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Abstract

This study mainly evaluated the responses in growth performance of growing pigs to different energy systems and energy levels in diets. Subsequently, we compared the nutrient digestibility and digestible nutrient concentrations of each energy level diet. In experiment 1, a total of 144 growing pigs with an average initial body weight of 26.69 ± 7.39 kg were randomly allotted to six dietary treatments (four pigs/pen; six replicates/treatment) according to a 2 × 3 factorial arrangement resulting from two energy systems (metabolizable energy [ME] and net energy [NE]) and three energy levels (low [LE], recommended [C], and high energy [HE]). Pigs were fed the experimental diets for 6 weeks and were allowed free access to feed and water during the experimental period. In experiment 2, 12 growing pigs with an average initial body weight of 27.0 ± 1.8 kg were randomly allotted to individual metabolism crates and fed the six diets in a replicated 6 × 6 Latin square design. The six dietary treatments were identical to those used in the growth trial. Pigs were fed their respective diets at 2.5 times the estimated energy requirement for maintenance per day, and this was divided into two equal meals provided twice per day during the experimental period. Differences in energy systems and energy levels had no significant effect on the growth performance or nutrient digestibility (except AEE) of growing pigs in the current study. However, the digestible concentrations of ether extract, acid-hydrolyzed ether extract, and acid detergent fiber (g/kg dry matter [DM]) in diets significantly increased ($p < 0.05$) with increasing energy levels. Additionally, there was a tendency ($p = 0.09$) for an increase in the digestible crude protein content (g/kg DM) as the energy content of the diet increased. Consequently, differences in energy systems and levels did not affect the body weight, average daily gain, and average daily feed intake of growing pigs. This implies that a higher variation in dietary energy levels may be required to significantly affect growth performance and nutrient digestibility when considering digestible nutrient concentrations.

Keywords: Energy system, Net energy, Energy level, Energy concentration, Metabolic response, Growing pigs

Introduction

Because feed cost is the most expensive part of animal production, feed must meet optimal energy and nutrient requirement levels for efficient animal production [1–3]. Among various factors, energy and amino acids should be considered first because they are a large part of diet formulation and is closely associated with feed costs [4,5]. Energy levels in animal diets, especially during the growing period, are an important factor affecting growth performance and fat deposition [6]. High energy intake in growing pigs can increase body weight gain by increasing muscle mass but also increases feed cost and fat deposition [7,8]. In contrast, a low energy intake may inhibit muscle development. Thus, it is crucial to provide optimal energy levels that correspond to the energy requirements of growing pigs. Thus, by accurately predicting the energy requirements, highly efficient growth performance and reduced feed cost can be achieved, and resource loss and environmental pollution can be reduced [9,10].

The energy evaluation system in animal nutrition estimates the energy requirements for essential physiological functions, body development, and various productive activity, thereby determining the amount of feed required. Consequently, an accurate evaluation system enables precise diet formulation and subsequently improves the profitability of animal production [11,12]. Various energy systems, such as gross energy (GE), digestible energy (DE), metabolizable energy (ME), and net energy (NE), are available for feed [12–15]. The ME is defined by excluding urinary energy and gaseous energy from DE, while NE is defined by taking into account the heat increment associated with feed utilization and the energy cost from normal physical activity in the ME system [2,12,16,17]. Accordingly, the NE system is regarded as the superior system that most closely accounts for the available dietary energy in the feed for animal maintenance and production [12–15]. Although the NE system provides an accurate estimation of the dietary energy available to pigs, there is little information from the NE system for growing pigs compared to other energy systems, such as DE and ME [18,19]. Another limitation of the NE system is that there may be discrepancies between the calculated and measured energy content of feed ingredients [20]. Therefore, the main purpose of this study was to evaluate the growth performance and nutrient digestibility of growing pigs in response to different energy systems and levels and to compare the nutrient digestibility and digestible nutrient concentrations of each dietary treatment.

Materials and Methods

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee of Chungnam National University, Daejeon, Republic of Korea (approval #0611).

