copper sulfate, 10 mg; Fe as iron sulfate, 125 mg; I as potassium iodate, 1.26 mg; Mn as manganese sulfate, 60 mg; Se as sodium selenite, 0.3 mg; and Zn as zinc oxide, 100 mg.

Following chemical analysis, the amount of energy lost in the feces and urine was calculated to determine the concentration of DE and ME in each of the 6 diets. The DE and ME in the corn diet were divided by 0.964 to obtain the DE and ME for corn (Stein et al., 2004). The contribution of DE or ME from corn to the other 5 diets was then calculated and subtracted from the DE and ME of those 5 diets to determine the DE and ME that were contributed by the test ingredients. These values were then divided by the inclusion rate of the ingredient in the diet to calculate DE and ME for each ingredient.

Data were analyzed using the MIXED procedure in SAS (SAS Inst. Inc., Cary, NC). The model included diet as the fixed variable and replication as the random variable. Data were analyzed for outliers using the UNIVARIATE procedure, but no outliers were identified. Least squares means were calculated, and the means were

Table 3. Composition of experimental diets for the phosphorus experiment (as-fed basis), Exp. 2

	Diet[1]					
Item	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal	P free
C-yeast	25.00	—	—	—	—	—
S-yeast	—	25.00	—	—	—	—
Brewers' yeast	—	—	25.00	—	—	—
Fish meal	—	—	—	15.00	—	—
Soybean meal, 48% CP	—	—	—	—	40.00	—
Cornstarch	57.70	57.70	57.70	69.30	43.30	49.22
Sugar	15.00	15.00	15.00	15.00	15.00	20.00
Gelatin	—	—	—	—	—	20.00
Soybean oil	—	—	—	—	—	4.00
Solca floc[2]	—	—	—	—	—	4.00
DL-Met	—	—	—	—	—	0.27
L-Thr	—	—	—	—	—	0.08
L-Trp	—	—	—	—	—	0.14
L-His	—	—	—	—	—	0.08
L-Ile	—	—	—	—	—	0.16
L-Val	—	—	—	—	—	0.05
Ground limestone	1.60	1.60	1.60	—	1.00	0.80
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.30	0.30	0.30	0.30	0.30	0.30
Potassium carbonate	—	—	—	—	—	0.40
Magnesium oxide	—	—	—	—	—	0.10
Analyzed composition						
DM, %	92.4	92.4	92.2	90.7	90.1	92.2
GE, kcal/kg	3,996	3,957	3,840	3,806	3,852	4,193
CP, %	12.2	10.2	13.1	10.9	19.2	24.2
Ca, %	0.57	0.76	0.67	0.89	0.54	0.38
P, %	0.31	0.54	0.39	0.42	0.27	0.003

[1]C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

[2]Fiber Sales and Development Corp., Urbana, OH.

[3]The vitamin-micromineral premix 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-α-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, 1.0 mg, and nicotinic acid, 43.0 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu as copper sulfate, 10 mg; Fe as iron sulfate, 125 mg; I as potassium iodate, 1.26 mg; Mn as manganese sulfate, 60 mg; Se as sodium selenite, 0.3 mg; and Zn as zinc oxide, 100 mg.

separated using the PDIFF option with Tukey's adjustment. The pig was the experimental unit, and an α level of 0.05 was used to determine differences among means.

Experiment 2: Phosphorus Digestibility

A total of 42 growing barrows with an initial BW of 28.3 kg (SD = 7.21) were used. Pigs were individually housed in metabolism cages equipped with a feeder and a nipple drinker. Pigs were assigned to 6 dietary treatments with 7 pigs per treatment in a randomized complete block design.

Six experimental diets were formulated (Table 3). Five diets contained C-yeast, S-yeast, brewers' yeast, fish meal, or soybean meal as the sole source of P. Sugar (15%) and cornstarch (43.3% to 69.3%) were also included in these diets. The last diet was a P-free diet that was used to estimate the basal endogenous loss of P (**EPL**; Almeida and Stein, 2010). Vitamins and minerals except P were added to all diets according to requirement estimates (NRC, 1998). All diet samples were analyzed in duplicate for DM, GE, and CP as explained in Exp. 1.

