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ORIGINAL ARTICLE

Nutritional strategies to cope with reduced litter weight gain and total tract digestibility in lactating sows

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Summary

Twelve lactating sows were used to evaluate the effects of reducing dietary crude protein (CP) (14% vs. 12%) and increasing neutral detergent fibre (NDF) levels (18% vs. 22%) on litter performance, total tract apparent digestibility and manure composition in a 4 × 4 latin square arrangement during a 36-day lactation period. Diets were isoenergetic (2.9 Mcal ME/kg) and had similar total lysine content (0.9%). In addition, a second aim was to compare a reference external marker method (Cr_2O_3) with an internal feed marker [acid-insoluble ash (AIA)] for the calculation of apparent total tract digestibility of nutrients in lactating sows. The reduction of dietary CP level in lactating sows had no effect on either live-weight or backfat thickness or apparent total tract digestibility of nutrients. However, the piglets' average daily gain (ADG) was reduced in low dietary CP diets, which suggests that sows reduced milk production due to an underestimation of certain essential amino acid requirements (e.g. valine). The increase of dietary NDF level did not affect sow and litter performance. Nevertheless, the total tract apparent digestibility of organic matter, CP and carbohydrates was reduced, and ether extract digestion was increased in high NDF compared to normal NDF diets equally balanced for ME and lysine content. The coefficients of total tract apparent digestibility of nutrients in lactating sows were greater when using AIA compared to Cr_2O_3 marker, regardless of dietary CP or NDF level, but their coefficients of variation were lower in the former than in the latter. In lactating sows, a trade-off between litter performance and nutrient digestion is established when reducing dietary CP or increasing NDF levels while maintaining similar lysine content through synthetic amino acids and balancing metabolizable energy through dietary fat sources.

Keywords swine, feed formulation, nutrient requirements, nutrient excretion, faecal digestibility, indigestible markers

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Introduction

In some European countries, for example Spain, the sow diets are normally lower in energy than in other world areas because high-fibre (and lower energy) ingredients are more economical relative to maize than in USA (Tokach and Golçalves, 2015). Therefore, ingredients with higher fibre content, such as sugar-beet pulp, wheat bran or sunflower meal, are often used at low levels in the lactation diet, which is normally supplied on an *ad libitum* pattern to meet nutrient requirements.

In addition, the current environmental concern leads to avoid nitrogen excretion, which can be achieved by increasing the quality of dietary protein (e.g. adding synthetic amino acids) to reduce feed crude protein (CP), together with an increase of dietary neutral detergent fibre (NDF) (as a measure of fermentable fibre). This combination may reduce the digesta transit time and shifts the nitrogen excretion balance from urine to faeces (Morgan and Whittemore, 1988), although its use has been mostly studied in growing-finishing pigs (Zervas and Zijlstra, 2002; Morazán et al., 2015). Results obtained in growing pigs cannot be fully extrapolated to lactating sows because adult intestine has a greater digestion capacity (Noblet and Shi, 1993). Moreover, digestibility data from dry sows have scarce value to apply to nursing sows, as feed composition and digestive traits (e.g. intake level) differ from non-lactating animals.

This experiment hypothesized that the reduction of dietary CP and increase of NDF would allow improved apparent digestibility coefficients of nutrients without detrimental effects on productive performance of lean lactating sows. In addition, a secondary aim was to compare a reference external marker method (Cr_2O_3)

with an internal feed marker [acid-insoluble ash (AIA)] for the calculation of apparent total tract digestibility of nutrients in lactating sows.

Materials and methods

Animals, diets and experimental design

This experiment was conducted in the research facilities of the *Centre d'Estudis Porcins* (Torrelameu, Lleida, North-eastern Spain, 41°42′24″N, 0°42′11″E; 201 m above sea level) between June 2012 and January 2013. All procedures were carried out under Project Licence CEEA 03/01-10 and approved by the in-house Ethics Committee for Animal Experiments at the University of Lleida. The care and use of animals were in accordance with the Spanish Policy for Animal Protection RD53/2013, which meets the European Union Directive 2010/63 on the protection of animals used for experimental and other scientific purposes.