Experimental diets and treatments

The pigs were randomly assigned to six dietary treatments composed of two energy systems (ME and NE) and three energy levels (low energy [LE], recommended energy [C], and high energy [HE]). The ME and NE diets were formulated by calculated ME and NE values of NRC [14], respectively. The low-energy and high-energy level diets were formulated to have the same difference in energy content compared to the control diet (C, 3.30 Mcal/kg ME or 2.43 Mcal/kg NE) in each energy system. Six experimental diets were formulated according to the energy and nutritive values of ingredients, as described by NRC [14], and all nutrients were included in all diets to meet or exceed the NRC [14] estimates of requirements (Table 1). The concentrations of standardized ileal digestible amino acids, including Lys, Met + Cys, Thr, and Trp, were adjusted according to the energy levels of each experimental diet. This adjustment aimed to maintain consistency with the energy-to-protein ratio of the control diet. No antibiotic growth promoters were used, and all diets were provided in meal form.

Experiment 1: growth trial

A total of 144 growing pigs ([Landrace × Yorkshire] × Duroc) with an average initial body weight (BW) of approximately 26.69 ± 7.39 kg were used for 6 weeks in the growth trial. The pigs were randomly assigned to one of six dietary treatments (four pigs/pen; six replicates/treatment) arranged in a 2 × 3 factorial design with two energy systems and three energy levels. All the pigs were housed in an environmentally controlled room and allowed *ad libitum* access to food and water throughout the experimental period.

The BW of each pig was recorded at the beginning and the end of the experiment. The amount of experimental diet provided per pen was recorded throughout the experimental period, and the remaining feed was weighed at the end of the experiment. At the end of the experiment, the average daily gain (ADG), average daily feed intake (ADFI), and the ratio between ADG and ADFI (G:F) for the pigs were calculated and summarized within each treatment.

Experiment 2: metabolism trial

A total of 12 growing pigs ([Landrace × Yorkshire] × Duroc) with an average initial BW of approximately 27.0 ± 1.8 kg were used in the metabolism trial. The pigs were allotted to a replicated 6 × 6 Latin square design with six diets and six periods. All pigs were housed individually in environmentally controlled metabolic cages. Pigs were fed their respective diets at 106 kcal of ME/kg $BW^{0.75}$ per day (approximately 2.5 times the estimated energy requirement for maintenance [21]). The total amount of daily feed was served as two equal meals twice per day (08:00 and 18:00) during the experimental period. Pigs were fed each experimental diet for 11 days. The body weight of the pigs was recorded individually at the initiation and termination of each feeding period and used to adjust the feed allowance. Water was provided *ad libitum* in the cages. The collection of total feces was conducted as previously described [9,22,23]. The first 5 days before the total collection commenced were considered an adaptation period to the diet and environment. After the adaptation period, ferric oxide was added to the diet on the morning of days 6 and 11 as an indigestible marker; each pig received 5 g of ferric oxide included in part of the morning feed (100 g of feed), and the remaining portion of the feed was given after pigs had consumed all the marked feed. The collection of feces commenced and terminated when the marker appeared in the feces. Feces were collected each morning, weighed, and stored at –20℃ until analysis.

All frozen feces were dried in a forced-air oven at 50℃ and then finely ground before chemical analysis. Bomb calorimetry (Model 6400, Parr Instruments Co., Moline, IL, USA) was used to determine the GE of all samples (diet and feces), and benzoic acid was used as the standard for calibration. Feed and fecal samples were analyzed for dry matter (DM), crude protein (CP), ash, ether extract (EE), acid-hydrolyzed ether extraction (AEE), and acid detergent fiber (ADF) according to the Association of Official Analytical Chemists (AOAC) [24] method. Apparent total tract digestibility (ATTD) and digestible nutrient concentrations were calculated according to standard procedures [9,25].

Statistical analyses

All data were analyzed using the MIXED procedure in SAS (SAS Inst. Inc., Cary, NC, USA). The experimental unit used was a pen. The statistical model included dietary treatment as a fixed effect and a block (Exp. 1 = BW; Exp. 2 = pig and period) as random effects. The results are presented as the mean ± standard error of the mean. Statistical significance and tendency were considered at $p < 0.05$ and $0.05 \leq p < 0.10$, respectively.