Feeding procedures, fecal collection methods, and sample preparation for analyses were the same as described for the energy experiment (Exp. 1), with the exception that urine was not collected in this experiment. Diets and fecal samples were analyzed for DM and P using inductively coupled plasma spectroscopy after wet ash sample preparation (method 985.01; AOAC International, 2007).

Values for the apparent total tract digestibility (**ATTD**) of DM and P in the 5 P-containing diets were calculated (Almeida and Stein, 2010), and because C-yeast, S-yeast, brewers' yeast, fish meal, or soybean meal was the only P-contributing ingredient in the corresponding diet, the values calculated for each diet also represent the ATTD of P for the test ingredient that was included in the diet.

The ATTD (%) of P in each diet were calculated using the following equation (Almeida and Stein, 2010):

$$\text{ATTD (\%)} = [(\text{Pi} - \text{Pf})/\text{Pi}] \times 100,$$

where Pi is the total P intake (g) from d 6 to 11 and Pf is the total fecal P output (g) from d 6 to 11.

The endogenous loss of P was estimated from pigs fed the P-free diet (Almeida and Stein, 2010). The basal EPL was calculated according to the following equation:

$$\text{EPL (mg/kg DMI)} = ([\text{Pf}/\text{Fi}] \times 1000 \times 1000),$$

where Fi is the total feed (g DM) intake from d 6 to 11. The daily EPL in pigs fed the P-containing diets were calculated by multiplying the calculated EPL per kilogram of DMI by the DMI of each pig.

By correcting the ATTD values for each diet for the endogenous losses, values for the STTD of P in each diet and ingredient were calculated using the following equation (Almeida and Stein, 2010):

$$\text{STTD (\%)} = [\text{Pi} - (\text{Pf} - \text{EPL})/\text{Pi}] \times 100.$$

Data were analyzed as described for Exp. 1.

Table 4. Energy balance of experimental diets fed to pigs (as-fed basis), Exp. 1[1]

	Diet							
Item	Corn	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal	SEM	*P*-value
Total diet intake, kg	6.02	6.11	5.98	6.18	5.91	6.06	0.180	0.928
Total fecal output, kg	0.554^{b,c}	0.704^{a}	0.676^{a,b}	0.541^{c}	0.522^{c}	0.533^{c}	0.0286	<0.001
Total urine output, kg	19.4	50.9	15.3	30.4	28.1	26.7	8.39	0.078
GE in feces, kcal/kg	4,718^{c}	5,318^{a}	4721^{c}	4,953^{b}	4,620^{c,d}	4,517^{d}	37	<0.001
GE in urine, kcal/kg	60.0	37.3	83.3	76.5	41.3	56.6	16.52	0.311
Total GE intake, kcal	22,717	25,643	25,319	24,620	23,722	23,291	736	0.049
Total GE fecal out, kcal	2,614^{c}	3,738^{a}	3,185^{a,b}	2,681^{b,c}	2,404^{c}	2,408^{c}	134	<0.001
Total GE urine out, kcal	625^{c}	1,182^{a,b}	1,007^{a,b,c}	1,429^{a}	895^{b,c}	1,013^{a,b,c}	113	<0.001
ATTD,[2] %	88.5^{a,b}	85.4^{c}	87.4^{b}	89.1^{a,b}	89.9^{a}	89.6^{a}	0.45	<0.001
DE in diet, kcal/kg	3,339^{d}	3,586^{b}	3,698^{a}	3,552^{b}	3,605^{b}	3,444^{c}	18	<0.001
ME in diet, kcal/kg	3,235^{d}	3,394^{b,c}	3,529^{a}	3,322^{c,d}	3,453^{a,b}	3,277^{d}	25	<0.001

$^{a–d}$Values without a common superscript letter within a row are different ($P < 0.05$).