One week before farrowing, twelve pregnant sows (Large White × Landrace) equally managed during gestation were allocated in individual farrowing crates (2 × 2.1 m²) in a controlled environment room equipped with a forced ventilation system which drove an airflow (78.4 ± 4.4 m^3/h) that allowed maintaining mean daily temperature (21.1 ± 1.8 °C) and mean relative humidity (59.6 ± 5.1%).

The experiment was designed as a repeated 4 × 4 Latin square arrangement, with 12 sows fed four different diets during four periods per block. Immediately after farrowing [nine primiparous (live-weight 209 ± 11 kg) and three multiparous sows (live-weight 285 ± 7 kg)], litters were standardized (10.2 ± 1.0 piglets) and dams were randomly assigned to 1 of 4 diets that were formulated to provide normal crude protein and normal NDF (14% CP and 18% NDF), normal crude protein and high NDF (14% CP and 22% NDF), low crude protein and normal NDF (12% CP and 18% NDF) or low crude protein and high NDF (12% CP and 22% NDF) (Table 1).

The diets were formulated to be isoenergetic [2.90 Mcal of metabolizable energy (ME)/kg of feed], and they were supplemented with synthetic amino acids to achieve an ideal amino acid ratio for lysine, methionine, threonine and tryptophan, on the basis that Lys was the first-limiting amino acid. In addition, diets were fortified to meet vitamin and mineral requirements (NRC (National Research Council), 2012) and they were added phytase to improve phosphorus digestibility.

The diets (milled-ground through a 6-mm screen, which yielded 1- to 2-mm-sized feed meal) mainly comprise cereals (maize and wheat), alfalfa meal and gluten feed as a source of CP, and/or oilseed meals, sugar-beet pulp and cereal straw as a source of NDF. The composition (based on FEDNA 2010 composition

Table 1 Feedstuff and nutrient composition of the experimental diets differing in crude protein (CP) content (low, LP vs. normal, NP) and neutral detergent fibre (NDF) content (normal, NF vs. high, HF)

	LP		NP	
Feedstuff, %	NF	HF	NF	HF
Maize	50.2	41.6	40.4	30
Wheat (CP, 112 g/kg)	20	9.7	20	14.3
Gluten feed (CP, 210 g/kg)	4.4	3.2	10	10
Soybean meal (CP, 470 g/kg)	5	–	9.2	2.1
Sunflower meal (CP, 360 g/kg)	1.3	15	1.5	15
Alfalfa meal (CP, 152 g/kg)	14.8	11.2	14.8	10.8
Sugar-beet pulp	–	8	–	8
Cereal straw	–	3	–	3
Sunflower oil	–	4.7	–	3.4
Calcium carbonate	1.4	1	1.4	1
Sodium chloride	0.5	0.5	0.5	0.5
L-Lysine	0.57	0.52	0.44	0.4
L-Threonine	0.13	0.06	0.03	–
L-Tryptophan	0.04	0.01	0.03	–
Bicalcium phosphate dihydrate	1.4	1.2	1.4	1.2
Vitamin–mineral premix*	0.3	0.3	0.3	0.3
Calculated composition†				
ME, Mcal/kg	2.90	2.90	2.90	2.90
NE, Mcal/kg	2.13	2.21	2.14	2.26
Lys, %	0.90	0.86	0.94	0.86
SID Lys, %	0.71	0.79	0.81	0.73
SID Lys/ME, g/Mcal	2.45	2.72	2.79	2.52
Met, %	0.21	0.26	0.24	0.28
Met+Cys, %	0.42	0.48	0.50	0.55
Thr, %	0.56	0.53	0.56	0.54
Trp, %	0.17	0.15	0.19	0.17
Val, %	0.54	0.62	0.64	0.70
Analysed composition				
DM, %	88	89.5	89	89.7
NDF, %	17.5	22.2	18.7	23
CP, %	11.8	11.5	14.1	13.7
Total Lys, %	0.90	1.11	1.00	0.94
Starch, %	43.7	34.1	37.8	33.8
Ash, %	7.5	7.1	7.6	7.5
Ether extract, %	2.3	6.9	2.3	5.4
Phosphorus, %	0.69	0.65	0.73	0.79
Potassium, %	0.53	0.59	0.71	0.69

