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The soybean oil equivalency of soybean meal indicates a high energy value of soybean meal when fed to growing pigs

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Abstract

An experiment was conducted to test the hypothesis that the energy in soybean meal (SBM) fed to pigs determined using a fat equivalency procedure is greater than current book values for net energy (NE). A total of 120 growing pigs were allotted to five dietary treatments. A diet based on corn, soy protein concentrate (SPC), and synthetic cellulose and three diets containing 2%, 4%, or 6% soybean oil (SBO) were formulated. A fifth diet that contained corn, SPC, and 12% SBM, but no SBO, was also formulated. Pigs were fed experimental diets for four weeks and daily gain, daily fed intake, and gain-to-feed ratio (G:F) were calculated. Regression of G:F for pigs fed diets without SBM against the increasing levels of SBO was used to create an equation to predict the response in G:F of adding SBO to the diets. Results demonstrated that G:F increased (linear, $P < 0.001$) by increasing SBO in the diets and the G:F of pigs fed the diet containing 12% SBM corresponded to a diet containing 4.70% SBO, which is equivalent to 2955 kcal NE per kg. In conclusion, the NE of SBM in diets for pigs is greater than previously thought.

Key words: net energy, pigs, soybean meal, soybean oil

Introduction

The most expensive component in swine diets is energy, and lipids are often included in diets for pigs due to their high energy content (Patience et al. 2015). Increasing the concentration of fat in diets improves dietary energy, growth performance, and gain-to-feed ratio (G:F) of pigs, but at the same time, dietary fat increases diet costs (Shurson et al. 2015). Therefore, accuracy in determining the energy provided by each ingredient is necessary to evaluate the tradeoff between growth performance and diet costs.

Soybean meal (SBM) is the primary source of amino acids (AA) in diets for pigs in most pig-producing countries in the world, and the net energy (NE) of SBM has been reported as 2087 kcal/kg (NRC 2012). However, results of recent research indicated that the NE of SBM is greater than this value (Li et al. 2017; Cemin et al. 2020). Improvements in feed efficiency with increasing levels of SBM in the diet have also been reported (Moran et al. 2017), which indicates that modern genotypes of pigs have a greater ability to utilize energy in SBM than previously thought and that NRC (2012) may underestimate the NE of SBM. Previously, the NE of SBM was determined using indirect calorimetry (Li et al. 2017) or estimated from G:F in pigs used in growth assays (Cemin et al. 2020). However, because the NE of soybean oil (SBO) is well defined, it is also possible to calculate the energy value of a feed ingredient in terms of SBO equivalency using G:F as the response variable, but to our knowledge, this approach has not been used to estimate the energy value of SBM. Therefore, the objective of this experiment was to test the hypothesis that the energy value of SBM is greater than the current NRC (2012) value and that the useable energy in SBM can be calculated from a regression equation that predicts the G:F response of pigs fed diets with different levels of dietary SBO.

Materials and methods

The protocol for the experiment was approved by the Institutional Animal Care and Use Committee at the University of Illinois, Urbana-Champaign, USA. Pigs used in the experiment were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

Pigs and housing

A total of 120 growing pigs (initial body weight: 24.76 ± 3.07 kg) were used in a 4-week experiment. Pigs were randomly allotted to five dietary treatments with two pigs per pen (one barrow and one gilt) for a total of 12 replicate pens per treatment. Pens (0.9 m × 1.8 m) had fully slatted concrete floors, a feeder, and a cup waterer. Feed and water were available at all times, and all diets were fed in a meal form. Experimental diets were formulated based on corn, soy protein concentrate (SPC; Stutzman's Feed & Supply, Arthur, IL, USA), and synthetic cellulose (Solka Floc, J.

Table 1. Ingredient composition of experimental diets, as-is basis.