[1]Each least squares mean represents 7 observations. C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

[2]ATTD = apparent total tract digestibility.

RESULTS

Composition of Ingredients

The concentration of GE was 5,103 kcal/kg in C-yeast, 4,926 kcal/kg in S-yeast, 4,524 kcal/kg in brewers' yeast, 4,461 kcal/kg in fish meal, and 4,136 kcal/kg in soybean meal (Table 1). The concentration of CP was 43.9% in C-yeast, 36.4% in S-yeast, 50.4% in brewers' yeast, 63.9% in fish meal, and 45.4% in soybean meal. The concentration of acid-hydrolyzed ether extract was 5.58% in C-yeast, 4.39% in S-yeast, 0.58% in brewers' yeast, 9.17% in fish meal, and 0.85% in soybean meal. The ash and P concentrations were 5.95% and 1.07% in C-yeast, 9.35% and 2.01% in S-yeast, 6.35% and 1.4% in brewers' yeast, 18.68% and 3.26% in fish meal, and 5.59% and 0.7% in soybean meal. C-yeast contained 18.88% total indispensable AA, 19.31% dispensable AA, and 38.19% total AA. S-yeast contained 15.19% total indispensable AA, 15.61% dispensable AA, and 30.80% total AA. Brewers' yeast contained 20.71% total indispensable AA, 21.98% dispensable AA, and 42.69% total AA. Finally, fish meal and soybean meal contained 28.55% and 19.91% total indispensable AA, 30.17% and 22.63% dispensable AA, and 58.72% and 42.54% total AA, respectively. The concentrations of NDF in C-yeast and S-yeast were 21.64% and 25.56%, respectively, but brewers' yeast and soybean meal contained only 0.40% and 10.38% NDF, respectively.

Experiment 1: Energy Measurements

The fecal output was greater ($P < 0.05$) for pigs fed the C-yeast diet than for pigs fed the corn diet, the brewers' yeast diet, the fish meal diet, or the soybean meal diet, and pigs fed the S-yeast diet also had greater ($P < 0.05$) fecal output than pigs fed the diets containing brewers' yeast, fish meal, or soybean meal (Table 4). The concentration of GE in feces from pigs fed the C-yeast diet was greater ($P < 0.05$) than that from pigs fed all other diets, and pigs fed the brewers' yeast diet had a greater ($P < 0.05$) concentration of GE in the feces than pigs fed all other diets except the C-yeast diet. Pigs fed the soybean meal diet also had a reduced ($P < 0.05$) concentration of energy in the feces compared with pigs fed the corn diet and the S-yeast diet.

Fecal energy excretion from pigs fed the C-yeast diet was greater ($P < 0.05$) than that from pigs fed the corn diet, the brewers' yeast diet, the fish meal diet, or the soybean meal diet, and fecal energy excretion from pigs fed the S-yeast diet was greater ($P < 0.05$) than that from pigs fed the corn diet, the fish meal diet, or the soybean meal diet. However, there were no differences in fecal energy excretion among pigs fed the diets based on corn, brewers' yeast, fish meal, or soybean meal. Urinary energy excretion from pigs fed the corn diet was less ($P < 0.05$) than from pigs fed the C-yeast diet and the brewers' yeast diet, and pigs fed the fish meal diet had urinary energy excretion that was less ($P < 0.05$) than that of pigs fed the brewers' yeast diet but not different from that of pigs fed the other diets.