*Provided by kilogram of completed diet: 12 000 IU of vitamin A, 1600 IU of vitamin D3, 37.5 mg of vitamin E (dl-alpha-tocopheryl acetate), 2 mg of vitamin K3; 0.2 mg of biotin, 172 mg of choline (choline chloride), 2.5 mg of folic acid, 21.3 mg of niacin, 11.5 mg of pantothenic acid, 3.9 mg vitamin B2, 1.2 mg of vitamin B1, 2.7 mg of vitamin B6, 0.02 mg of vitamin B12; 0.9 mg of sepiolite, 0.1 mg of ethoxyquin, 0.02 mg of propyl gallate; 250 phytase units (FTU/kg) (EC 3. 1. 3. 26); 0.05 mg of cobalt (cobalt carbonate monohydrate), 10 mg of copper sulphate, 0.7 mg of iodine (anhydrous calcium iodate), 90 mg of iron (ferrous carbonate), 39.3 mg of manganese oxide, 0.2 mg of sodium selenite, 105.5 mg of zinc oxide.
†Based on FEDNA (2010).

tables) and analysed nutrient value (AOAC International 2000) of the diets are shown in Table 1. Chromic oxide (in feed incorporated at a dose of 2 g/kg of feed) and AIA were used as external and internal indigestible digestibility markers respectively.

Each experiment consisted of four phases (9 ± 1 day each) and lasted 36 ± 2 days. Every phase included an adaptation period of 6 days and an excreta collection period of 3 days. At the first day of diet adaptation, the sows received 3.5 kg of feed and it was gradually increased (+0.5 kg/day) until a maximum of 7 kg or 9 kg in primiparous and multiparous sows respectively. The sows were fed three times a day (09:00, 13:00 and 18:00 h) in mash form (2:1, water-to-feed ratio). Fresh water (pH = 8.15, electric conductivity = 490 μS/cm, sodium concentration = 20.0 mg/l; chloride concentration = 24.1 mg/l) was offered *ad libitum* through additional nipple drinkers.

The piglets were provided dextran iron supplement intramuscular (Dextrafer-200, Laboratorios Syva, León, Spain) and coccidiostatic (Tratol, Pfizer Salud Animal, Alcobendas, Spain) on the 5th day of age. During the period 3 and 4 of the experiment (from day 19 of age onwards), the litters were creep fed with a pre-starter diet (19.5% CP, 1.4% total lysine and 6.2% crude fat) at a fixed amount of 75 g/piglet and 200 g/piglet, during period 3 and 4 respectively.

Measurements

Feed and water use were recorded daily. Every morning between 08:00 and 09:00 h, feed refusals were weighed and removed and diets were supplied according to the amount refused the previous day. Feed intake was calculated daily as the difference between feed allowance and refusals collected on the next morning on a dry matter basis. The water intake of each farrowing crate was measured by water flow meters within the delivery lines and recorded every morning. Extreme values that deviated more than ±4 SD from the mean of the measured data were excluded from the data sets.

A drawer was located beneath each lactation crate to allow the collection of slurry (faeces and urine). During the excreta collection (days 6 to 9 of each period), the excreta was collected once daily from the drawers below lactation crates and weighed to calculate the manure yield. In addition, the pH and electrical conductivity (EC) of slurry were measured *in situ* with a hand-held electrode (MM40; Crison Instruments S.A., Alella, Spain). Thereafter, 1 kg homogeneous samples were collected for subsequent analysis of physical and chemical composition and stored at −20 °C.

Faecal samples (approximately 50 g) were collected using rectal stimulation at 09:00 h the last 3 days of each dietary period. Faecal samples were stored at −20 °C until chromium and proximate chemical analysis. After thawing, faecal samples from each sow were pooled to produce one grab sample per collection period.