Item	No SBM				
SBO, %:	0	2	4	6	SBM, 12%
Ingredient, %					
Ground corn	70.03	70.03	70.03	70.03	70.03
Soybean meal, 46% crude protein	–	–	–	–	12.00
Soy protein concentrate	14.38	14.38	14.38	14.38	14.38
Solka floc[a]	12.00	10.00	8.00	6.00	0.89
Soybean oil	–	2.00	4.00	6.00	–
L-Lys·HCl, 78.8%	0.40	0.40	0.40	0.40	–
DL-Met, 99%	0.12	0.12	0.12	0.12	–
L-Thr, 99%	0.13	0.13	0.13	0.13	–
L-Trp, 99%	0.03	0.03	0.03	0.03	–
L-Val, 99%	0.02	0.02	0.02	0.02	–
Dicalcium phosphate	1.25	1.25	1.25	1.25	1.00
Ground limestone	0.74	0.74	0.74	0.74	0.80
Sodium chloride	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[b]	0.50	0.50	0.50	0.50	0.50
Total	100	100	100	100	100
Analyzed nutrients[c]					
Dry matter, %	88.79	89.17	89.11	89.02	87.66
Ash, %	3.03	3.07	3.04	3.17	4.33
Gross energy, kcal/kg	3848	4014	4142	4224	3914
Crude protein, %	15.36	15.99	15.80	16.01	20.44
Acid hydrolyzed ether extract, %	2.78	4.58	6.63	8.12	2.89
Indispensable amino acids, %					
Arg	0.87	0.93	0.97	0.92	1.33
His	0.39	0.42	0.43	0.41	0.56
Ile	0.65	0.70	0.72	0.67	0.94
Leu	1.34	1.44	1.44	1.42	1.83
Lys	1.13	1.15	1.12	1.09	1.16
Met	0.30	0.32	0.33	0.32	0.30
Phe	0.72	0.78	0.79	0.76	1.04
Thr	0.64	0.64	0.67	0.65	0.74
Trp	0.19	0.20	0.21	0.19	0.21
Val	0.75	0.80	0.81	0.76	1.00
Dispensable amino acids, %					
Ala	0.77	0.81	0.82	0.82	1.06
Asp	1.42	1.47	1.57	1.45	2.08
Cys	0.24	0.24	0.26	0.24	0.32
Glu	2.63	2.80	2.88	2.76	3.75
Gly	0.59	0.61	0.64	0.60	0.86
Pro	0.96	1.01	1.01	1.01	1.30
Ser	0.60	0.63	0.68	0.65	0.89
Tyr	0.43	0.46	0.48	0.48	0.67
Total amino acids, %	14.62	15.41	15.83	15.2	20.04

Note: SBO, soybean oil; SBM, soybean meal.
[a]J. Rettenmaier USA LP., Schoolcraft, MI, USA.
[b]The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10 622 IU; vitamin D_3 as cholecalciferol, 1660 IU; vitamin E as DL-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine hydroiodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.
[c]Crude protein was calculated by multiplying analyzed nitrogen by 6.25.

Rettenmaier, MI, USA; Tables 1 and 2). Diets were formulated to meet current estimates for nutrient requirements for 25–50 kg pigs (NRC 2012). The basal diet contained corn, SPC, and 12% synthetic cellulose, and this diet contained no SBO, but synthetic Lys, Met, Thr, Trp, and Val were included in the diet to meet the requirement for digestible

Table 2. Analyzed nutrient composition of ingredients, as-is basis.

Item	Corn	SBM	Soy protein concentrate
Dry matter, %	87.46	89.66	91.88
Ash, %	1.26	6.41	5.01
Gross energy, kcal/kg	3784	4101	4629
Crude protein, %	7.48	45.76	64.74
Acid hydrolyzed ether extract, %	3.37	1.05	2.99
Indispensable amino acids, %			
Arg	0.22	3.35	4.55
His	0.14	1.08	1.40
Ile	0.19	2.15	3.09
Leu	0.84	3.32	5.36
Lys	0.20	3.16	3.79
Met	0.15	0.76	1.01
Phe	0.29	1.41	4.38
Thr	0.25	2.06	2.32
Trp	0.03	0.56	0.78
Val	0.30	2.43	2.84
Dispensable amino acids, %			
Ala	0.70	1.66	2.92
Asp	0.44	5.11	7.38
Cys	0.11	0.10	0.62
Glu	1.28	8.44	11.82
Gly	0.21	2.09	2.85
Pro	0.56	2.43	3.48
Ser	0.28	2.06	3.03
Tyr	0.25	1.79	1.96
Total amino acids, %	6.43	43.95	63.56

Note: SBM, soybean meal.

indispensable AA. Three additional diets were formulated by adding 2.0%, 4.0%, or 6.0% SBO to the basal diet. A fifth diet containing corn, SPC, and 12% SBM, but only 0.89% synthetic cellulose and no SBO or synthetic AA, was also formulated. Individual pig weights were recorded at the beginning of the experiment and at the conclusion of the experiment. Feed addition was recorded daily, and the weight of feed left in the feeder was recorded at the conclusion of the experiment. At the end of the 28-day experiment, pig weight and feed allowance data were summarized and used to calculate total feed consumption, average daily gain (ADG), average daily feed intake (ADFI), and G:F for each pen and treatment group.

