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Original Research Article

Evaluation of energy values of high-fiber dietary ingredients with different solubility fed to growing pigs using the difference and regression methods

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ABSTRACT

The objective of this study was to compare the energy values of high-fiber dietary ingredients with different solubility (sugar beet pulp [SBP] and defatted rice bran [DFRB]) in growing pigs using the difference and the regression methods. A total of 21 barrows (initial BW, 40.5 ± 1.2 kg) were assigned to 3 blocks with BW as a blocking factor, and each block was assigned to a 7 × 2 incomplete Latin square design with 7 diets and two 13-d experimental periods. The 7 experimental diets consisted of a corn-soybean meal basal diet and 6 additional diets containing 10%, 20%, or 30% SBP or DFRB in the basal diet, respectively. Each of the experimental periods lasted 12 d, with a 7 d dietary adaptation period followed by 5-d total fecal and urine collection. Results showed that the digestible energy (DE) and metabolizable energy (ME) of the SBP determined by the difference method with different inclusion levels (10%, 20%, or 30%) were 2,712 and 2,628 kcal/kg, 2,683 and 2,580 kcal/kg, and 2,643 and 2,554 kcal/kg DM basis, respectively. The DE and ME in the DFRB evaluated by the difference method with 3 different inclusion levels were 2,407 and 2,243 kcal/kg, 2,687 and 2,598 kcal/kg, and 2,630 and 2,544 kcal/kg DM basis, respectively. Different inclusion levels had no effects on the energy values of each test ingredient estimated by the difference method. The DE and ME of the SBP and the DFRB estimated by the regression method were 2,562 and 2,472 kcal/kg and 2,685 and 2,606 kcal/kg DM basis, respectively. The energy values of each ingredient determined by the regression method were similar to the values estimated by the difference method with the 20% or 30% inclusion level. However, the energy values of the SBP and DFRB estimated by the difference method with the 10% inclusion level were inconsistent with the values determined by the regression method ($P < 0.05$). In conclusion, the regression method was a robust indirect method to evaluate the energy values for high-fiber ingredients with different solubility in growing pigs. If the number of experimental animals was limited, the difference method with a moderate inclusion level (at least 20%) of the test high-fiber ingredient in the basal diet could be applied to substitute the regression method.

1. Introduction

An increasing use of high-fiber feed ingredients in swine diets has been observed over the last decade, and this is expected to continue in the future (Zijlstra and Beltranena, 2013; Woyengo et al., 2014; Zou et al., 2020). The cost of ingredients that supply energy for pigs contributes the largest portion of total feed costs, and therefore, an accurate estimation of energy values for high-fiber ingredients can reduce the costs of pig production (Noblet et al., 1994; Kil et al., 2013). The energy concentration of diets fed to pigs is widely evaluated using digestible energy (DE) or metabolizable energy (ME) systems

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(Noblet and Van Milgen, 2004; NRC, 2012; Kong and Adeola, 2014). However, it is not possible to feed high-fiber feed ingredients to pigs as the only source of energy in a test diet, due to low palatability and anti-nutritional factors (Kong and Adeola, 2014; Zhang and Adeola, 2017). Therefore, the difference method and the regression method are 2 classic indirect methods used to determine the DE and ME values of high-fiber feed ingredients (Adeola et al., 2001; Zhang and Adeola, 2017). The basic assumption in the use of the difference and regression method is that there is no energy digestibility interaction between the test ingredient and the basal diet (Adeola et al., 2001; Kong and Adeola, 2014; Zhang and Adeola, 2017). However, sometimes this assumption might be not true. It has been found that the energy values of some ingredients determined by the difference method with a specific inclusion level are different from the energy values with other inclusion levels or by the regression method (Villamide et al., 1991; Huang et al., 2013; Zhao et al., 2018a, 2018b). This may be due to different test ingredients or the differences in the procedures using indirect methods. Therefore, the difference and regression methods are not suitable for all ingredients. The physical–chemical properties (solubility, viscosity, and fermentability) of dietary fiber could affect the energy utilization and nutrients digestibility in swine diets, and the viscosity and fermentability of the ingredient are correlated with the solubility of dietary fiber (Gao et al., 2015; Chen et al., 2017; Navarro et al., 2019). Thus, we hypothesized that the solubility of dietary fiber might affect the energy values of the ingredients determined by the regression method or by the difference method with different inclusion levels.