The total tract apparent digestibility of nutrients was calculated using the nutrient-to-marker ratio in the diet and faeces, as follows:

$$\text{Apparent digestibility coefficient (\%)} = 100 \times [100 \times (\text{marker}_{\text{diet}} / \text{marker}_{\text{faeces}}) \times (Z_{\text{faeces}}/Z_{\text{diet}})]$$

where Z_{faeces} and Z_{diet} are the nutrient concentrations (%) in the faeces and in the diet respectively; $\text{marker}_{\text{faeces}}$ and $\text{marker}_{\text{diet}}$ are the concentrations (%) of chromium oxide or AIA in the faeces and in the diet respectively.

Individual piglet live-weight was recorded within 24 h after birth. The sows and their litters were individually weighed at the beginning and at the end of each excreta collection period (days 6 and 9; days 15 and 18; days 24 and 27; and days 33 and 36 of lactation for phase I to IV respectively). Sows' backfat thickness was measured at the same time at 6.5 cm from the midline on both sides of the last rib (P2 site) by A-mode ultrasonography (Lean-meater, Renco Corporation, Minneapolis, MN, USA).

Milk samples of approximately 40 ml of four sows were manually extracted at days 26 (phase III) and 35 (phase IV) of lactation. After suckling on these days, the piglets were separated from the dam, and sows were injected with 10 IU oxytocin i.m. and 10 min later all functional glands were hand milked. The samples were stored at −20 °C until composition analysis.

During the phases I and II, before creep feeding was offered, milk production was estimated from initial piglet live-weights (LW) and subsequent ADG at each phase according the equation developed by Noblet and Etienne (1989):

$$\text{Milk production (g/day)} = (2.50 \times \text{piglet ADG}) + (80.2 \times \text{initial piglet LW}) + 7$$

Chemical analyses

Feed and faecal dry matter (DM) (index no. 934.01), ash (index no. 942.05), acid hydrolysed ether extract (EE) (index no. 920.39) contents were determined according to the AOAC methods (AOAC, 2000). Neutral detergent fibre analyses were carried out following the sequential procedure of Van Soest et al. (1991), with the Ankom200/220 fibre analyzer 6 (Ankom Technology, 1998). The NDF assay was conducted with a heat stable amylase and expressed exclusive of residual ash (aNDFom). Feed samples were also analysed for total lysine (HPLC–fluorescence), crude fibre (Weende method), starch (polarimetry), phosphorus (ultraviolet–visible spectroscopy) and potassium (atomic absorption spectrometry). All the samples were analysed in duplicate.

The concentration of carbohydrates (CHO) in diets and faeces was calculated as follows (Urriola and Stein, 2012):

$$\text{CHO} = \text{DM} - (\text{CP} + \text{EE} + \text{Ash})$$

Feed and faecal samples were analysed for Cr concentration after nitro-perchloric acid (ratio 5:1) digestion (De Vega and Poppi, 1997) using inductively coupled plasma optical emission spectroscopy (HORIBA Jobin Yvon, Activa family, with AS-500 Autosampler; HORIBA Scientific, Madrid, Spain).

Acid-insoluble ashes were analysed according to a standard procedure (BOE, 1995) based on the method of Shrivastava and Talapatra (1962). Briefly, 5 g of ground samples of feed or excreta was hydrolysed in a beaker with 75 ml of 3 N HCl and 25 ml of distilled water and boiled for 30 min. The sample was then filtered through ash-free filter paper and washed the residue with 50 ml of hot distilled water. The filter with residue was put in a tared crucible, dried at 103 °C for 24 h and ashed at 550 °C for 3 h for crude ash determination. Afterwards, ashes were transferred again to a beaker with 75 ml of 3 N HCl and gently boiled for 15 min. The dilution was filtered again through an ash-free filter and washed with hot distilled water until disappearance of acid reaction. Finally, the filter with residue was dried and ashed on a tared crucible at 550 °C for 3 h. The crucible and its content were cooled in a desiccator to room temperature and weighed to calculate the AIA content.