Results and Discussion

The effects of energy systems and levels on ADG, ADFI, and G:F during the experimental period are presented in Table 2. Pigs that were fed diets formulated using the ME and NE systems showed similar ADG, ADFI, and G:F values (p = 0.49, p = 0.21, and p = 0.30, respectively). There were no significant differences in the ADG, ADFI, and G:F of growing pigs among the low-, moderate-, and high-energy-level diets (p = 0.53, p = 0.26, and p = 0.24, respectively). No interactions between energy systems and energy levels were observed in the growth performance of growing pigs. The energy system did not affect (p > 0.05) the ATTD of DM, CP, EE, AEE, organic matter, and ADF (Table 3). In contrast, there were main effects of energy level on the ATTD of EE and AEE (p = 0.08 and p = 0.01, respectively). Table 4 shows the digestible nutrient concentrations (g/kg DM) of the experimental diets. While the energy level did not exhibit a significant difference (p > 0.05) in digestible organic matter, there was a tendency (p = 0.09) for an increase in the digestible crude protein content as the energy content of the diet increased. Furthermore, a significant (p < 0.05) increase in the level of digestible ether extract, acid-hydrolyzed ether extract, and acid detergent fiber was observed as the energy content of the diet increased.

Pigs regulate feed consumption to meet their energy requirements, and voluntary feed intake can be influenced by various factors such as feed composition and characteristics of the feed ingredients [20,26,27]. Moreover, depending on the characteristics of the feed ingredients, the energy values may be overestimated or underestimated in each energy system, which may affect the physical feed intake capacity [26,28]. In general, an increase in dietary energy density leads to a decrease in the feed intake of pigs [22,29,30]. However, an increase in dietary energy content leads to an increase in body weight gain or feed efficiency in pigs [31,32]. This agrees with the data from Liu et al. [7], who observed that growth performance improved as dietary energy concentrations increased. Several previous studies have shown similar results; increasing the energy level affects growth performance positively [22,33]. In contrast, there were no differences in growth performance among the treatments in this study. We can infer that the pigs acquired sufficient energy to grow from their diet throughout the experimental period, regardless of the energy system and energy level. This may explain why there were no differences in ADG, ADFI, and G:F among the dietary treatments, although dietary energy levels and digestible nutrient concentrations differed. This result is consistent with that of the previous study by Quiniou and Noblet [30]. They suggested that only extreme differences in energy density could cause a noticeable change in the energy intake of pigs when they were allowed free access to the diet. Additionally, including fiber ingredients in the diet tends to increase the water-holding capacity, which may result in a decrease in voluntary feed intake [34–36]. However, in this study, high-fiber sources were not used for energy dilution, which may explain why there was no difference in the ADFI among the dietary treatments.

The digestible nutrient concentrations varied with increasing energy levels in the respective energy systems in this study. This is consistent with data reported by Lee et al. [22], who reported that digestible nutrient concentrations increased linearly with increasing dietary NE concentrations. However, differing results were obtained for nutrient digestibility. The current study showed no significant difference in the ATTD of nutrients (except AEE) with an increase in energy; however, a previous study revealed that the ATTD of nutrients (except ADF) increased with increasing dietary NE concentration [22]. This difference may be due to the composition of the experimental diets, especially fiber content. The experimental diets had similar fiber content in the present study. Generally, it has been reported that increasing fiber content in diet formulations decreases dietary energy concentration and digestibility [30,37,38]. The different energy levels among the dietary treatments in this study were obtained by modulating the fat source, not the fiber source, which was used to modulate energy concentration in the study by Lee et al. [22]. Moreover, during the growing and finishing phases of pigs, it is generally considered adding fat to the diet did not affect digestibility [39].

