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Non Ruminant Nutrition

Evaluation of energy and nutrient utilization for corn, barley, and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period

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Abstract

Despite extensive research focusing on feed ingredients for growing pigs, limited studies have systematically evaluated the effect of physiological stage and parity on feed ingredient utilization in sows. This study aimed to evaluate the energy and nutrient utilization of corn, barley, and wheat bran in primiparous and multiparous sows across different physiological stages. A total of 20 primiparous sows (initial body weight 186.9 ± 4.2 kg) and 24 multiparous sows (initial body weight 253.9 ± 6.1 kg) were used across the gestation (50 d), lactation, and post-weaning period, using a completed randomized design with 4 dietary treatments (control, corn, barley, and wheat bran), where primiparous and multiparous sows had 5 and 6 replicates per treatment, respectively. For primiparous sows, the apparent total tract digestibility **(ATTD)** of neutral detergent fiber (**NDF**) and gross energy (**GE**) in barley was higher during lactation than during the post-weaning period ($P < 0.05$), and the ATTD of NDF in wheat bran was also higher during lactation than post-weaning period ($P < 0.05$). Across all three ingredients, NDF digestibility was consistently higher during lactation compared to post-weaning period ($P < 0.05$). In multiparous sows, the ATTD of crude protein (**CP**) in corn was higher during gestation and lactation than during post-weaning period ($P < 0.05$). Digestible energy and ATTD of GE in wheat bran were greater during lactation than gestation ($P < 0.05$). For three ingredients, metabolizable energy (**ME**) was higher during lactation than during gestation and post-weaning period, and CP digestibility during lactation and gestation exceeded that in the post-weaning period ($P < 0.05$). Parity also influenced nutrient utilization. During gestation, primiparous sows showed higher ATTD of CP in wheat bran ($P < 0.05$), while multiparous sows had higher ATTD of ether extract (**EE**) in both barley ($P < 0.01$) and wheat bran ($P < 0.05$). During lactation, corn digestibility was not different between different physiological stages. Primiparous sows showed higher ATTD of NDF in barley compared with multiparous sows ($P < 0.01$), whereas multiparous sows exhibited higher ATTD of EE in both barley and wheat bran ($P < 0.05$). In the post-weaning period, primiparous sows had higher ME and ATTD of CP in corn ($P < 0.05$), while multiparous sows had higher ATTD of EE in both barley ($P < 0.05$) and wheat bran ($P < 0.01$). In conclusion, this study demonstrated that physiological stage and parity affect nutrient digestibility and energy utilization in sows. Lactation period improved the utilization of barley and wheat bran, and multiparous sows exhibited greater EE digestibility.

Lay Summary

Feed ingredient evaluation for sows has often been extrapolated from data on growing pigs, which may not accurately reflect nutrient utilization in sows. This study systematically evaluated the digestibility of energy and nutrients from corn, barley, and wheat bran in primiparous and multiparous sows across gestation, lactation, and post-weaning stages. Results showed that apparent total tract digestibility of nutrients, especially fiber and energy, varies with physiological stage and parity. For example, the digestibility of neutral detergent fiber was higher during lactation compared to post-weaning period for barley and wheat bran, and multiparous sows generally showed higher digestibility of ether extract. These findings emphasize the importance of considering both parity and physiological stage when formulating sow diets to optimize nutrient utilization and improve feeding precision.

Key words: barley, corn, digestibility, gestation, lactation, wheat bran

Abbreviations: ATTD, apparent total tract digestibility; ADF, acid detergent fiber; CP, crude protein; CSM, cottonseed meal; DE, digestive energy; DM, dry matter; DMI, dry matter intake; EE, ether extract; GE, gross energy; ME, metabolizable energy; NDF, neutral detergent fiber; OM, organic matter; SCFA, short-chain fatty acid.

Introduction

Nutrient digestibility and energy values for sows in NRC databases are incomplete (NRC, 2012). Many energy values are derived from growing pigs or extrapolated from models that were not specifically developed for sows, which makes them not directly applicable to sows (Noblet and

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Perez, 1993; Le Goff and Noblet, 2001). Le Goff and Noblet (2001) demonstrated that the apparent total tract digestibility (**ATTD**) of nutrients and energy is higher in adult sows compared to growing pigs. However, feed evaluation studies in sows remain limited due to their larger body size and complex physiological stages. It has been proposed to use two sets of energy values: one for growing-finishing pigs and another for adult sows (Noblet, 2000; Le Goff and Noblet, 2001). Thus, there is an urgent need to refine and expand the feed database for sows to better address their nutritional requirements.

Physiological stage and parity influence sow weight, intestinal structure, metabolism, and gut microbiota (Noblet and Shi, 1994; Koren et al., 2012; Ji et al., 2019; Liu et al., 2019). However, major databases (NRC, INRA, CVB, and BR-PIG) do not distinguish nutrient digestibility of feed ingredients across sow physiological stages. Casas and Stein (2017) found higher ATTD of gross energy (**GE**) and digestible energy (**DE**), metabolizable energy (**ME**) concentrations in rice bran for gestating sows than growing gilts; lactating sows had even higher ATTD for GE, dry matter (**DM**), neutral detergent fiber (**NDF**), and organic matter (**OM**) than gestating sows (Casas and Stein, 2017; Casas et al., 2022). Wang et al. (2022) reported that late-gestating sows had greater ME and metabolizable energy/digestible energy (**ME:DE**) than mid-gestating sows when fed soybean meal. Conversely, Zhuo et al. (2023) demonstrated that the DE, ME, and ME:DE of cottonseed meal (**CSM**) were similar between pregnant and non-pregnant sows. Similarly, Wang et al. (2023) found that ME values of extruded full-fat soybeans were identical in both non-gestating and gestating sows. These findings suggest that DE, ME, and digestibility vary by feed ingredient and physiological stage. However, systematic studies on the effects of parity and the physiological stage of sows on nutrient and energy digestibility remain limited.