Chemical analysis

All diet and ingredient samples were ground using a 500G stainless steel swing-type mill grinder (Model RRH-500, Zhejiang Winki Plastic Industry Co., Ltd., Zhejiang, China) prior to chemical analyses. Diet and ingredient samples were analyzed for dry matter (method 927.05; AOAC Int. 2019) and ash (method 942.05; AOAC Int. 2019). Gross energy was analyzed using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL, USA). Benzoic acid was used for standard calibration. The concentration of nitrogen was analyzed by combustion (method 990.03; AOAC Int. 2019) using a LECO FP628 analyzer (LECO Corp., Saint Joseph, MI, USA) with subsequent calculation of crude protein as nitrogen × 6.25. All diets and ingredients were analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc.; Pleasanton, CA, USA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C (method 982.30 E(a); AOAC Int. 2019). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E(b); AOAC Int. 2019). Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C (method 982.30 E(c); AOAC Int. 2019). Ingredients and diets were also analyzed for acid hydrolyzed ether extract using the acid hydrolysis filter bag technique (Ankom HCl Hydrolysis System; Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (method 2003.06, AOAC Int. 2019) in an AnkomXT15 Extractor (Ankom Technology).

Statistical analysis

Data were analyzed using the MIXED procedure (SAS Inst. Inc., 2023) with the pen as the experimental unit. Model assumptions of the residuals were confirmed using the MIXED procedure and the Brown–Forsythe test of the GLM procedure of SAS. Outliers were detected using the ROBUSTREG procedure and were removed before final statistical analyses. Two outliers were removed from the diet containing no SBO and no SBM. Linear and quadratic effects of increasing dietary SBO were determined using orthogonal polynomial CONTRAST statements. For all treatments, means were calculated and separated using the LSMEANS statement and the PDIFF option of PROC MIXED, respectively. Statistical significance and tendencies were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively. A *t*-test was used to compare the effect of the diet containing 12% SBM and no SBO with the diet containing no SBO and no SBM. A regression equation to estimate the improvement in G:F that was observed for pigs fed the diet containing SBM against the levels of dietary oil (i.e., 0%, 2%, 4%, or 6%) was developed using the REG procedure in SAS, with SBO as the independent variable. Using the developed equation, the SBO level that corresponded to the G:F of pigs fed the diet containing SBM was calculated. By assuming an NE of 7545 kcal/kg in SBO (NRC 2012), the corresponding NE in SBM was calculated.

Results

The final body weight of pigs increased (quadratic, $P < 0.05$) as SBO increased in diets containing no SBM (Table 3). However, the weight of pigs was not different for pigs fed the diets containing 12% SBM compared with the weight of pigs fed the diet without SBO oil and no SBM. Increasing SBO in the diets increased (quadratic, $P < 0.001$) ADG, and pigs fed the diet containing SBM had a greater ($P < 0.001$) ADG than pigs fed the diet with no SBO or SBM. ADFI decreased (quadratic, $P < 0.001$) as dietary SBO increased, but G:F increased (linear,

Table 3. Overall growth performance of pigs fed diets containing 0%, 2%, 4%, or 6% soybean oil (SBO) and 12% soybean meal (SBM)[a].

							Contrast P-value			
Item	No SBM				SBM, 12%		No SBM		SBO vs. SBO + SBM	
SBO, %:	0	2	4	6	0	Pooled SEM	Linear	Quadratic	Pooled SEM	P-value
Initial BW[b], kg	24.69	24.78	24.67	24.64	24.78	—	—	—	—	—
ADG[b], kg	0.84	0.80	0.76	0.88	0.94	0.05	0.198	<0.001	0.03	0.005
ADFI[b], kg	1.79	1.62	1.48	1.62	1.80	0.14	0.001	<0.001	0.09	0.849
G:F[b]	0.47	0.50	0.51	0.55	0.53	0.02	<0.001	0.795	0.02	0.004
Final BW, kg	48.14	47.04	45.85	49.39	51.18	3.84	0.451	0.003	1.92	0.249

[a]Least square means represent 12 observations, except for the diet containing no SBO and no SBM (n = 10).
[b]BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain-to-feed ratio.

Table 4. Regression coefficients used for estimating gain-to-feed ratio (G:F) response of including soybean oil (SBO) in diets[a,b].