The excreta samples were analysed for dry matter (forced air oven at 60° C), bulk density (densimetry), electrical conductivity (EC) (conductometry), pH (electrometry), ammonium-N (volumetric titration), phosphorus (ultraviolet-visible spectroscopy) and potassium (atomic absorption spectrometry), according to the standard methods for the examination of water and wastewater (APHA, 1995). Organic N content of manure was calculated as the difference between total N and ammonium-N content on DM basis.

The milk samples were allowed to thaw at room temperature and agitated to obtain a homogeneous mixture. An aliquot of milk was freeze-dried for the analysis of gross energy (GE) using a bomb calorimeter (Gallenkamp auto bomb CBA-305-010M; Sussex, UK) and CP (total N × 6.25) according to AOAC 7 (2000) (Table 2).

Statistical analysis

The data were analysed using the SAS statistical software (SAS Institute, Cary, NC, USA) by means of a repeated-measures mixed model (PROC MIXED):

$$\begin{aligned} Y_{ijklm} = {} & \mu + \text{PHASE}_i + A_j + \text{CP}_k + \text{NDF}_l + \text{BATCH}_m \\ & + (\text{PHASE}_i \times \text{CP}_j) + (\text{PHASE}_i \times \text{NDF}_l) + \\ & (\text{CP}_k \times \text{NDF}_l) + E_{ijklmn} \end{aligned}$$

where Y_{ijklm} = dependent variable, μ = overall mean, PHASE_i = phase of lactation effect (i = 1, 2, 3, 4), A_j = sow random effect j, CP_k = dietary CP level effect (k = LP, NP), NDF_l = dietary NDF level effect (l = NF, HF), BATCH_m = batch effect (1, 2, 3) and E_{ijklmn} = residual error.

The models analysing the sources of variation of the coefficients of apparent total tract digestibility of nutrients in the sows considered the marker (AIA, Cr_2O_3) and its second degree interactions with dietary CP and dietary NDF effects. In this case, the phase of lactation effect was omitted to simplify these models as it did not reduce the residual variance. The experimental unit for the parameters included in the study was the individual sow. Variances were unequal; therefore, calculations of the standard error (SE) and degrees of freedom were based on the Kenward–Roger method. Differences between least square means were assessed using the Tukey test. Values are presented as least square means ± SE. The level of significance was set at 0.05, but tendencies were commented if the level of significance was below 0.10. Second-degree interaction effects were retained in the models, and they are specifically commented in the text if they reached statistical significance.

Table 2 Milk composition in lactating sows at days 26 and 35 (phase 3 and 4 respectively) when fed diets differing in crude protein (CP) content (low, LP vs. normal, NP) and neutral detergent fibre (NDF) content (normal, NF vs. high, HF)

	CP		NDF	
Item	LP	NP	NF	HF
Gross energy, Mcal/kg of milk	1.24	1.22	1.22	1.24
CP, g/100 g of milk	5.25	5.54	5.41	5.38

Results

Sow and litter productive performance

The productive performance of sows is presented in Table 3. Feed intake was similar between CP dietary levels ($p > 0.05$) and between dietary NDF levels ($p > 0.05$). As expected, the lactation phase did affect sow consumption. Average daily feed intake was lower during the first lactation period than subsequently (4.8 vs. 6.5 ± 0.14 kg DM/day for lactation phase 1 vs. respectively).

The reduction of dietary CP and/or the increase of dietary NDF did not affect either water intake or the water-to-dry matter feed ratio disappearance (Table 3, $p > 0.05$). The proportion of sows LW and backfat thickness variation were not different among treatments ($p > 0.05$). However, the estimated milk production between sows fed low and normal CP dietary levels was significantly different ($p < 0.001$). Milk yield was reduced by decreasing CP dietary level.