Therefore, in this study, we selected three feed ingredients—corn, barley, and wheat bran—to further investigate the effects of parity and different physiological stages on the digestibility of energy and nutrients in sows. The purpose of this experiment was to evaluate and analyze the DE, ME, and nutrient digestibility of corn, barley, and wheat bran during the gestation, lactation, and post-weaning stages in both primiparous and multiparous sows.

Materials and Methods

The animal protocol for this research was approved by the Animal Care and Use Committee of the Institute of Feed Research of the Chinese Academy of Agricultural Sciences (IFR-CAAS-20230718).

Diets, animals, and experimental design

The corn and wheat bran were procured from Hebei Kangda Co., Ltd. (Langfang, China), while the barley was obtained from Guangdong Haida Co., Ltd. (Guangzhou, China). Before commencing the experiment, an analysis of the chemical composition of the corn, barley, and wheat bran samples was conducted (Table 1) (Wei et al., 2025). In this study, all diets were uniformly prepared as mash after the ingredients were purchased and stored under appropriate conditions (cool, dry, and dark) to prevent deterioration.

Twenty primiparous sows (Landrace × Yorkshire; initial body weight 186.9 ± 4.2 kg) and twenty-four multiparous sows (Landrace × Yorkshire; average parity 5.07; initial body weight 253.9 ± 6.1 kg) were selected for the experiment. The experiment was conducted in a sequential manner, starting with gestation (50 d), lactation, and post-weaning periods. At each stage, both primiparous and multiparous sows were randomly allocated to one of four dietary treatments in a completely randomized design. The primiparous treatment group included 5 replicates, while the multiparous treatment group had 6 replicates. The diets consisted of a corn-soybean-based control diet and three experimental diets, each supplemented with corn, barley, or wheat bran to replace 50% of the corn and soybean in the basal diet (Table 2). Nutrient analysis values for the primiparous and multiparous diets are presented in Tables 3 and 4, respectively. The DE, ME, and ATTD of corn, barley, and wheat bran were determined using the total fecal and urine collection method for gestating, lactating, and post-weaning sows.

During the experimental phase, gestating sows and post-weaning sows were individually housed in stainless-steel metabolism crates (1.80 m × 0.62 m × 1.30 m). Lactating sows were housed in larger stainless-steel metabolism crates (3.80 m × 1.24 m × 1.30 m) to facilitate the suckling of piglets. Sows underwent a 7-d acclimation period to flush the intestines and acclimate to the diets, followed by the collection of all feces produced from the 5 consecutive days of experimental diet feeding. Taking the beginning of the trial diet as day 1, a color index (2% ferric oxide) was mixed with the diet in the morning on days 8 and 13. The average dry matter intake (**DMI**) of primiparous and multiparous sows was recorded during the collecting period and is presented in Table 5. Sows were maintained in an environment held steadily at 22 ± 2 °C and were provided continuous access to drinking water. Gestating sows were allowed 2.5 kg/d of feed. Lactating and post-weaning sows had ad libitum access to experimental diets. Diets were provided daily in two equal meals offered at 0800 and 1600 h, with records of daily feed consumption.

Sample collection

Feces and urine are easily collected separately in specialized metabolism crates. To make the feces collection accurate, we placed an extra layer of long plastic with grooves between the crates and the floor. We implemented procedures to avoid feces and urine contamination, following the methods described in a previous study (Wei et al., 2024). Fecal collection began on day 8 after the appearance of the first red marker in the feces and ended on day 13, when the red marker reappeared in the feces, indicating the end of the collection period. Fecal weight was recorded every day, and feces were stored at −20°C as soon as collected. Urine collections were initiated on the morning of day 8 at 0900 h and ceased on the morning of day 13 at 0900 h. Urine was collected in buckets placed under the metabolism crates with 50 mL of 6 N hydrochloric acid (Yang et al., 2021). The buckets were emptied three to four times as scheduled after the total volume of urine had been recorded (Pedersen et al., 2007). One tenth of the collected urine was stored at −20 °C. Feed refusals and spillages were gathered, dried, and weighed daily to record accurate feed intake. At the end of the experiment, fecal samples collected on different days were thawed at room temperature and pooled for each sow. Similarly, urine samples from different collection days were thawed and pooled for each sow for subsequent analysis of energy. Finally, a portion of the feces samples was dried at 65 °C and crushed, along with a part of the urine samples,

Table 1. Nutrient composition of corn, barley, and wheat bran samples (%, as-fed basis)

Items	Corn	Barely	Wheat bran
Dry matter	91.20	90.39	88.38
Gross energy, MJ/kg	17.32	16.54	18.22
Crude protein	8.61	9.37	19.27
Ether extract	3.63	1.56	4.29
Organic matter	90.10	88.47	83.40
Crude fiber	1.03	3.01	5.85
Neutral detergent fiber	11.52	23.02	37.27
Acid detergent fiber	3.98	6.86	11.84
Ash	1.10	1.92	4.98
Indispensable amino acids			
Arginine	0.36	0.45	1.34
Histidine	0.17	0.14	0.19
Isoleucine	0.25	0.29	0.44
Leucine	1.03	0.67	1.19
Lysine	0.24	0.32	0.74
Methionine	0.16	0.12	0.21
Phenylalanine	0.41	0.47	0.69
Threonine	0.26	0.12	0.17
Tryptophan	0.05	0.12	0.24
Valine	0.37	0.41	0.80
Dispensable amino acids			
Alanine	0.66	0.42	1.01
Aspartate	0.57	0.63	1.32
Cysteine	0.10	0.11	0.17
Glutamate	1.68	2.23	3.18
Glycine	0.34	0.40	1.14
Serine	0.46	0.44	0.79
Tyrosine	0.21	0.24	0.45

Note: The nutritional components and amino acid levels of corn, barley, and wheat bran were analyzed in the experiment.

and sent to the laboratory for analysis of energy and nutrients (Yang et al., 2021; Lyu et al., 2023).