Sugar beet pulp (SBP) and defatted rice bran (DFRB) are commonly used high-fiber dietary ingredients in swine diets, however the solubility of dietary fiber from these 2 ingredients is different. The SBP is a soluble dietary fiber (SDF)-rich ingredient, whereas the DFRB is an insoluble dietary fiber (IDF)-rich ingredient (NRC, 2012; Flis et al., 2017; Nguyen et al., 2019). Therefore, the objective of this study was to compare the energy values of SBP and DFRB, determined by the regression method and the difference method, with different dietary ingredient inclusion levels in the basal diet fed to growing pigs.

2. Materials and methods

The experimental procedures were approved by the Experimental Animal Welfare and Ethical Committee of the Institute of Animal Science, Chinese Academy of Agriculture Sciences (Ethics Approval Code: IAS 2019-32).

2.1. Ingredients and diets

Nutrient and gross energy (GE) contents of the SBP and DFRB were determined in the present study (Table 1). Dietary treatments consisted of a corn-soybean meal (CSBM) diet and 6 test diets. The CSBM diet was formulated to contain corn, soybean meal (SBM), and soybean oil as the sources of energy to meet or exceed the energy requirements of growing pigs (NRC, 2012). In 6 additional test diets, each with solubility type of high-fiber ingredients (SBP or DFRB) were added at 10%, 20%, or 30% of diets, respectively, to partly replace corn, SBM, and soybean oil of the CSBM diet in such a way as to maintain the same ratio of corn, SBM, and soybean oil across all experimental diets (Table 2).

2.2. Animals, housing, and experimental design

A total of 21 Duroc × Landrace × Yorkshire barrows (initial BW = 40.5 ± 1.3 kg) were assigned to 3 blocks based on the individual BW. Each block was assigned to a 7 × 2 incomplete Latin square design with 7 diets and two 13-d experimental periods. Daily feed intake of each pig was calculated as 4% of their corresponding initial BW at the beginning of each period, and 1 of 2 equal portions of a daily feed allowance was administered at 08:00 and 16:00 (Liu et al., 2018).

Table 1
Analyzed composition of sugar beet pulp and defatted rice bran (%, as-fed basis).

Item	Sugar beet pulp	Defatted rice bran
Dry matter	93.39	91.06
Organic matter[1]	83.11	80.53
Crude protein	9.58	16.80
Ether extract	2.80	3.34
Neutral detergent fiber	38.56	23.05
Acid detergent fiber	21.49	9.63
Ash	10.28	10.53
Total dietary fiber (TDF)	61.68	32.02
Insoluble dietary fiber	45.53	30.44
Soluble dietary fiber (SDF)[1]	16.15	1.58
SDF:TDF ratio	26.18	4.93
Gross energy, kcal/kg	3,623	3,834

[1] Calculated values.

All pigs were housed in stainless-steel metabolism crates (1.2 m × 1.5 m) equipped with feeders and low-pressure waterers. Room temperature was maintained at 23 ± 2 °C, and humidity varied from 55% to 65% during the experiment. An adjustable screen was placed under each cage that permitted the total collection of feces and urine.

2.3. Samples collection and chemical analyses

Each experiment period lasted for 13 d, after the 7-d adaptation period, total fecal and urine collection started at 08:30 on d 8 and end at 08:30 on d 13 (Liu et al., 2020b). A preservative of 50 mL of 6 mol/L HCl was added to collection buckets placed under the metabolism crates that were used to collect the urine. Feces and urine were collected twice daily, and all the feces and a 20% subsample of the urine were stored at −20 °C until further analysis. During the collection period, feed refusals and spillage were collected twice daily and subsequently dried and weighed. Both feces and urine samples of each pig were successfully collected during the experimental periods.