The ATTD of energy was greater ($P < 0.05$) in the fish meal (89.9%) and soybean meal (89.6%) diets than in the C-yeast (85.4%) and S-yeast (87.4%) diets, and the ATTD of energy in the corn (88.5%) and brewers' yeast (89.1%) diets was also greater ($P < 0.05$) than in the C-yeast diet. The ATTD of energy in the S-yeast diet was greater ($P < 0.05$) than in the C-yeast diet. The DE and ME in the S-yeast diet (3,698 and 3,529 kcal/kg, respectively) were greater ($P < 0.001$) than in all other

Table 5. Energy values for ingredients fed to pigs[1]

	Ingredient							
Item[2]	Corn	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal	SEM	*P*-value
As-fed basis								
DE, kcal/kg	3,463[d]	4,119[a,b]	4,283[a]	4,015[b,c]	4,153[a,b]	3,826[c]	53	<0.001
ME, kcal/kg	3,355[c]	3,746[a,b]	4,016[a]	3,530[b,c]	3,860[a]	3,514[b,c]	71	<0.001
DM basis								
DE, kcal/kg DM	4,004[c]	4,344[a,b]	4,537[a]	4,290[b]	4,544[a]	4,362[a,b]	57	<0.001
ME, kcal/kg DM	3,879[b]	3,952[a,b]	4,255[a]	3,771[b]	4,224[a]	4,007[a,b]	76	<0.001

[a–d]Values without a common superscript letter within a row are different ($P < 0.05$).

[1]Each least squares mean represents 7 observations. C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

diets, except the ME in the S-yeast diet was not different from that in the fish meal diet. The DE and ME in the C-yeast diet (3,586 and 3,394 kcal/kg, respectively) were greater ($P < 0.05$) than in the corn diet (3,339 and 3,235 kcal/kg, respectively) and the soybean meal diet (3,444 and 3,277 kcal/kg, respectively) but were not different from value for the brewer's yeast diet (3,552 and 3,322 kcal/kg, respectively) and the fish meal diet (3,605 and 3,453 kcal/kg, respectively). The DE in the soybean meal diet was greater ($P < 0.05$) than in the corn diet but less ($P < 0.05$) than in all other diets. The ME in the corn and the soybean meal diets was also less than in all other diets except for the brewers' yeast diet.

On an as-fed basis, the DE in C-yeast (4,119 kcal/kg) and S-yeast (4283 kcal/kg) was not different from the DE in fish meal (4,153 kcal/kg) but was greater ($P < 0.05$) than the DE in corn (3,463 kcal/kg) and soybean meal (3,826 kcal/kg; Table 5). The DE in brewers' yeast (4,015 kcal/kg) was less ($P < 0.05$) than in S-yeast but greater ($P < 0.05$) than in corn and not different from the other ingredients. The DE in soybean meal was greater ($P < 0.05$) than in corn, was not different from brewers' yeast, but was less ($P < 0.05$) than in the other ingredients. The ME in C-yeast (3,746 kcal/kg) and S-yeast (4,016 kcal/kg) was not different from the ME in fish meal (3,860 kcal/kg) but was greater ($P < 0.05$) than the ME in corn (3,355 kcal/kg). The ME in soybean meal (3,514 kcal/kg) and brewers' yeast (3,530 kcal/kg) was less ($P < 0.05$) than in S-yeast and fish meal but was not different from that in the other ingredients.

On a DM basis, the DE in C-yeast (4,344 kcal/kg) was greater ($P < 0.05$) than the DE in corn (4,004 kcal/kg), and the DE in S-yeast (4,537 kcal/kg) was greater ($P < 0.05$) than the DE in corn and brewers' yeast (4,290 kcal/kg). The DE in corn was less ($P < 0.05$) than in brewers' yeast. The ME in C-yeast (3,952 kcal/kg) was not different from the ME of the other ingredients, but the ME in S-yeast (4,255 kcal/kg) was greater ($P < 0.05$) than the ME in corn (3,879 kcal/kg) and brewers' yeast (3,771 kcal/kg). No other differences among ingredients were observed when ME was calculated on a DM basis.