Chemical analysis and calculations

The samples of ingredients, diets, and feces were ground to pass through 40 mesh screens were subsequently analyzed for dry matter (method 930.15), crude protein (CP; method 990.03), ether extract (EE; method 920.39), and ash (method 942.05) according to AOAC (2007) methods (AOAC, 2007). Filter bags (model F57; Ankom Technology, Macedon, NY, USA) and fiber analyzer equipment (ANKOM200 Fiber Analyzer, Ankom Technology, Macedon, NY, USA) were used to determine the NDF and acid detergent fiber (**ADF**) contents (Van Soest et al., 1991). Samples of ingredients, diets, feces, and urine were analyzed for GE using an automatic isoperibol oxygen bomb calorimeter (model 6400; Parr1281 Calorimeter, Moline, IL, USA).

The ATTD of a nutrient in the test feedstuff was calculated using the difference method as described by Adeola (2001). The formula is as follows (Adeola, 2001):

$$A = ((T \times Tp)\,(B \times Bp))\,/Ap \times 100\,(\,\%\,)$$

Table 2. Ingredient components of experimental diets (as-fed basis)

Ingredients, %	Basal diet	Corn diet	Barley diet	Wheat bran diet
Corn	82.00	89.25	41.00	41.00
Soybean meal, Crude protein 46 %	14.50	7.25	7.25	7.25
Barley	-	-	48.25	-
Wheat bran	-	-	-	48.25
Dicalcium phosphate	1.30	1.30	1.30	1.30
Salt	0.40	0.40	0.40	0.40
Limestone	0.80	0.80	0.80	0.80
Vitamin-mineral permix[1]	1.00	1.00	1.00	1.00
Total	100.00	100.00	100.00	100.00

[1]Premix supplied per kg of diet: vitamin A, 12075 IU; vitamin D_3, 2450 IU; vitamin E, 67 IU; vitamin K_3, 2.98 mg; vitamin B_1, 1.78 mg; vitamin B_2, 3.64 mg; vitamin B_6, 4.46 mg; vitamin B_{12}, 40 µg; Niacin, 42 mg; Calcium pantothenate, 25 mg; Folic acid, 6.92 mg; Biotin, 0.70 mg; Zinc ($ZnSO_4 \cdot H_2O$), 79 mg; Copper ($CuSO_4 \cdot 5H_2O$), 23 mg; Iron ($FeSO_4 \cdot H_2O$), 150 mg; Cobalt ($CoCl_2$), 1.00 mg; Manganese ($MnSO_4 \cdot H_2O$), 100 mg; Iodine ($Ca(IO_3)_2$), 0.23 mg; Selenium (Na_2SeO_3), 0.50 mg.

Table 3. Chemical compositions of the experimental diets of primiparous sows in different physiological stages (%, DM basis)

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
Gestation				
GE, MJ/kg	17.80	17.93	17.85	18.01
DM	89.93	90.01	90.14	90.34
CP	13.80	11.30	11.59	16.49
NDF	9.93	8.87	13.52	23.21
ADF	2.76	2.10	3.38	5.88
EE	2.11	2.45	1.58	1.86
OM	84.41	85.38	84.82	83.16
Lactation				
GE, MJ/kg	17.95	17.72	17.79	17.98
DM	90.04	90.04	90.12	90.28
CP	13.81	10.32	11.52	16.15
NDF	9.59	9.01	14.28	22.52
ADF	2.33	2.29	4.10	5.63
EE	2.15	2.12	2.77	3.11
OM	84.74	84.89	84.62	82.81
Post-weaning				
GE, MJ/kg	17.94	17.84	17.73	17.93
DM	89.94	89.88	90.09	90.33
CP	13.88	11.05	12.00	16.83
NDF	10.23	9.69	14.25	21.99
ADF	2.80	2.28	4.08	5.33
EE	1.77	2.07	2.76	2.59
OM	84.30	84.97	84.55	83.00

ADF, acid detergent fiber; CP, crude protein; DM, dry matter; EE, ether extract; GE, gross energy; NDF, neutral detergent fiber; OM, organic matter.

where: A = apparent digestibility (%) of the nutrient in the test stuff; T = apparent digestibility (%) of the nutrient in the test diet (basal diet + test feedstuff); B = apparent digestibility

Table 4. Chemical compositions of the experimental diets of multiparous sows in different physiological stages (%, DM basis)

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
Gestation				
GE, MJ/kg	17.54	17.49	17.69	18.15
DM	87.03	86.80	87.81	88.47
CP	13.84	10.61	11.91	16.50
NDF	11.13	10.97	15.18	23.17
ADF	2.77	2.41	5.17	6.14
EE	2.13	2.29	1.82	2.55
OM	81.64	81.97	81.99	80.84
Lactation				
GE, MJ/kg	17.64	17.57	17.86	18.06
DM	87.02	86.80	87.97	88.42
CP	13.88	11.34	12.10	15.50
NDF	10.13	9.45	14.66	24.33
ADF	2.69	2.25	4.14	6.65
EE	2.52	1.99	1.70	2.63
OM	81.27	81.88	82.42	81.25
Post-weaning				
GE, MJ/kg	17.78	17.46	17.62	18.24
DM	86.88	87.05	87.93	88.49
CP	13.85	11.57	12.11	16.05
NDF	11.18	11.61	15.57	23.89
ADF	2.94	2.56	4.69	6.33
EE	2.14	2.21	2.06	2.52
OM	81.43	82.41	82.31	81.26

ADF, acid detergent fiber; CP, crude protein; DM, dry matter; EE, ether extract; GE, gross energy; NDF, neutral detergent fiber; OM, organic matter.