Experimental diets, ingredients, and oven-dried fecal samples were ground to pass through a 0.5-mm screen before analyses. Dry matter (DM, method 934.01), crude protein (CP, Nitrogen × 6.25, method 990.03), ash (method 942.05), ether extract (EE, method 954.02), total dietary fiber (TDF, method 991.43), and IDF (method 991.43) contents of diets and samples were determined according to AOAC (2012) as previously described by Liu et al. (2020a). The organic matter (OM, %) content in the ingredients, diets, and feces was calculated according to the following equation, OM = DM − ash. The content of SDF (%) in the ingredients and diets was calculated according to the difference between TDF (%) and IDF (%). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined using filter bags and fiber analyzer equipment (Fiber Analyzer; ANKOM Technology, Macedon, NY, USA) following a modification of the procedures (Van Soest et al., 1991). GE contents in the ingredients, diets, feces, and urine samples were analyzed using an adiabatic oxygen bomb calorimeter (model 6400, Parr Instruments, Moline, IL). Benzoic acid (6,318 kcal GE/kg; Parr Instrument Co.) was used as the internal standard for calibration.

2.4. Calculations

Energy digestibility and metabolizability of experimental diets were calculated using the following equations as described by Adeola et al. (2001) and Huang et al. (2018b):

Table 2
Ingredients and analyzed nutrient compositions of the experimental diets (%, as-fed basis).

Item	Basal diet	Sugar beet pulp diet			Defatted rice bran diet		
		10%	20%	30%	10%	20%	30%
Ingredients							
Corn	67.50	60.36	53.21	46.07	60.36	53.21	46.07
Soybean meal	25.00	22.35	19.71	17.06	22.35	19.71	17.06
Soybean oil	2.00	1.79	1.58	1.37	1.79	1.58	1.37
Sugar beet pulp	0.00	10.00	20.00	30.00	0.00	0.00	0.00
Defatted rice bran	0.00	0.00	0.00	0.00	10.00	20.00	30.00
Dicalcium phosphate	1.35	1.35	1.35	1.35	1.35	1.35	1.35
Limestone	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Premix[1]	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Nutrient compositions							
Dry matter	89.68	89.37	89.91	90.14	89.26	89.46	89.64
Organic matter[2]	82.53	81.93	82.16	82.08	81.58	81.16	80.52
Crude protein	16.06	15.00	14.49	13.86	15.99	16.01	15.83
Ether extract	7.20	6.62	6.18	5.67	6.32	6.09	5.78
Neutral detergent fiber	10.37	13.77	16.38	18.07	12.99	13.99	14.58
Acid detergent fiber	3.31	5.89	7.60	9.66	4.52	5.01	5.36
Ash	7.15	7.44	7.75	8.06	7.68	8.30	9.12
Total dietary fiber (TDF)	13.92	20.39	24.99	30.64	15.97	17.81	19.56
Insoluble dietary fiber	11.82	16.17	18.68	22.35	13.45	15.02	16.62
Soluble dietary fiber (SDF)[2]	2.10	4.22	6.31	8.29	2.52	2.79	2.94
SDF:TDF ratio	15.09	20.70	25.25	27.06	15.78	15.67	15.03
Gross energy, kcal/kg	3,885	3,869	3,826	3,799	3,863	3,838	3,815

[1] Provided the following quantities per kilogram of diet: vitamin A, 9,140 IU; vitamin D_3, 4,405 IU; vitamin E, 11 IU; menadione sodium bisulfite, 7.30 mg; riboflavin, 9.15 mg; D-pantothenic acid, 18.33 mg; niacin, 73.50 mg; choline chloride, 1,285 mg; vitamin B_{12}, 200 μg; biotin, 900 μg; thiamine mononitrate, 3.67 mg; folic acid, 1,650 μg; pyridoxine hydrochloride, 5.50 mg; I, 1.85 mg; Mn, 110.10 mg; Cu, 7.40 mg; Fe, 73.50 mg; Zn, 73.50 mg; Se, 500 μg.