Experiment 2: Phosphorus Digestibility

Because of the greater concentration of P in S-yeast, the intake of P was also greater ($P < 0.05$) for pigs fed the S-yeast diet than for pigs fed C-yeast, brewers' yeast, or soybean meal diets (Table 6). The total fecal output and the DM output from pigs fed the C-yeast diet were greater ($P < 0.05$) than from pigs fed the brewers' yeast diet or the fish meal diet, but the DM concentration was greater ($P < 0.05$) in the feces from pigs fed the fish meal diet than in the feces from pigs fed the C-yeast, S-yeast, or soybean meal diet. The P concentration in the feces was also greater ($P < 0.05$) in pigs fed fish meal than in pigs fed all other diets, and pigs fed S-yeast or soybean meal had a greater ($P < 0.05$) concentration of P in the feces than pigs fed C-yeast or brewers' yeast. The total fecal P output was, however, less ($P < 0.05$) from pigs fed the brewers' yeast diet than from pigs fed the diets containing S-yeast, fish meal, or soybean meal.

The ATTD of DM in the C-yeast diet (94.1%) was less ($P < 0.05$) than in the diets containing brewers' yeast (96.0%), fish meal (96.5%), or soybean meal (95.7%). The ATTD of P for C-yeast (67.4%) was also less ($P < 0.05$) than for brewers' yeast (80.2%) but was greater ($P < 0.05$) than for soybean meal (49.7%) and not different from for S-yeast (72.0%) and fish meal (62.7%). The ATTD of P in S-yeast was greater ($P < 0.05$) than in soybean meal.

The endogenous loss of P was estimated to be 212 mg/kg DMI from pigs fed the P-free diet, and this value was used to calculate the STTD of P in each ingredient. The STTD of P was greater ($P < 0.05$) in brewers' yeast (85.2%) than in C-yeast (73.9%), fish meal (67.3%), and soybean meal (56.7%), and the STTD of P in C-yeast and S-yeast (75.7%) was also greater ($P < 0.05$) than in soybean meal. The STTD of P in fish meal was not different from the STTD of P in soybean meal.

Table 6. Digestibility of DM and P in C-yeast, S-yeast, brewers' yeast, fish meal, and soybean meal fed to pigs[1]

Item	C-yeast	S-yeast	Brewers' yeast	Fish meal	Soybean meal	SEM	*P*-value
Feed intake							
Total feed intake, g	5,099	5,165	5,060	4,836	5,356	507	0.962
Total DM intake, g	4,714	4,771	4,665	4,386	4,824	465	0.966
Total P intake, g	15.6^{b}	27.7^{a}	19.8^{b}	20.4^{a,b}	14.5^{b}	1.98	<0.001
Fecal output							
Total fecal output, g	316^{a}	246^{a,b}	191^{b}	158^{b}	222^{a,b}	28.4	0.004
DM in feces, %	91.3^{b}	91.2^{b}	93.4^{a,b}	95.8^{a}	92.6^{b}	0.71	<0.001
P in feces, %	1.66^{c}	3.14^{b}	1.98^{c}	4.67^{a}	3.26^{b}	0.114	<0.001
Total DM output, g	287^{a}	225^{ab}	178^{b}	152^{b}	206^{a,b}	25.7	0.006
Total P output, g	5.29^{a,b}	7.79^{a}	3.76^{b}	7.41^{a}	7.31^{a}	0.779	0.002
Digestibility, %							
ATTD of DM[2]	94.1^{b}	95.3^{a,b}	96.0^{a}	96.5^{a}	95.7^{a}	0.34	<0.001
ATTD of P	67.4^{b}	72.0^{a,b}	80.2^{a}	62.7^{b}	49.7^{c}	2.79	<0.001
STTD of P[2,3]	73.9^{b}	75.7^{a,b}	85.2^{a}	67.3^{b,c}	56.7^{c}	2.79	<0.001

$^{a–c}$Values without a common superscript letter within a row are different ($P < 0.05$).

[1]Each least squares mean represents 7 observations. C-yeast = yeast produced by adding *Saccharomyces cerevisiae* yeast to the solubles; S-yeast = yeast produced by adding *Pichia stipitis* yeast to the solubles.