(%) of the nutrient in the basal diet; Tp is the sum of Bp and Ap; Bp = proportion (%) of the nutrient in the test diet that originates from the basal diet; Ap = proportion (%) of the nutrient in the test diet that originates from the test feedstuff. Note that Bp + Ap = Tp = 100%, both B and T were determined using the total collection method. This method assumes that the contribution of nutrients from each ingredient is additive and that the substitution does not alter the digestibility of the unchanged portion of the diet.

Energy values (DE and ME) of the diets and raw materials were calculated using the equations as follows (Kong and Adeola, 2014):

(1) DE_f (MJ/kg) = $(GE_i - GE_f)/DM_i$
(2) ME_f (MJ/kg) = $(GE_i - GE_f - GE_u)/DM_i$
(3) $DE_{fc} = DE_f/0.965$
(4) $ME_{fc} = ME_f/0.965$
(5) $DE_t = (DE_{fc} - (100\% - X\%) \times DE_{fc(basal)})/ X\%$
(6) $ME_t = (ME_{fc} - (100\% - X\%) \times ME_{fc(basal)})/ X\%$

The apparent digestible energy (**DE**$_f$) and metabolizable energy (**ME**$_f$) content in each diet (MJ/kg of DM) are calculated by equations (1) and (2), where the total GE intake (**GE**$_i$) of each pig (MJ/kg of DM) is calculated as the result of the GE content of the diet intake. The DM_i is the actual total dry matter intake during the collection period; GE_f and GE_u are the GE content of feces and urine (MJ/kg of DM) and are calculated by the

Table 5. The dry matter intake (DMI) of primiparous sows and multiparous sows at different physiological stages fed basal, corn, barley, and wheat bran diets

Sow category	Physiological stage	Basal diet DMI[1] (kg/day)	Corn diet DMI (kg/day)	Barley diet DMI (kg/day)	Wheat bran diet DMI (kg/day)	SEM[2]
Primiparous sows	Gestating	2.10	2.10	2.21	2.08	0.109
	Lactating	2.77	3.23	3.62	3.71	0.381
	Post-weaning	4.85	5.00	5.25	3.68	0.368
Multiparous sows	Gestating	2.16	2.17	2.20	2.21	0.005
	Lactating	4.55	4.34	4.45	3.92	0.270
	Post-weaning	4.20	4.36	4.24	4.56	0.136

[1]DMI (kg/day): dry matter intake in grams per day for each type of diet.
[2]SEM: standard error of the mean for each measurement.

product of GE content of the feces or urine multiplied by the dry weight of total feces or the volume of urine record over the collection period, respectively. The corrected apparent digestible and metabolizable energy, excluding the premix, is represented by DEfc and MEfc. The variable X represents the proportion of the test ingredient replacing the ingredient in the basal diets. The digestible and metabolizable energy of the test ingredient is represented by DEt and MEt, respectively.

Statistical analysis

All data analyses were performed using SAS 9.4 (SAS Inst. Inc., Cary, NC, USA). Data normality and the presence of outliers were assessed using the UNIVARIATE procedure. The primary statistical analysis was conducted using the PROC MIXED, with individual sows as the experimental units. The statistical model used to analyze the effects of parity and physiological stage on the response variables is as follows:

$$Y_{ij} = \mu + S_j + e_{ij}$$

where Y_{ij} is the observed value of the dependent variable, μ is the overall mean, S_j is the fixed effect of the j-th physiological stage or parity, and e_{ij} is the random error associated with the observation.

Least squares means were calculated for each treatment group, and multiple comparisons were performed using Tukey's multiple range test to determine significant differences among treatments. For the comparison of different parities, we used an independent samples *t*-test. For all statistical analyses, significance and tendency were set at $P < 0.05$ and $0.05 \le P < 0.10$, respectively.

Results

Comparative energy and nutrient utilization in different diets for primiparous sows across physiological stages

The energy balance for primiparous sows was shown in Supplementary Table 1. The comparative results of energy and nutrient utilization across different feed ingredients for primiparous sows at various physiological stages are presented in Table 6, while the energy and ATTD of primiparous sows' diets are detailed in Supplementary Table 2. The ATTD of nutrients

Table 6. Comparative energy and nutrient utilization of different ingredients on a dry matter basis in primiparous sows at different physiological stages (gestation, lactation, and post-weaning period)

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Corn									
Gestation	16.71	16.36	97.88	91.94	88.70	50.92	84.70	93.43	96.46
Lactation	16.75	16.56	98.88	91.61	86.20	58.72	87.30	93.26	96.12
Post-weaning	16.88	16.58	98.28	89.24	86.68	38.76	84.01	93.70	91.81
Mean	16.78	16.50	98.35	90.93	87.19	49.47	85.34	93.46	94.80
SEM	0.46	0.36	0.58	2.72	3.60	7.22	6.92	2.24	2.60
Barley									
Gestation	15.91	15.43	96.90	83.86	81.58	59.18[ab]	59.59	86.40	88.78[ab]
Lactation	16.19	15.88	99.38	87.77	81.27	67.52[a]	59.77	89.32	90.63[a]
Post-weaning	15.09	14.27	97.62	80.62	76.55	41.95[b]	55.22	84.31	83.21[b]
Mean	15.73	15.19	97.97	84.08	79.80	56.22	58.19	86.68	87.54
SEM	0.41	0.40	0.84	2.60	3.69	5.82	7.58	2.03	2.30
Wheat bran									
Gestation	13.95	13.52	97.03	70.79	85.03	52.63[ab]	54.93	73.21	76.86
Lactation	14.26	13.70	96.42	73.75	83.76	64.39[a]	68.04	78.21	77.85
Post-weaning	12.78	12.52	98.13	62.95	77.40	42.02[b]	58.49	69.44	68.81
Mean	13.66	13.25	97.19	69.16	82.06	53.01	60.49	73.62	74.51
SEM	0.67	0.70	1.11	4.00	3.15	5.26	5.54	3.16	3.68
Three ingredients									
Gestation	15.78	15.41	97.59	84.02	85.72	55.40[ab]	77.36	85.94	88.86
Lactation	15.97	15.68	98.18	85.51	84.79	60.08[a]	80.42	88.09	88.62
Post-weaning	14.92	14.61	98.01	77.60	80.21	40.91[b]	73.91	82.48	81.28
Mean	15.56	15.23	97.93	82.38	83.57	52.13	77.23	85.50	86.25
SEM	0.42	0.48	0.46	2.74	2.01	3.33	3.54	2.39	2.48
***P*-value**									
Stage[1]-Corn	0.973	0.945	0.508	0.751	0.877	0.199	0.877	0.985	0.530
Stage-Barley	0.195	0.227	0.173	0.195	0.500	0.025	0.489	0.272	0.037
Stage-Wheat bran	0.323	0.492	0.654	0.203	0.265	0.043	0.305	0.199	0.218
Stage-Three ingredients	0.439	0.472	0.410	0.268	0.250	0.001	0.686	0.508	0.181
Interaction	0.634	0.742	0.372	0.754	0.869	0.977	0.461	0.535	0.849