There were no differences in the coefficient of variation (CV) of litter LW at the end of each phase, while the piglets' ADG was affected by the interaction between CP level and lactation phase (Fig. 1; $p < 0.05$); and between NDF level and lactation phase (Fig. 1; $p < 0.05$). The normal dietary CP levels produced greater piglet ADG than low CP dietary levels at phase II and IV ($p < 0.05$). Moreover, piglets from dams fed high dietary NDF level had higher ADG than those from normal dietary NDF level at phase 4 of the study (28 to 36 days of lactation) ($p < 0.05$).

Faecal dry matter content and total tract digestibility of nutrients

The reduction of dietary CP level triggered an increase of faecal DM content during the first lactation phase (from parturition until day 9 of lactation) (27.1 vs. 23.5 ± 0.7% of DM, in LP and NP diets respectively; $p < 0.05$). Subsequently, these differences between diets were not significant (phases 2, 3 and 4, or from day 10 until day 36 of lactation) (overall 24.8 vs. 24.6 ± 0.6% of DM, in LP and NP diets respectively). The increase of dietary NDF did not affect faecal DM content throughout the experimental period (overall 24.6 vs. 25.1 ± 0.35%, in NF and HF diets respectively; $p > 0.05$).

The apparent total tract digestibility of nutrients in sows fed different dietary CP and NDF levels and according to each marker methodology is presented in Table 4. There were no interactions ($p > 0.05$) between dietary CP level, NDF level and marker method for any of the analysed variables.

The reduction of dietary CP did not alter significantly the coefficient of apparent total tract digestibility of the analysed nutrients ($p > 0.05$). However, there was a tendency ($p = 0.08$) for reduced total tract CP digestibility in LP compared to NP diets. Likewise, dietary NDF level affected organic matter, DM, CP, CHO and EE coefficients of apparent total tract digestibility. In all of them, except for EE, a reduction of total tract digestibility coefficient was observed when increasing dietary NDF levels.

Table 3 Productive performance of lactating sows fed diets varying crude protein (CP) content (low, LP vs. normal, NP) and neutral detergent fibre (NDF) content (normal, NF vs. high, HF)

	CP		NDF			p-Value		
Item	LP	NP	NF	HF	SE	CP	NDF	CP × NDF
Sows parameters								
Feed intake, kg DM/day	6.14	6.04	6.18	6.00	0.10	0.452	0.195	0.420
Water intake, litres/day	30.0	27.7	30.31	27.31	3.20	0.512	0.380	0.301
Water-to-feed ratio, litres/kg	4.58	4.29	4.62	4.26	0.479	0.613	0.521	0.194
Initial LW, kg	202.0	201.2	201.9	201.3	4.00	0.759	0.819	0.221
Individual LW variation, %	−2.94	−2.55	−2.85	−2.65	0.76	0.732	0.867	0.643
Initial backfat thickness, mm	8.81	9.05	9.13	8.74	0.59	0.434	0.208	0.060
Back fat thickness variation, mm*	−0.54	−0.72	−0.77	−0.50	0.20	0.549	0.375	0.158
Estimated milk yield, kg/day	7.70[b]	9.70[a]	8.87	8.53	5.27	<0.001	0.603	0.893
Litter parameters								
Piglet ADG, g	217[b]	252[a]	233	236	9.9	0.031	0.802	0.223
Coefficient of variation of litter LW at the end of phase, %	16.93	16.43	16.99	16.37	1.73	0.577	0.464	0.625

Within rows, least square means with different superscript letters (a,b) are different ($p < 0.05$).
*Backfat thickness measured at the P2 position (65 mm from the midline).