[2] Calculated values.

$$\text{Digestibility (\%)} = [(E_{\text{input}} - E_{\text{output}})/E_{\text{input}}] \times 100,$$

$$\text{Metabolizability (\%)} = [(E_{\text{input}} - E_{\text{output}} - E_{\text{urine}})/E_{\text{input}}] \times 100,$$

where E_{input}, E_{output}, and E_{urine} are the amount of energy ingested, and the amount of energy voided via the feces and the urine, respectively.

The DE and ME values in ingredients were calculated using the difference method according to the equations described by Adeola et al. (2001) and Huang et al. (2018b). The calculation was as follows:

$$D_{\text{ti}} = [D_{\text{td}} - (D_{\text{bd}} \times P_{\text{bd}})]/P_{\text{ti}},$$

in which D_{bd}, D_{td}, and D_{ti} are the energy digestibility (%) in the basal diet, test diets, and test ingredients, respectively, and P_{bd} and P_{ti} are the proportional contribution of the energy by the basal diet and test ingredient to the test diet, respectively. The energy metabolizability of test ingredients was also calculated using the above equation.

2.5. Statistical analysis

Data of DE, ME, and apparent total tract digestibility (ATTD) of GE and nutrients in diets were analyzed using the PROC GLM of SAS (Version 9.4, SAS Institute, Cary, NC, USA). Least squares means were calculated and separated by the PDIFF option with Tukey's adjustment. Orthogonal polynomial contrast was conducted to determine the linear and quadratic effects of the inclusion level of SBP or DFRB on the energy values of experimental diets (SBP or DFRB). Regression equations to estimate the DE and ME in the SBP and DFRB were generated using the REG procedure in SAS (Noblet et al., 1993). The dependent variables in the prediction equation were SBP- or DFRB-associated DE or ME intake (kcal, DM basis) respectively, and the independent variable was test ingredients intake (kg, DM basis). The slope from the regression equation is the actual energy value of the test ingredient. The CLB statement in SAS was used to determine the 95% confidence levels for the regression coefficients used to estimate the DE and ME in the test ingredients (Kim et al., 2018). The energy values of test ingredients determined by the difference method were considered not different from regression-derived energy values if these values were within the 95% confidence interval of the regression-derived energy values. Probability of $P < 0.05$ was considered significant.

3. Results

3.1. Nutrient composition of test ingredients and diets

The concentrations of GE and nutrients of SBP and DFRB are shown in Table 1. The concentrations of dietary fiber (NDF, ADF, TDF, IDF, and SDF) were found to be numerically greater in the SBP than those respective values in the DFRB. Further, the SDF:TDF ratio in the SBP (26.2%) was numerically greater than in the DFRB (6.5%).

The GE and EE concentration of experimental diets were numerically decreased with the increasing level from 10% to 30% in the SBP and DFRB, but the dietary fiber contents of experimental diets (NDF, ADF, TDF, and IDF) were numerically increased as the SBP and DFRB inclusion level increased (Table 2). The CP contents of SBP diets were numerically decreased, whereas SDF contents of diets were numerically increased as the inclusion level of SBP increased in the diets. The SDF:TDF ratios in the SBP diets were increased from 15.09% to 27.06%, while the ratios among the DFRB diets were similar (range from 15.03% to 15.78%).