[a,b]Different superscripts within the same ingredient indicate significant differences among physiological stages ($P < 0.05$).
[1]Stage (corn, barley, wheat bran, and three ingredients) indicates the significance of different physiological stages on the ingredient; Interaction refers to the interaction between physiological stages and the three ingredients.
Each physiological stage included 5 replicates.
Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

and energy in the corn showed no differences across different physiological stages in primiparous sows. The ATTD of NDF in barley was higher in the lactation than in the post-weaning period ($P < 0.05$), and the ATTD of GE in the barley was also higher during lactation than in the post-weaning period ($P < 0.05$). The ATTD of NDF in wheat bran was higher in the lactation period than in the post-weaning period ($P < 0.05$). Across all ingredients, the ATTD of NDF during lactation was higher than during post-weaning ($P < 0.05$).

Comparative energy and nutrient utilization in different ingredients for multiparous sows across physiological stages

The energy balance for multiparous sows was shown in Supplementary Table 3. The comparative results of energy and nutrient utilization across different feed ingredients for multiparous sows at various physiological stages are presented in Table 7, while the energy and ATTD of multiparous sows' diets are detailed in Supplementary Table 4. For corn, the ATTD of CP during gestation and lactation was higher than during post-weaning period ($P < 0.05$). For barley, the ATTD of nutrients and energy showed no differences across different physiological stages in multiparous sows. For wheat bran, the DE and the ATTD of GE during lactation were higher than during gestation ($P < 0.05$). For the three ingredients, ME during lactation was higher than during gestation and the post-weaning period, and the ATTD of CP during lactation and gestation was higher than in the post-weaning period ($P < 0.05$).

Comparative nutrient digestibility and energy utilization between primiparous and multiparous sows across physiological stages

The results comparing energy and nutrient digestibility between primiparous and multiparous sows at different

Table 7. Comparative energy and nutrient utilization of different ingredients on a dry matter basis in multiparous sows at different physiological stages (gestation, lactation, and post-weaning period)

Items	DE, MJ/kg	ME, MJ/kg	ME/DE,	Apparent total tract digestibility of diets, %					
			%	DM	CP	NDF	EE	OM	GE
Corn									
Gestation	16.44	15.44^{y}	94.05^{y}	89.62	84.92^{a}	65.09	84.87	92.78	91.55
Lactation	16.56	16.32^{x}	98.55^{x}	93.09	85.84^{a}	58.44	79.48	94.97	92.27
Post-weaning	16.07	15.08^{y}	95.12^{xy}	88.04	73.57^{b}	54.37	76.54	92.14	88.63
Mean	16.36	15.61	95.91	90.25	81.44	59.30	80.30	93.30	90.82
SEM	0.29	0.32	1.43	1.92	3.04	7.64	3.65	1.22	1.59
Barley									
Gestation	15.57	14.52	93.54	81.28	77.22	47.09	83.48	85.43	83.95
Lactation	15.82	15.77	99.59	85.32	78.74	45.11	79.76	88.13	85.30
Post-weaning	15.47	15.35	98.63	82.53	69.30	53.61	85.54	86.83	83.48
Mean	15.62	15.21	97.25	83.04	75.09	48.60	82.93	86.80	84.24
SEM	0.25	0.43	1.95	1.56	2.99	3.55	5.33	1.02	1.33
Wheat bran									
Gestation	12.70^{b}	12.56	98.74	64.84^{y}	74.90	39.49	79.51	73.74	69.20^{b}
Lactation	14.61^{a}	14.17	97.05	76.22^{x}	77.77	54.03	87.48	80.23	78.75^{a}
Post-weaning	13.28^{b}	12.67	95.55	66.68^{y}	71.66	45.61	81.68	74.04	72.24^{ab}
Mean	13.53	13.13	97.11	69.25	74.78	46.38	82.89	76.00	73.40
SEM	0.46	0.60	1.53	3.38	2.59	4.78	4.52	2.95	2.28
Three ingredients									
Gestation	14.90	14.17^{b}	95.44	78.58	79.01^{a}	50.56	82.62	83.98	81.57
Lactation	15.66	15.42^{a}	98.40	81.08	80.78^{a}	52.53	82.24	87.78	85.44
Post-weaning	14.88	14.36^{b}	96.30	79.08	71.51^{b}	51.20	81.25	84.34	81.45
Mean	15.15	14.65	96.71	79.58	77.10	51.43	82.04	85.37	82.82
SEM	0.35	0.37	1.05	2.85	1.80	3.58	2.62	2.03	2.03
***P*-value**									
Stage[1]-Corn	0.511	0.060	0.095	0.216	0.027	0.647	0.341	0.283	0.227
Stage-Barley	0.628	0.154	0.211	0.268	0.119	0.261	0.761	0.218	0.578
Stage-Wheat bran	0.033	0.163	0.376	0.073	0.295	0.139	0.442	0.252	0.036
Stage-Three ingredients	0.223	0.036	0.156	0.819	0.001	0.931	0.927	0.366	0.291
Interaction	0.309	0.681	0.324	0.660	0.747	0.229	0.430	0.691	0.135