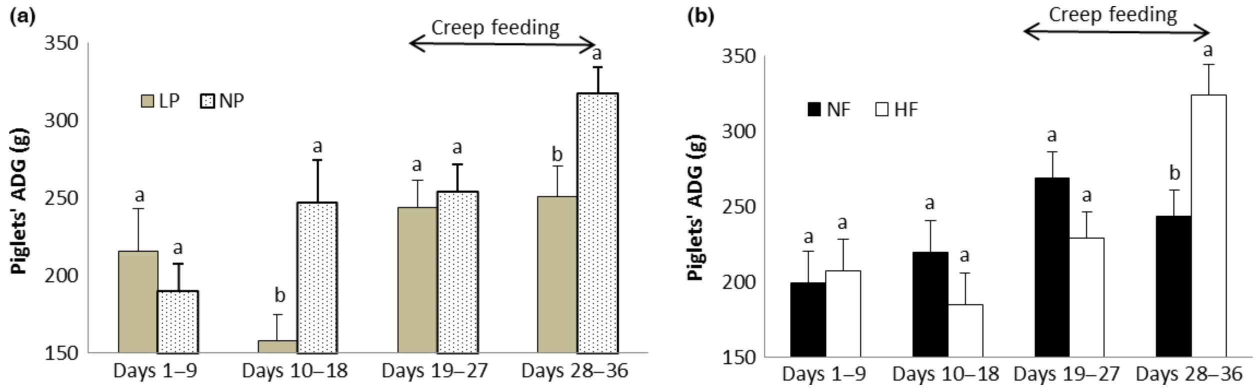

Fig. 1 Effect of dietary crude protein (CP) level (low, LP vs. normal, NP) (a) and neutral detergent fibre (NDF) (b) according to lactation phase on piglets' average daily gain (ADG, g). Different letters above each bar indicate significant differences between dietary CP and/or NDF level ($p < 0.05$). 13

Table 4 Coefficients of apparent total tract digestibility of nutrients in lactating sows fed diets varying crude protein (CP) content (low, LP vs. normal, NP) and neutral detergent fibre (NDF) content (normal, NF vs. high, HF)

	CP		NDF		Marker			p-Value*		
(%)	LP	NP	NF	HF	AIA	Cr_2O_3	SE	CP	FND	Marker
Organic matter, OM	92.94	93.11	94.05^x	92.00^y	93.87^a	92.18^b	0.40	0.750	<0.001	0.002
Dry matter, DM	91.86	92.14	93.08^x	90.92^y	92.99^a	91.02^b	0.43	0.652	0.001	0.002
Neutral detergent fibre, NDF	35.89	38.99	39.32	35.56	43.32^a	31.57^b	3.38	0.376	0.281	0.001
Crude Protein, CP	64.14	68.41	69.36^x	63.19^y	70.32^a	62.24^b	1.88	0.079	0.012	0.001
Carbohydrates, CHO	78.76	77.44	82.19^x	74.01^y	80.73^a	75.47^b	1.27	0.425	<0.001	0.002
Ether extract, EE	35.46	33.96	15.41^y	54.00^x	41.09^a	28.33^b	3.30	0.691	<0.001	0.002
Phosphorus, P	35.72	38.28	37.09	36.87	39.73	34.59	1.95	0.445	0.947	0.158 8

Within rows, least square means with different superscript letters (a,b) are different ($p < 0.05$).
*The interactions between CP levels. FND level and marker were not significant in any parameter ($p > 0.05$).

In addition, marker methodology affected total tract digestibility results. All nutrients except phosphorus showed higher digestibility values ($p < 0.05$) when the inert marker (AIA) was used as a reference substance compared to the external marker (Cr_2O_3). The coefficients of variation of the total tract digestibility of nutrients were approximately twice in Cr_2O_3 compared to AIA (12.2% and 7.5% for carbohydrates, 19.9% and 11.8% for CP and 84.8% and 38.5% for NDF respectively).

Manure composition

The daily amount of manure produced per sow differed statistically between dietary CP levels ($p = 0.05$, Table 5). Sows fed low dietary CP levels produced less manure per day. There were no statistical differences between dietary NDF levels or among lactation phases in the daily amount of fresh manure produced per sow ($p > 0.05$). Nevertheless, manure output (on a DM basis) was affected by dietary NDF level ($p < 0.05$). The increase of dietary NDF increased manure output (kg DM/day).

Manure composition was not affected by CP dietary levels ($p > 0.05$), but pH of manure was lower in sows fed low CP compared to normal CP diets ($p < 0.01$). The increase of the dietary NDF level reduced the density ($p < 0.01$), the EC ($p < 0.05$), and the phosphorus (P_2O_5) content of slurry ($p < 0.05$). In addition, there was a tendency for greater OM content ($p = 0.09$) and lower ammonium-N content ($p = 0.07$) in manure from sows fed high NDF compared to normal NDF diets.