In conclusion, differences in energy systems and levels did not affect the growth performance or nutrient digestibility (except AEE) of growing pigs. This implies that differences in the growth performance and nutrient digestibility of growing pigs may be observed by increasing variations in feed ingredient composition and dietary energy levels. Further studies may be required to explore the effects of various factors, including the characteristics of feed ingredients (e.g., fiber or fat content, protein quality, etc.) and animal factors, and the interactions between these factors, on the growth performance, energy, and nutrient digestibility of pigs.

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Tables

Table 1. Ingredients and compositions of the experimental diets (as-fed basis)[1)]

Energy system (S)	ME			NE		
Energy level (L)	LE	C	HE	LE	C	HE
Ingredient (%)						
Corn	38.44	42.11	46.75	30.83	33.15	37.00
Soybean meal (44%)	20.10	22.00	23.73	20.10	22.00	22.35
Corn DDGS	9.90	6.59	3.00	15.00	10.00	6.19
Wheat (Hard Red)	19.70	18.23	15.40	19.00	19.00	19.00
Molasses (sugar beets)	8.37	5.00	2.30	10.00	8.00	5.00
Soybean oil	0.19	2.68	5.26	1.86	4.51	6.89
Limestone	1.09	1.06	1.03	1.11	1.06	1.04
Mono-calcium phosphate	0.79	0.86	0.95	0.70	0.81	0.91
Salt	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin-mineral premix[2)]	0.50	0.50	0.50	0.50	0.50	0.50
Lys-HCL	0.34	0.36	0.39	0.34	0.36	0.42
DL-Methionine	0.03	0.04	0.08	0.02	0.04	0.08
L-Threonine	0.05	0.07	0.10	0.04	0.07	0.11
L-Tryptophan	-	-	0.01	-	-	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition[3)]						
Dry matter (%)	84.75	85.52	86.18	84.78	85.33	86.00
GE (Mcal/kg)	3.91	4.04	4.17	4.05	4.15	4.26
DE (Mcal/kg)	3.28	3.43.	3.58	3.32	3.47	3.60
ME (Mcal/kg)	3.15	3.30	3.45	3.19	3.33	3.47
NE (Mcal/kg)	2.32	2.43	2.54	2.32	2.43	2.54
Crude protein (%)	18.81	18.52	18.06	19.66	19.14	18.37
Ether extract (%)	2.50	4.97	7.53	4.07	6.62	8.98
Crude fiber (%)	3.21	3.16	3.07	3.35	3.22	3.08
SID amino acids (%)						
Lys	0.94	0.98	1.03	0.94	0.98	1.03
Met	0.28	0.28	0.32	0.27	0.29	0.32
Met + Cys	0.55	0.55	0.58	0.55	0.56	0.58
Thr	0.57	0.59	0.62	0.57	0.60	0.63
Trp	0.17	0.17	0.19	0.17	0.18	0.18
Calcium (%)	0.67	0.66	0.66	0.66	0.66	0.66
Phosphorus (%)	0.56	0.56	0.56	0.56	0.56	0.56
Analyzed composition (%)						
Crude protein	18.3	18.2	18.7	17.8	18.0	18.7
Ash	5.1	5.1	5.3	5.2	5.5	4.6
Ether extract	4.8	5.3	5.7	4.7	5.5	5.9
AEE[4)]	6.2	6.8	7.8	6.1	6.9	7.8
Acid detergent fiber	5.5	5.8	5.5	5.6	5.8	5.7

[1)]ME, metabolizable energy system; NE, net energy system; LE, low energy level; C, control energy level; HE, high energy level.

[2)]Provided per kilogram of diet: vitamin A, 10,000 IU; vitamin D_3, 2,000 IU; vitamin E, 48 IU; vitamin K_3, 1.5 mg; riboflavin, 6 mg; niacin, 40 mg; D-pantothenic acid, 17 mg; biotin, 0.2 mg; folic acid, 2 mg; choline, 166 mg; vitamin B_6, 2 mg; and vitamin B_{12}, 28 µg; Fe, 90 mg from iron sulfate; Cu, 15 mg from copper sulfate; Zn, 50 mg from zinc oxide; Mn, 54 mg from manganese oxide; I, 0.99 mg from potassium iodide; Se, 0.25 mg from sodium selenite.