		Standard error		P-value		Statistical parameter		
Dependent variable	Prediction equation	Intercept	Slope	Intercept	Slope	R^2	RMSE	P-value
G:F	0.468 + 0.013 (SBO, %)	0.009	0.002	<0.001	<0.001	0.406	0.034	<0.001

[a]Data were subjected to linear regression analysis with the % inclusion of SBO as the independent variable and G:F as the dependent variable. The regression coefficients indicate the change in G:F for each % point change of SBO included in the diet.
[b]RMSE, root means square of error; R^2 = coefficient of determination.

Table 5. Soybean oil equivalence (%) of soybean meal (SBM) in the diet containing 12% SBM[a].

	12% SBM
Item	0% SBO
Gain-to-feed ratio	0.528
SBO equivalence, %	4.70

Note: SBO, soybean oil.
[a]Equivalence was calculated from the prediction equation [0.468 + 0.013 (SBO, %); Table 4] used to estimate the corresponding SBO inclusion for a given gain-to-feed ratio in SBO.

P < 0.001) as SBO increased in diets containing no SBM. However, addition of 12% SBM to the diet without SBO increased (P < 0.001) G:F of pigs.

A prediction equation for G:F of pigs fed the four diets containing no SBM, and from 0% to 6% SBO, was developed (Table 4). Results indicated that G:F increased (P < 0.001) by 0.013 for each percentage unit increase in SBO inclusion in the diet. From the prediction equation, it was calculated that the G:F of pigs fed the diet with 12% SBM was equivalent to that of pigs fed a diet containing 4.70% SBO (Table 5).

Discussion

Soybean meal is the most commonly used protein source in diets for pigs due to its excellent AA profile and favorable digestibility of AA (Cervantes-Pahm and Stein 2008). However, besides providing AA, SBM also provides other nutrients and energy to the diet. Although it is not a nutrient, energy is necessary for all biological processes in pigs. Because most of the variable costs in swine production are related to diet cost (Patience et al. 2015), and because energy is the costliest component of diets, accurate estimation of feed energy values may reduce production costs (Noblet et al. 1994; Kil et al. 2013). The NE in SBM is around 77% of the NE in corn according to current book values, which corresponds to 2319 kcal/kg DM (Sauvant et al. 2004; Rostagno et al. 2011; NRC 2012). However, Sotak-Peper et al. (2015) calculated the NE of 22 sources of SBM from determined values for digestible energy and concluded that the average NE in SBM was around 2467 kcal/kg DM. Likewise, Li et al. (2017) conducted an experiment using indirect calorimetry and determined that the NE of SBM was 2710 kcal/kg DM. Results from an experiment conducted under commercial conditions that used caloric efficiency to estimate the energy in SBM indicated that the energy value of SBM ranges between 105% and 125% of the NE in corn, which correspond to NE values of 3171 to 3752 kcal/kg DM, respectively (Cemin et al. 2020). Thus, results of all recently conducted experiments indicate that current book values may significantly underestimate the NE of SBM. To address this uncertainty, the current research aimed to determine the energy value of SBM using G:F as the response variable. Because the NE in SBO is well-defined and has been measured by indirect calorimetry and prediction equations (NRC 2012; Li et al. 2018), and growth assays to test the energetic values of ingredients have been conducted (Boyd et al. 2010; Cemin et al. 2020), we calculated the energy value of SBM as the SBO equivalency using G:F as the response variable. To our knowledge, estimation of the SBO equivalency of SBM using G:F as the response criteria has not been reported before, but it is recognized that this approach does not take possible changes in body composition into account. Changes in body composition may influence feed efficiency (Campbell and Taverner 1988), and values obtained from this procedure are not always equivalent to NE values determined using indirect calorimetry.

The analyzed AA composition of ingredients and diets were within the expected values and consistent with calculated values (NRC 2012). Likewise, by removing the synthetic AA from the SBM containing diet, it was possible to formulate all diets with equivalent concentrations of the limiting indispensable AA. The basal diet was formulated to contain 12% synthetic cellulose and increasing concentrations of SBO were included at the expense of synthetic cellulose. Dietary fiber is resistant to digestion by the enzymes of pigs, and fermentation of non-digested nutrients in the hindgut can be a source of energy for the pigs. However, the source of synthetic cellulose used in the current experiment is completely unfermentable and contributes no energy to the diet (Cervantes-Pahm et al. 2014). Dietary fiber can contribute to the loss of endogenous lipids, which can decrease the apparent digestibility of lipids (de Lange 2000; Urriola et al. 2013). However, cellulose consists of sugars arranged in a crystalline, straight-chain structure, which limits its accessibility to microbial degradation and reduces its interaction with dietary fats, minimizing its effect on fat digestibility (Ndou et al. 2019). Additionally, increasing levels of purified cellulose do not significantly affect lipid digestibility, suggesting that the simplified chemical structure of purified fiber is less likely to interfere with lipid digestion (Kil et al. 2010). The calculated metabolizable energy was 2926, 3098, 3269, and 3441 kcal/kg in the diets containing 0%, 2%, 4%, and 6% SBO, respectively (NRC 2012). The linear increase in G:F of pigs fed the diets with increasing concentrations of SBO is likely a result of the increased energy density of the diets containing SBO. This effect was expected and has been demonstrated in previous research (Kil et al. 2011; Adeola et al. 2013; Espinosa et al. 2021). Therefore, by including four levels of SBO in the diets, it was possible to establish a regression equation that could be used to calculate the response in G:F of SBM (Espinosa et al. 2021).