^{a,b}Different superscripts within the same ingredient indicate significant differences among physiological stages ($P < 0.05$).
^{x,y}Different superscripts within the same ingredient indicate a significant tendency among physiological stages ($0.05 \le P < 0.1$).
[1]Stage (corn, barley, wheat bran, and three ingredients) indicates the significance of different physiological stages on the ingredient; Interaction refers to the interaction between physiological stages and the three ingredients.
Each physiological stage included 6 replicates.
Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

physiological stages are presented in Table 8. There was no difference in the digestibility of nutrients and energy in corn between multiparous and primiparous sows during gestation. Primiparous sows had a higher ATTD of CP in wheat bran than multiparous sows ($P < 0.05$) during gestation. Multiparous sows had a higher ATTD of EE in barley than primiparous sows ($P < 0.01$) and had a higher ATTD of EE in wheat bran than primiparous sows ($P < 0.05$) during gestation. There was also no difference in the digestibility of energy nutrients in corn between multiparous and primiparous sows during lactation. Primiparous sows had a higher ATTD of NDF in barley than multiparous sows ($P = 0.006$), while multiparous sows showed a higher ATTD of EE in barley during lactation ($P < 0.05$). Multiparous sows had a higher ATTD of EE in wheat bran than primiparous sows during lactation ($P < 0.05$). During post-weaning period, primiparous sows had higher ME and ATTD of CP in the corn than multiparous sows ($P < 0.05$). Multiparous sows had a higher ATTD of EE in the barley than primiparous sows ($P < 0.05$) and had a higher ATTD of EE in the wheat bran than primiparous sows during post-weaning ($P < 0.01$).

Discussion

Studies investigating the effects of physiological stage and parity on feed evaluation in sows remain scarce. The present

Table 8. Comparative energy and nutrient utilization of different ingredients on a dry matter basis between primiparous and multiparous sows

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Gestation									
Corn									
Primiparous sow	16.71 ± 0.33	16.36 ± 0.40	97.88 ± 0.86	91.94 ± 2.13	88.70 ± 2.94	50.92 ± 6.86	84.70 ± 4.19	93.43 ± 1.71	96.46 ± 1.91
Multiparous sow	16.44 ± 0.31	15.44 ± 0.27	94.05 ± 1.54	89.62 ± 1.67	84.92 ± 2.15	65.09 ± 8.64	84.87 ± 2.44	92.78 ± 1.18	91.55 ± 1.61
P-value	0.566	0.083	0.053	0.395	0.293	0.251	0.318	0.765	0.076
Barley									
Primiparous sow	15.91 ± 0.48	15.43 ± 0.74	96.90 ± 1.68	83.86 ± 3.02	81.58 ± 4.02	59.18 ± 6.12	59.59 ± 5.51	86.40 ± 2.38	88.78 ± 2.69
Multiparous sow	15.57 ± 0.15	14.52 ± 0.54	93.54 ± 3.84	81.28 ± 0.77	77.22 ± 1.72	47.09 ± 2.12	83.48 ± 4.06	85.43 ± 0.53	83.95 ± 0.81
P-value	0.476	0.338	0.481	0.443	0.293	0.073	0.005	0.652	0.095
Wheat bran									
Primiparous sow	13.95 ± 0.58	13.52 ± 0.77	97.03 ± 1.80	70.79 ± 3.38	85.03 ± 2.21	52.63 ± 5.13	54.93 ± 7.33	73.21 ± 2.95	76.86 ± 3.21
Multiparous sow	12.70 ± 0.31	12.56 ± 0.37	98.74 ± 0.78	64.84 ± 2.22	74.90 ± 1.60	39.49 ± 3.39	79.51 ± 5.11	73.74 ± 3.12	69.20 ± 1.55
P-value	0.076	0.262	0.333	0.134	0.005	0.054	0.021	0.886	0.055
Lactation									
Corn									
Primiparous sow	16.75 ± 0.79	16.56 ± 0.79	98.88 ± 0.38	91.61 ± 4.35	86.20 ± 5.97	58.72 ± 9.32	80.30 ± 10.00	93.26 ± 3.63	94.53 ± 4.48
Multiparous sow	16.56 ± 0.25	16.32 ± 0.19	98.55 ± 1.07	93.09 ± 1.48	85.84 ± 2.76	58.44 ± 4.18	79.48 ± 2.74	94.97 ± 0.86	92.27 ± 1.30
P-value	0.816	0.755	0.687	0.810	0.979	0.978	0.331	0.621	0.644
Barley									
Primiparous sow	16.19 ± 0.37	16.13 ± 0.40	99.64 ± 0.38	87.77 ± 2.46	81.72 ± 3.17	67.52 ± 5.27	59.77 ± 8.12	89.32 ± 1.84	90.63 ± 2.08
Multiparous sow	15.82 ± 0.30	15.77 ± 0.41	99.59 ± 0.81	85.32 ± 1.72	78.74 ± 2.97	45.11 ± 3.89	79.76 ± 5.10	88.13 ± 1.28	85.30 ± 1.57
P-value	0.454	0.544	0.916	0.446	0.442	0.006	0.046	0.591	0.064
Wheat bran									
Primiparous sow	14.26 ± 0.95	13.70 ± 0.87	96.42 ± 1.02	73.75 ± 5.73	83.76 ± 4.23	64.39 ± 7.47	68.04 ± 6.68	78.21 ± 4.10	77.85 ± 5.27
Multiparous sow	14.61 ± 0.53	14.17 ± 0.67	97.05 ± 1.68	76.22 ± 3.38	77.77 ± 2.70	54.03 ± 4.99	87.48 ± 3.25	80.23 ± 2.69	78.75 ± 2.64
P-value	0.744	0.675	0.723	0.148	0.241	0.267	0.020	0.692	0.881
Post-weaning period									
Corn									
Primiparous sow	16.88 ± 0.26	16.58 ± 0.24	98.28 ± 0.51	89.24 ± 1.68	86.68 ± 1.89	38.76 ± 5.48	84.01 ± 6.56	93.70 ± 1.37	94.53 ± 4.48
Multiparous sow	16.07 ± 0.31	15.35 ± 0.33	95.12 ± 1.67	88.04 ± 2.63	73.57 ± 4.21	54.37 ± 10.09	76.54 ± 5.77	92.14 ± 1.63	88.63 ± 1.85
P-value	0.101	0.031	0.114	0.745	0.026	0.233	0.151	0.482	0.201
Barley									
Primiparous sow	15.09 ± 0.39	14.72 ± 0.44	97.62 ± 0.46	80.62 ± 2.32	76.55 ± 3.88	41.95 ± 6.07	55.22 ± 9.11	84.31 ± 1.86	83.21 ± 2.12
Multiparous sow	15.47 ± 0.30	15.08 ± 0.50	98.63 ± 1.20	82.53 ± 2.20	69.30 ± 4.30	53.61 ± 4.65	85.54 ± 6.84	86.83 ± 1.24	83.48 ± 1.61
P-value	0.454	0.270	0.512	0.551	0.246	0.148	0.024	0.299	0.898
Wheat bran									
Primiparous sow	12.78 ± 0.48	12.52 ± 0.53	98.13 ± 0.52	62.95 ± 2.91	77.40 ± 3.01	42.02 ± 3.19	58.49 ± 2.61	69.44 ± 2.42	77.85 ± 5.27
Multiparous sow	13.28 ± 0.53	12.67 ± 0.78	95.55 ± 2.13	66.68 ± 4.54	71.66 ± 3.45	45.61 ± 5.97	81.68 ± 5.20	74.04 ± 3.05	72.24 ± 2.64
P-value	0.511	0.877	0.325	0.535	0.238	0.636	0.004	0.277	0.354