[3)]GE, gross energy; DE, digestible energy; ME, metabolizable energy; NE, net energy; SID, standardized ileal digestibility.

[4)]AEE, acid-hydrolyzed ether extract.

Table 2. Growth performance of growing pigs that were fed dietary treatments[1)]

Energy system (S)	ME			NE			SEM	p-value[2)]		
Energy level (L)	LE	C	HE	LE	C	HE		S	L	S × L
Initial body weight (kg)	26.54	26.56	26.72	26.75	26.83	26.75	4.65	0.95	1.00	1.00
Final body weight (kg)	64.29	63.15	63.73	62.25	63.29	63.23	5.44	0.80	1.00	0.96
ADG (kg/d)	0.89	0.87	0.88	0.85	0.87	0.87	0.03	0.49	0.53	0.53
ADFI (kg/d)	2.19	2.04	1.97	2.13	2.01	1.95	0.08	0.21	0.26	0.25
G:F ratio (kg/kg)	0.41	0.43	0.45	0.42	0.43	0.45	0.009	0.30	0.24	0.14

[1)]ME, metabolizable energy system; NE, net energy system; LE, low energy level; C, control energy level; HE, high energy level; ADG, average daily gain; ADFI, average daily feed intake; G:F ratio, ratio of ADG to ADFI.

[2)]S: energy system effect; L: energy level effect; S × L: interaction between the energy system and energy level.

Table 3. Apparent total tract digestibility (ATTD, %) of nutrients in experimental diets (as-fed basis)[1)]

Energy system (S)	ME			NE			SEM	*p*-value[2)]		
Energy level (L)	LE	C	HE	LE	C	HE		S	L	S × L
DM	83.3	85.4	84.0	85.4	86.0	83.3	1.65	0.48	0.22	0.49
CP	83.0	84.2	83.2	84.3	84.8	83.0	1.64	0.53	0.51	0.79
EE	85.1	88.6	91.3	88.9	89.3	89.7	2.15	0.44	0.08	0.22
AEE	58.3	68.9	70.0	62.9	67.8	68.7	4.27	0.77	0.01	0.56
OM (DM basis)	83.5	84.7	83.8	85.5	85.0	83.7	1.49	0.40	0.55	0.57
ADF	48.2	58.3	53.3	55.7	59.9	51.2	5.68	0.49	0.15	0.49

[1)]ME, metabolizable energy system; NE, net energy system; LE, low energy level; C, control energy level; HE, high energy level; DM, dry matter; CP, crude protein; EE, ether extract; AEE, acid-hydrolyzed ether extract; OM, organic matter; ADF, acid detergent fiber.

[2)]S: energy system effect; L: energy level effect; S × L: interaction between the energy system and energy level.

Table 4. Digestible nutrient concentrations (g/kg) of experimental diets (dry matter basis)[1)]

Energy system (S)	ME			NE			SEM	*p*-value[2)]		
Energy level (L)	LE	C	HE	LE	C	HE		S	L	S × L
DCP	152	153	156	150	152	156	3.04	0.64	0.09	0.97
DEE	51	60	71	55	62	70	1.82	0.16	<0.0001	0.15
DAEE	36	47	54	38	47	54	2.93	0.71	<0.0001	0.75
DOM	831	842	833	850	846	832	14.85	0.39	0.54	0.58
DADF	26	34	30	31	35	29	3.26	0.40	0.04	0.47

[1)] ME: metabolizable energy system; NE: net energy system; LE: low energy level; C: control energy level; HE: high energy level; DCP: digestible crude protein; DEE: digestible ether extract (DEE concentrations were calculated using the amounts of feed EE and fecal AEE); DAEE: digestible acid-hydrolyzed ether extract; DOM: digestible organic matter; DADF: digestible acid detergent fiber.

[2)]S: energy system effect; L: energy level effect; S × L: interaction between the energy system and energy level.