[2]ATTD = apparent total tract digestibility; STTD = standardized total tract digestibility.

[3]Values for STTD were calculated by correcting ATTD values by the basal endogenous loss of P. The basal endogenous loss of P was 212 ± 34.5 mg/kg DMI in pigs fed the P-free diet.

DISCUSSION

Composition of Ingredients

The nutrient composition of fish meal concurs with published values (NRC, 2012; Rojas and Stein, 2013; Almaguer et al., 2014), with the exception that CP and AA concentrations in soybean meal were less than previous values (Cervantes-Pahm and Stein, 2008; Baker and Stein, 2009; Baker et al., 2014). This difference may be a result of differences among sources of soybean meal (Cromwell et al., 1999; Sotak and Stein, 2014).

There are limited data on the nutritional value of C-yeast and S-yeast. Compared with S-yeast, C-yeast had greater concentrations of GE, CP, and AA but a lower concentration of P. This difference is possibly due to differences between the 2 yeasts used in the process of producing these 2 ingredients. It has been indicated that *Saccharomyces cerevisiae* and *Pichia stipitis* exhibit different modes of metabolic regulation in glucose-containing media (Fiaux et al., 2003). Therefore, it is possible that the modified *S. cerevisiae* utilized the carbohydrates in the solubles more effectively than *P. stipitis*.

Energy

The values for DE and ME in corn that were obtained in this experiment are in very good agreement with published values (NRC, 1998, 2012; Sauvant et al., 2004; Baker and Stein, 2009). Because corn is used as the basal ingredient in all diets, an accurate estimation of the DE and ME in corn is essential for obtaining accurate values for the DE and ME in the test ingredients. The fact that the values for corn that were obtained in this experiment concur with published values gives confidence that the values obtained for the test ingredients are also reasonable.

The ME value for soybean meal that was obtained in this experiment is, however, greater than published values of 3,685, 3,681, and 3,511 kcal/kg from NRC (1998, 2012) and Sauvant et al. (2004), respectively, but is in agreement with other values (Goebel and Stein, 2011; Sotak and Stein, 2014). The reason for these differences is most likely that there are differences in the composition of soybean meal among sources (Cromwell et al., 1999; Sotak and Stein, 2014). The ME that was calculated for fish meal in this experiment is greater than previously published values of 3,360, 3,528, and 3,487 kcal/kg (NRC, 1998, 2012; Sauvant et al., 2004). The DE value that was calculated for brewers' yeast in this experiment is also greater than the value of 3,798 kcal/kg reported by Sauvant et al. (2004). The reason for these differences among published values is most likely that there is some variation in the concentration of energy-containing nutrients among batches of the same ingredient.

Information about DE and ME values of yeast products for pigs is limited, although the use of yeast single-cell protein in pig diets was studied more than 30 yr ago (Pearson et al., 1978). The greater excretion of GE in the urine from pigs fed the diets containing the yeast products, fish meal, or soybean meal compared with that from pigs fed the corn diet indicates that these diets contained more CP. The increased excretion of GE in feces from pigs fed diets containing the C-yeast or S-yeast compared with that from pigs fed the diet containing brewers'

yeast indicates that C-yeast and S-yeast contained much more ADF and NDF than the brewers' yeast.

The DE and ME values in the C-yeast and S-yeast obtained in the present study are greater than previously reported values from a yeast single-cell protein that was produced using British Petroleum's technology (Pearson et al., 1978). However, we are not aware of any other information on the DE and ME of yeast products. The fact that the DE and ME in C-yeast and S-yeast are similar to or greater than than values obtained for in brewers' yeast, fish meal, and soybean meal indicates that both of these sources of yeast are good energy sources if they are included in diets fed to pigs. The main reason for this observation is the relatively high concentration of acid-hydrolyzed ether extract in these 2 yeast products (5.58% in C-yeast and 4.39% in S-yeast) compared with the concentration in brewers' yeast (0.58%) and soybean meal (0.85%). On the basis of these observations, it is expected that the DE and ME of a mixed diet will not be changed if C-yeast or S-yeast is included in the diet at the expense of other protein-containing ingredients.