The observation that addition of SBM to the diet with no SBO increased ADG of pigs is in agreement with data indicating that partially or fully replacing crystalline AA with SBM may improve growth performance of pigs (Holen et al. 2022). In the current experiment, concentrations of indispensable AA met or exceeded requirements for 25–50 kg pigs (NRC 2012). Diet analysis indicated that the concentration of the first limiting AA in the SBM diet was not greater than in the diets without SBM because the synthetic AA were removed from the SBM diet, but all diets met requirements. Therefore, the increase in G:F of pigs fed the diet containing 12% SBM and no SBO compared with the diet containing no SBM, and no SBO was not due to an increase in limiting AA in the diets. It may be speculated that the fiber in the diet with no SBM would increase passage rate. This could theoretically reduce digestibility of energy and nutrients, which could be a reason for the difference between the two diets, but because we did not measure passage rate, we cannot confirm this hypothesis. However, the inclusion rate of high-fiber ingredients in diets for growing pigs did not impact the energy value of the ingredients (Navarro et al. 2018) and it is, therefore, unlikely that differences in the concentration of fiber among diets impacted energy digestibility.

The observation that G:F of pigs fed the diet containing 12% SBM corresponded to an inclusion of 4.70% SBO indicates that NE under the condition of this experiment was close to 2955 kcal per kg, assuming that the NE of SBO reported by the NRC (2012) is accurate. This value is much greater than current book values (Sauvant et al. 2004; Rostagno et al. 2011; NRC 2012), but a greater NE in SBM than current book values has been reported numerous times in recent years, indicating that the energy value of SBM is underestimated in current feed tables (Sotak-Peper et al. 2015; Li et al. 2017; Cemin et al. 2020; Lee et al. 2021). However, as mentioned above, energy estimations of SBM using changes in G:F may overestimate NE because possible changes in body composition of pigs are not taken into account, which may explain why the value obtained in the current experiment may be different from NE values obtained from pigs placed in calorimeter chambers. The current experiment was conducted with only one source of SBM containing 46% protein. Soybean meals vary in composition due to differences in residual oil, dehulling, and processing methods, which may affect nutrient composition and energy digestibility. Although only minor variability among different sources of SBM in digestible energy and metabolizable energy is observed (Sotak-Peper et al. 2015), it cannot be ruled out that a different response would be obtained if a different source of SBM was used. Nevertheless, because results from this and other recently conducted experiments demonstrated a greater energy value in SBM than book values, and because no experiments observed NE in SBM to be less than book values, there is strong evidence that the NE in SBM is currently being underestimated. This conclusion is supported by results from recently published experiments in which it was observed that the NE of corn-SBM diets were greater than those calculated from ingredient NE values (NRC 2012; Kim et al. 2020; Lyu et al. 2023; Ibagon et al. 2024; Lee et al. 2024; Ochoa et al. 2024). Assuming that the NE of corn is accurate, these results support the hypothesis that SBM contributes more NE to the diets than previously estimated.

Conclusion

Results of this experiment indicate that the overall G:F of pigs increased as SBO increased in diets containing no SBM. From the prediction equation, it was calculated that the G:F of pigs fed the diet containing 12% SBM corresponded to that of a diet containing 4.70% SBO. Assuming there is 7545 kcal NE per kg in SBO, this corresponds to an NE value of 355 kcal/kg from 12% SBM, which corresponds to 2955 kcal NE per kg SBM.

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Data availability

All data from this research are included in the manuscript.

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Author notes

Su A Lee served as Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by another editorial board member.

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Investigation: JAI, HHS, SAL
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Supervision: HHS, SAL
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Competing interests

The authors have no real or perceived conflicts of interest.

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