Each physiological stage included 5 replicates for primiparous sows and 6 replicates for multiparous sows. The values presented in the table are mean ± standard error.
Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

study, to our knowledge, is the first to explore the effects of both physiological stages and parity on nutrient and energy digestibility using various feed ingredients, including corn, barley, and wheat bran.

Effects of physiological stage on nutrient digestibility and feed value in sows

Currently, there is limited research on the effects of physiological stages on nutrient digestibility in sows. Moreover, due to variations in the nutrient composition and content of different feed ingredients, the observed differences lack consistency and generalizability. An experiment by Wang et al. (2024) demonstrated that the nutritional value of feed ingredients may vary with the physiological state of sows, suggesting that such differences should be considered when formulating diets. Zhuo et al. (2023) conducted a comparison study in which energy values and ATTD of CSM were compared between pregnant and non-pregnant sows. The study revealed that non-pregnant sows exhibited higher ATTD for OM and CP compared to pregnant sows, although no significant differences were observed for DE and ME. The energy values and nutrient digestibility of CSM were found to vary depending on its chemical composition, with a higher protein and lower fiber content exhibiting superior DE and ME values (Zhuo et al., 2023). In our experiment, both primiparous and multiparous sows exhibited higher values in certain digestibility and energy value for barley and wheat bran during lactation compared to the gestation or the post-weaning period. For primiparous sows, the ATTD of NDF and GE in barley and the ATTD of NDF in wheat bran were higher during lactation than during the post-weaning period. For multiparous sows, the ATTD of CP in corn was greater during gestation and lactation than post-weaning. Across all ingredients, ME values and CP digestibility were generally higher during lactation compared to gestation and post-weaning period. These findings suggest that part of nutrient digestibility was relatively higher during lactation compared to gestation and the post-weaning period. Our results are consistent with the study of Casas et al. (2022), which reported that lactating sows exhibited significantly higher ATTD for GE, DM, NDF, and OM compared to pregnant sows, regardless of whether they were fed a basal diet or a rice bran-based diet. Lactating sows have higher energy requirements compared to gestating sows, which are often difficult to meet through voluntary feed intake alone. The enhanced digestive capacity during lactation may be related to the increased energy and nutrient demands required to support lactation compared to gestation and the post-weaning period (Noblet and Etienne, 1987). Similarly, studies have shown that lactating sows, compared to pregnant and non-pregnant sows, exhibit an increased abundance of gut microbiota responsible for fermenting dietary fiber, leading to a higher production of short-chain fatty acids (SCFA). This elevated SCFA production stabilizes by day 28 of lactation. In addition to maintaining gut health, SCFA also serve as a direct or indirect energy source for the host (Liu et al., 2019; Wang et al., 2020). Both the research of Casas et al. (2022) on rice bran and our findings for the wheat bran and barley indeed indicate that fiber-rich ingredients exhibit greater differences in digestibility and energy values between lactation and gestation when compared to low-fiber ingredients. As indicated by our results, for corn, which has a lower fiber content compared to barley and wheat bran, no significant differences in energy and digestibility were observed across different physiological stages in both primiparous and multiparous sows. We speculate that this disparity can be attributed to the increased population of gut microbiota capable of fiber degradation during lactation. However, Wang et al. (2023) demonstrated that for full-fat soybeans, the ATTD of NDF was higher in non-pregnant and pregnant sows compared to lactating sows, while the energy values did not show significant differences across physiological stages. This suggests that more comparative studies on feeding different feed ingredients across physiological stages are needed to confirm whether the higher digestibility during lactation is limited to high-fiber ingredients. Differences in feed intake across physiological stages may have contributed to the observed variation in the evaluation of ingredient digestibility. In a recent study by Kim et al. (2025), gestating sows showed greater DE values for corn compared with lactating sows, which was primarily attributed to the lower DMI during gestation. However, in our study, the feed intake of lactating sows—both primiparous and multiparous—was lower than the 5.4 kg/day reported in their study. This difference in intake may help explain why no difference in DE values between gestating and lactating sows was observed in our experiment. Moreover, the overall digestibility values in our study were slightly higher than those reported in previous studies (Lowell et al., 2015; Kim et al., 2025), which may be attributed to differences in ingredient types, experimental design, and calculation methods. Overall, our results indicate that the type of feed ingredient influences the digestibility of different nutrients across physiological stages. Corn showed relatively stable energy values and nutrient utilization, while both barley and wheat bran exhibited increased digestibility during lactation. The relatively high ME:DE observed in this experiment may be partially attributed to incomplete nitrogen retention due to insufficient acidification during urine collection (Kim et al., 2022).