Phosphorus

The ATTD of P in fish meal in the present study was less than the value reported by Sauvant et al. (2004) and NRC (2012). The ash concentration (18.7%) for the fish meal used in this experiment indicates that a large proportion of this fish meal is fish bones because the concentration of ash in whole menhaden fish is approximately 5.5% (Deegan, 1986). It has been demonstrated that the ATTD of P in meat and bone meal is reduced if the concentration of bones increases because P in bone tissue has a reduced digestibility compared with P in bone tissue (Hua et al., 2005; Sulabo and Stein, 2013). Therefore, a possible reason for the relatively poor ATTD of P in the fish meal used in the present experiment is the high concentration of bone. It is also possible that the relatively high Ca concentration in fish meal may have slightly reduced the ATTD of P in fish meal, but because no limestone was added to the fish meal diet, it was not possible to reduce the concentration of Ca in this diet. As a consequence, all diets were formulated to have a Ca:P ratio that was similar to that in the fish meal diet. However, soybean meal in the present study had greater ATTD of P than the values of 32% and 39% reported by Sauvant et al. (2004) and NRC (2012), respectively, but both the ATTD and STTD of P obtained for soybean meal in this experiment are in agreement with the values of 56% and 62% reported by Rodríguez et al. (2013) and are also reasonably close to the values of 41% and 49% reported by Almeida and Stein (2010). It is therefore unlikely that the Ca:P ratios used in this experiment negatively influenced the values for ATTD of P that were observed.

The ATTD and STTD of P in brewers' yeast obtained in this experiment are greater than the values published by Bünzen et al. (2008), but we are not aware of other published values for the ATTD and STTD of P in brewers' yeast. The fact that we obtained values for the ATTD and STTD of P in C-yeast and in S-yeast that were in good agreement with the values obtained for brewers' yeast indicates that all of these yeast products are excellent sources of digestible P if included in diets fed to pigs. The greater ATTD and STTD of P in these 3 yeast products than in soybean meal also demonstrate that P in these products is well digested by pigs.

The basal endogenous loss of P that was determined in this experiment (212 mg/kg DMI) is in very good agreement with previous values (207 mg/kg DMI in Stein et al., 2006; 211 mg/kg DMI in Widmer et al., 2007; 199 mg/kg DMI in Almeida and Stein, 2010). The STTD of P was approximately 6.5% units greater than the ATTD of P in C-yeast (73.9% vs. 67.4%), whereas in S-yeast, the STTD was only 3.7% percentage units greater than the ATTD of P (75.7% vs. 72.0%). The reason for this observation is that the concentration of P in C-yeast is less than that in S-yeast. The relative contribution of endogenous P to the total P output is therefore greater in pigs fed the C-yeast than in pigs fed the S-yeast. The relatively high concentration of P in S-yeast further indicates that inclusion of S-yeast in the diet will provide a relatively large amount of digestible P. However, the concentration of Ca in both C-yeast and S-yeast is very low compared with fish meal, which makes it necessary to add more limestone to diets containing these yeast sources than to diets containing fish meal.

In conclusion, the ME values in C-yeast and S-yeast are similar to or greater than the ME values in corn, fish meal, and soybean meal. It is therefore likely that these ingredients can be successfully included in diets fed to pigs, and it is not necessary to fortify diets with extra energy if C-yeast or S-yeast is used instead of other protein sources. The STTD of P was greater in C-yeast and S-yeast than in soybean meal, which indicates that the inclusion of inorganic P can be reduced if C-yeast or S-yeast is used in pig diets. However, the concentration of Ca in both yeast sources is very low. In addition, C-yeast and S-yeast have AA concentrations that are slightly lower than than in brewers' yeast.

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