3.2. Energy values and the ATTD of GE and nutrients of experimental diets

Compared with the CSBM diet, the addition of SBP and DFRB to the basal diet linearly decreased the ATTD of GE, DM, OM, CP, EE, and ash of experimental diets ($P < 0.05$, Table 3). In addition, the ATTD of NDF and ADF of DFRB diets were also linearly decreased with the increasing inclusion levels of the DFRB added to the CSBM diet ($P < 0.05$). On the contrary, the ATTD of NDF and ADF in the SBP diets were linearly increased as the inclusion levels of the SBP increased in the SBP diets ($P < 0.01$). No quadratic effects of dietary SBP or DFRB inclusion levels on the ATTD of GE and nutrients in experimental diets for pigs were observed.

The DE and ME were linearly decreased with the increasing inclusion ratio of SBP in CSMB diet ($P < 0.01$). Similarly, the DE and ME were linearly decreased as the DFRB inclusion level of DFRB increased in CSBM diet ($P < 0.01$). However, there were no quadratic effects of inclusion levels when SBP or DFRB was added in the diets on the DE and ME of experimental diets for pigs.

3.3. *Energy values of the test ingredients*

The DE and ME of the SBP ranged from 2,643 to 2,712 kcal/kg and from 2,554 to 2,628 kcal/kg DM basis estimated by the difference method with different inclusion levels, respectively (Table 4). The DE and ME of the DFRB ranged from 2,407 to 2,687 kcal/kg and 2,243 to 2,598 kcal/kg DM basis estimated by the difference method with different inclusion levels, respectively. Different inclusion levels had no significant effects on the energy values of each test ingredient estimated by the difference method.

Linear regression analyses were used to estimate the relationship between energy contents and the inclusion ratio of dietary SBP or DFRB, the slope from the regression equation is the actual energy value of the test ingredient (Table 5). The DE and ME of SBP estimated by the regression method were 2,562 and 2,472 kcal/kg DM basis, respectively. The DE and ME of DFRB estimated by the regression method were 2,685 and 2,606 kcal/kg DM basis, respectively. Besides, all the R^2 of the prediction equation for dietary DE and ME of SBP or DFRB were more than 0.96.

The DE and ME of test ingredients determined by the difference and regression methods were compared in Table 6. The DE and ME of the test ingredients estimated by difference method with 20% or 30% inclusion levels were within the 95% confidence intervals of

Table 3
Energy values and apparent total tract digestibility of gross energy and nutrients by pigs fed experimental diets.

Item[1]	Basal diet	Sugar beet pulp diet			Defatted rice bran diet			SEM	*P*-value				
		10%	20%	30%	10%	20%	30%		Diet	Linear[2]	Quadratic[2]	Linear[3]	Quadratic[3]
Apparent total tract digestibility, %													
Dry matter	87.18^{a}	85.41^{a,b}	84.02^{b,c}	81.60^{d,e}	83.44^{c,d}	80.95^{e}	77.47^{f}	0.48	<0.001	<0.001	0.761	<0.001	0.455
Organic matter	90.78^{a}	89.22^{a,b}	87.8^{b}	85.93^{c}	87.72^{b}	85.84^{c}	82.84^{d}	0.39	<0.001	<0.001	0.945	<0.001	0.693
Crude protein	86.70^{a}	82.61^{b}	79.04^{c,d}	75.24^{e}	83.58^{a,b}	82.22^{b,c}	78.61^{d}	0.60	<0.001	<0.001	0.738	<0.001	0.841
Ether extract	86.41^{a}	83.73^{a,b}	81.02^{a,b}	76.90^{b}	83.90^{a,b}	81.86^{a,b}	80.03^{a,b}	0.78	0.027	0.016	0.854	<0.001	0.702
Neutral detergent fiber	73.21^{a}	76.48^{a}	78.50^{a}	78.25^{a}	65.76^{b}	60.56^{b}	52.29^{c}	1.54	<0.001	<0.001	0.802	0.023	0.281
Acid detergent fiber	73.95^{b}	79.43^{a,b}	81.50^{a}	82.12^{a}	62.84^{c}	54.77^{d}	47.93^{d}	2.04	<0.001	<0.001	0.208	0.001	0.154
Ash	45.36^{a}	43.46^{a,b,c}	43.93^{a,b}	37.21^{c,d}	37.88^{b,c,d}	33.13^{d,e}	29.73^{e}	1.00	<0.001	<0.001	0.180	0.001	0.116
Gross energy	89.54^{a}	87.69^{a,b}	85.65^{c}	83.32^{d}	86.33^{b,c}	84.40^{c,d}	81.36^{e}	0.42	<0.001	<0.001	0.845	<0.001	0.593
Digestible energy, kcal/kg DM	3,880^{a}	3,796^{b}	3,644^{c}	3,512^{d}	3,737^{b}	3,621^{c}	3,462^{d}	23	<0.001	<0.001	0.683	<0.001	0.210
Metabolizable energy, kcal/kg DM	3,807^{a}	3,722^{a,b}	3,565^{c,d}	3,434^{e}	3,655^{b,c}	3,545^{d}	3,387^{e}	22	<0.001	<0.001	0.895	<0.001	0.344