Comparison of energy value and nutrient digestibility between primiparous and multiparous sows

Currently, no relevant studies have been reported comparing the digestibility of feed ingredients between primiparous and multiparous sows. In our experiment, we compared the energy utilization and ATTD of nutrients in sows with different parities (primiparous vs. multiparous). Although most parameters showed no differences, we observed that multiparous sows exhibited higher ATTD of EE compared to primiparous sows for barley in three different physiological stages, and multiparous sows also exhibited higher ATTD of EE for wheat bran compared to primiparous sows. We hypothesize that this difference may be related to the maturity of the gastrointestinal tract and the composition of the gut microbiota. Primiparous sows are still in the growth and developmental stage, with certain organs, such as the pancreas, potentially not yet fully developed (Charbonneau et al., 1982; Owsley et al., 1986). The pancreas, as the primary source of lipase secretion, might not function at its full capacity in primiparous sows, leading to relatively lower lipase secretion levels and consequently reduced fat digestibility. Zhang et al. (2024) reported that the species richness of the gut microbiota in fifth-parity pregnant sows was significantly higher than that in primiparous sows. The gut microbiota of multiparous sows is generally more stable, which may contribute to enhanced fat breakdown and promote the secretion of lipase. Lim et al. (2019) found that the relative abundance of microbiota associated with lipid metabolism pathways increased with age in micro-pigs. The relatively high EE values observed in this experiment may be partially attributed to the analytical method used, such as whether acid hydrolysis was performed prior to ether extraction. In feces, EE can bind to calcium and other minerals to form insoluble complexes, potentially leading to an overestimation of EE digestibility. The NDF content in our study was determined using the Ankom filter bag technique, which is widely used for feed analysis. However, when applied to animal feces, this method may lead to an overestimation of NDF digestibility (Barbosa et al., 2015; Koh et al., 2025). Additionally, our results revealed that primiparous sows exhibited a higher ATTD of GE for the corn during gestation compared to multiparous sows. During lactation, the ATTD of NDF and GE for the barley in primiparous sows was also higher than that in multiparous sows. These findings suggest that, while the ATTD of EE in primiparous sows may be relatively lower than that in multiparous sows, the ATTD of other nutrients is not necessarily inferior and may even surpass that of multiparous sows. Studies have shown a direct relationship between body weight and ATTD of energy in growing pigs. Noblet and Shi (1994) investigated the effect of body weight on feed digestibility by feeding growing pigs at different body weights (45 kg, 100 kg, and 150 kg). This study revealed differences in nutrient digestibility and energy coefficients between the 45 kg group and the 100 kg group. However, the differences between the 100 kg group and the 150 kg group were minimal, with the energy digestibility coefficient differing by only 0.8% (Noblet and Shi, 1994; Noblet, 2000). In our experiment, although the body weight of primiparous sows was smaller compared to multiparous sows, it was still far above 150 kg, and there were no significant differences in most DE and ME between the two groups of sows. This suggests that body weight cannot be used as a direct reference indicator for evaluating energy utilization and the ATTD of nutrients in sows. Additionally, Haydon et al. (1984) reported that feed intake levels have an influence on the apparent digestibility of nutrients throughout the digestive tract in growing pigs; as feed intake levels decrease, digestibility may slightly increase. Primiparous sows typically have lower feed intake compared to multiparous sows in the lactating period, which may result in longer feed retention time in the gastrointestinal tract. This extended retention allows digestive enzymes and gut microbiota to act more effectively on the nutrients. Moreover, primiparous sows require higher nutrient levels to support their growth, and we speculate that aging of the digestive organs in high-parity multiparous sows may also influence nutrient digestibility outcomes (Whittemore, 1996).

Conclusions

Our study investigated the effects of physiological stages and parity on the ATTD of nutrients and energy utilization in sows. The results showed that the physiological stage played a critical role, with lactating sows exhibiting higher digestibility of certain nutrients and greater energy utilization for barley and wheat bran compared with post-weaning sows. Parity also influenced nutrient digestibility; multiparous sows generally showed higher EE digestibility for barley and wheat bran, while primiparous sows exhibited higher digestibility of certain nutrients under specific conditions.

Supplementary Data

Supplementary data are available at the *Journal of Animal Science* online.

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Author Contributions

Zi-Xi Wei (Data curation, Formal analysis, Investigation, Writing—original draft), Lei Xu (Data curation, Investigation, Methodology), Jiaqi Yang (Data curation, Investigation), Qingyue Bi (Data curation, Investigation), Martine Schroyen (Supervision, Writing—review & editing), Xian-Ren Jiang (Funding acquisition, Methodology, Writing—review & editing), Sheng Cui (Funding acquisition, Writing—review & editing), Xi-Long Li (Conceptualization, Funding acquisition, Resources, Supervision, Writing—review & editing), and Yu Pi (Conceptualization, Funding acquisition, Project administration, Supervision, Writing—review & editing)

Conflict of interest statement.

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and 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.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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