^{a,b,c,d,e,f} Means in the same row with different superscripts differ ($P < 0.05$).

[1] Data are means of 6 observations.

[2] Linear and quadratic contrasts for the sugar beet pulp diet.

[3] Linear and quadratic contrasts for the defatted rice bran diet.

Table 4
Energy values of sugar beet pulp and defatted rice bran by the difference method with different inclusion level (kcal/kg, dry matter basis).

Item[1]	Inclusion level			SEM	*P*-value		
	10%	20%	30%		Inclusion level	Linear	Quadratic
Sugar beet pulp							
Digestible energy	2,712	2,683	2,643	82	0.949	0.751	0.975
Metabolizable energy	2,628	2,580	2,554	85	0.943	0.74	0.952
Defatted rice bran							
Digestible energy	2,407	2,687	2,630	92	0.452	0.345	0.407
Metabolizable energy	2,243	2,598	2,544	142	0.572	0.410	0.517

[1] Data are means of 6 observations.

Table 5
Regression coefficients used for estimating digestible energy and metabolizable energy in sugar beet pulp and defatted rice bran (dry matter basis).

Item[1]	Regression equations	RMSE	R^2	Slope		Intercept	
				SEM	*P*-value	SEM	*P*-value
Sugar beet pulp							
Digestible energy, kcal/kg	$Y = 2{,}562 \times X + 0$	33	0.99	61	<0.001	11	0.987
Metabolizable energy, kcal/kg	$Y = 2{,}472 \times X + 0$	35	0.99	64	<0.001	12	0.986
Defatted rice bran							
Digestible energy, kcal/kg	$Y = 2{,}685 \times X - 10$	43	0.98	78	<0.001	15	0.518
Metabolizable energy, kcal/kg	$Y = 2{,}606 \times X - 13$	60	0.96	110	<0.001	21	0.541

RMSE = root-mean-square error.

[1] Y is test ingredient-associated digestible energy and metabolizable energy intake in kilocalories, X is test ingredient intake in kilograms (DM basis), the intercept is in kilocalories, and the slopes are in kilocalories per kilogram DM.

Table 6

Energy values of sugar beet pulp and defatted rice bran by the difference method with different inclusion levels or estimated from the regression method (dry matter basis).

Item	Difference method			Regression method	95% confidence interval
	10%	20%	30%		
Sugar beet pulp					
Digestible energy, kcal/kg	2,712	2,683	2,643	2,562	2,436 – 2,688
Metabolizable energy, kcal/kg	2,628	2,580	2,554	2,472	2,340 – 2,605
Defatted rice bran					
Digestible energy, kcal/kg	2,407	2,687	2,630	2,685	2,523 – 2,847
Metabolizable energy, kcal/kg	2,243	2,598	2,544	2,606	2,378 – 2,834

values obtained using the regression method. The DE and ME of the SBP estimated by difference method with the 10% inclusion level were higher than the 95% confidence intervals of values obtained using the regression method ($P < 0.05$). In addition, the DE in the DFRB evaluated by the difference method with the 10% inclusion level was less than the DE estimated by the regression method ($P < 0.05$).

4. Discussion

The analyzed components of GE and nutrients in the SBP and DFRB were within the range of reported data (NRC, 2012; Stein et al., 2015; Stein et al., 2016). The concentrations of GE, CP, and EE were numerically greater in the DFRB than in the SBP, but numerically greater concentrations of dietary fiber (NDF, ADF, TDF, IDF, or SDF) in the SBP were found rather than in the DFRB. Notably, the SBP had greater contents of SDF and SDF:TDF ratio than the DFRB. Therefore, the SBP diets had numerically greater SDF content and SDF:TDF ratio than the DFRB diets.

In the present experiment, the concentrations of DE, ME, and ATTD of GE and most nutrients of diets linearly decreased as the inclusion levels of the SBP or DFRB increased, which was in agreement with the previous studies that illustrated the negative effects of high-fiber ingredients on the concentration of DE, ME, and ATTD of GE and most nutrients of high-fiber diets (Chen et al., 2013; Wang et al., 2016; Zhong and Adeola, 2019). The reason may be that high-fiber ingredients contained less GE and digestible compositions but more dietary fiber compared with the CSBM diet (Degen et al., 2007; Le Gall et al., 2009; Zhao et al., 2018b). In contrast, in the DFRB diets, the ATTD of NDF and ADF in the SBP diets were linearly increased as the inclusion levels of the SBP increased, which agreed with the previous studies (Bindelle et al., 2009; Zhang et al., 2018). This difference may be due to the higher SDF content of SBP compared with DFRB. The SDF could increase the viscosity of digesta, which could result in the decrease of digesta passage rate through the digestive tract and the increase of digesta fermentation time in the hindgut (Navarro et al., 2018; Zhang et al., 2018).

The difference method is a classic indirect method to determine the DE and ME of high-fiber dietary ingredients such as the SBP and DFRB which cannot be fed to pigs as the only source of energy and nutrients in the diet directly (Wiseman and Cole, 1985; Adeola et al., 2001; Zhang and Adeola, 2017). In the present study, the DE and ME of the SBP estimated by the difference method with different inclusion levels (10%, 20%, and 30%, respectively) were within the range of previously reported values (NRC, 2012; Navarro et al., 2018; Zhang et al., 2018). The DE and ME of the DFRB determined by the difference method with different inclusion levels (10%, 20%, and 30%, respectively) were also within the range of published data (Kunrath et al., 2010; NRC, 2012; Huang et al., 2018a). There were no effects of different inclusion levels on the DE or ME of these 2 high-fiber ingredients with different solubility estimated by the difference method, which agreed with previous studies that different inclusion levels of wheat bran (15% and 30%, respectively), canola meal (15% and 30%, respectively), SBP (15% and 30%, respectively; 14.6%, 24.4%, 34.2%, 43.9%, and 53.7%, respectively), corn germ meal (15% and 30%, respectively; 4.85%, 9.70%, 19.40%, 29.10%, 38.80%, and 48.50%, respectively), konjac flour residues (15% and 30%, respectively), and ramie (15% and 30%, respectively) in test diets did not affect the DE and ME in these high-fiber ingredients for pigs determined by difference method (Jaworski et al., 2016; Kim et al., 2018; Li et al., 2018; Navarro et al., 2018; Zhang et al., 2018, 2019). This may indicate that the difference method could be applied to estimate the energy values for most ingredients. No interaction between the test ingredients and the basal diet is the basic assumption for using the difference method to determine the energy values of ingredients (Adeola et al., 2001; Zhang and Adeola, 2017). But this assumption may be not always true. The standard errors (SE) of DE and ME for the high-fiber ingredients with different solubility were dependent on the inclusion level, lower inclusion level resulted in greater SE of energy values (Villamide, 1996; Huang et al., 2013; Zhao et al., 2018a). In addition, it has been found that different inclusion levels resulted in variable DE and ME values of wheat middlings and wheat bran estimated by difference method (Huang et al., 2013; Zhao et al., 2018b). These indicate that the test ingredients and the inclusion levels of the test ingredients in the basal diet might be the most important factors that affect the energy values of these ingredients evaluated by the difference method.

Compared with the difference method, the regression method presents a robust indirect method due to the fact that at least 2 proportions of the component in the basal diet are replaced by the test ingredients when the regression method is used (Adeola et al., 2001). Bolarinwa and Adeola (2012, 2016) indicated that the regression and the direct methods do not give different estimates of DE and ME in barley, sorghum, and wheat for pigs. Similarly, Villamide et al. (2003), Jaworski et al. (2016) and Kim et al. (2018) also obtained similar energy values in the grape pulp, wheat bran, sunflower seed meal, and canola meal for pigs by using the regression method or the difference method with different inclusion levels. However, inconsistent results of estimated energy values of ingredient between the regression method and the difference method with a specific inclusion level have been found in some research. For example, the DE values of soybean meal for rabbits evaluated by the difference method with the 15% inclusion level was lower than those by the regression method (Villamide et al., 1991). In the present study, there was no difference in energy values of test high-fiber ingredients with different solubility estimated by the regression method compared with those values obtained by the difference method at 20% or 30% inclusion levels. However, the energy values of test high-fiber ingredients determined by the difference method with a 10% inclusion level were inconsistent with the values estimated by the regression method. The inconsistent energy values derived from the difference or the regression method indicated that there may be an interaction between the test ingredient and the CSBM diet (Villamide, 1996).

There were no effects of inclusion levels on the energy values of the high-fiber ingredients with different solubility, however, numerically greater SE of DE and ME of the SBP or DFRB determined by the difference method with the lower inclusion level were observed compared to those with other inclusion levels (Villamide, 1996; Huang et al., 2013; Zhao et al., 2018a). Maybe whether the nutrient components of the basal diet were balanced might be another reason that affected the energy values of the test ingredient. The study reported by Zhao et al. (2018a) found that the DE and ME of SBM determined by the regression method were significantly different with those values estimated by the difference method with different inclusion levels (15%, 25%, and 31%, respectively), with the supplementation of crystalline amino acids in corn basal diet. Similarly, Wang et al. (2019) also found that the DE and ME of the soybean oil estimated by the regression method were increased by 8.07% and 9.05% with the supplementation of crystalline amino acids in the basal diet. Thus, to increase the accuracy of the energy values for the test high-fiber ingredients, the regression method with a nutrient-balance basal diet was recommended. However, using the regression method to determine the energy values in the test ingredient needs a large scale of experimental animals, as well as a lot of tedious work. If the number of experimental animals was limited, the difference method with a moderate inclusion level of the test high-fiber ingredient in the basal diet could be applied to substitute the regression method.

5. Conclusion

In conclusion, results from the present study indicated that the regression method was a robust indirect method to evaluate the energy values in high-fiber ingredients with different solubility properties. The accuracy of the energy values in the high-fiber ingredients determined by the difference method was affected by the test ingredient inclusion levels. Therefore, the regression method was recommended to evaluate the energy values for the high-fiber ingredients with different solubility properties. However, if the number of experimental animals was limited, the difference method with a moderate inclusion level (at least 20%) of the test high-fiber ingredient in the basal diet could be applied to substitute the regression method.

Author contributions

L. Chen and **H. Zhang** designed the experiment and supervised the project. **Z. Liu**, **R. Zhong**, **K. Li**, **B. Zhang**, and **L. Liu** performed the experiments and conducted lab work. **Z. Liu** and **R. Zhong** conducted the statistical analysis. **Z. Liu** wrote the paper. All authors read and approved the final manuscript.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that might inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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