Discussion

Effect of reducing dietary CP on sow and litter performance, apparent total tract digestibility and manure composition

The reduction of dietary CP did not affect significantly sow feed intake, LW change or backfat losses, in agreement with earlier studies (Dourmad et al., 1998;

Table 5 Manure yield and composition from lactating sows housed with their litters and fed diets varying crude protein (CP) content (low, LP vs. normal, NP) and neutral detergent fibre (NDF) content (normal, NF vs. high, HF)

	CP		NDF			p-Value*	
Item	LP	NP	NF	HF	SE	CP	NDF
Manure production, kg/day	13.43[a]	17.33[b]	15.55	15.20	1.66	0.050	0.118
Manure output, kg DM/day	2.29	2.62	2.25[b]	2.66[a]	0.18	0.118	0.050
Manure composition†							
pH	6.45[a]	6.76[b]	6.65	6.55	0.07	0.001	0.246
EC (dS/m)	12.04	13.02	13.33[b]	11.72[a]	0.72	0.230	0.038
Density, g/l	1029.64	1034.63	1036.82[b]	1027.45[a]	2.801	0.144	0.007
Dry matter, %	16.46	15.38	13.72[a]	18.12[b]	1.32	0.336	<0.001
Organic matter, % on a DM basis	83.27	85.08	82.50	85.85	1.52	0.347	0.089
Total N, g/kg DM	34.91	35.06	38.84	31.13	3.18	0.971	0.106
Ammonium-N, g/kg DM	8.09	8.85	10.33	6.59	1.39	0.664	0.073
Organic N, g/kg DM	26.83	26.21	28.50	24.54	1.90	0.797	0.161
Phosphorus, g/kg DM	14.10	12.89	15.74[b]	11.25[a]	1.32	0.504	0.022
Potassium, g/kg DM	23.32	20.31	24.12	19.52	2.23	0.294	0.166

*The interactions between CP level and FND level were not significant in any parameter ($p > 0.05$).
†Manure elements are expressed in the form they may be uptaken by plants: NH4+-N (ammonium-N), P_2O_5 (phosphorus) and K_2O (potassium).

Yang et al., 2009; Huber et al., 2015). A positive relationship between dietary CP level (from 5% to 23% of CP) and feed intake was observed in gilts during a 4-week lactation (Shields et al., 1985; King et al., 1993). In the present study, the maintenance of similar dietary lysine levels in all diets attenuated the potential differences in sow feed intake. Before creep feeding was applied (phases 1 and 2, days 1–18), the estimated energy balance (Noblet and Etienne, 1989) would have been lower in the sows fed NP diets compared to their counterparts fed LP diets. However, the reduction in litter growth rate (and subsequently milk yield) in the LP group was not counterbalanced by lower body reserves mobilization.

The piglets' ADG from sows fed LP diets was 36% less than piglets' ADG from sows fed NP diets during phase 2 (days 10–18) of lactation. Because litter growth rate and milk production are closely related (Noblet and Etienne, 1989), the reduction of litter litter growth rate suggests that dietary CP may be the main limiting factor for piglets' growth. Therefore, milk yield, that peaks at 3rd week post-farrowing (Etienne et al., 2000), may be impaired by low dietary CP (around 12% of CP). Similar results were reported in primiparous sows by King et al. (1993) and Manjarin et al. (2012), who found a decreased litter growth rate and milk production in response to a deficient dietary CP supply (below 13.5%). Accordingly, Kusina et al. (1999) found a positive relationship between dietary CP level (graded values from 5.5% to 15.5% of dietary CP) and milk production, and Huber et al. (2015) reported increased efficiency of using retained N for milk protein production in response to improvement in dietary amino acid balance with crystalline amino acid supplementation.

Applying creep feeding at the third phase (days 19–27) of lactation compensated the differences between piglets' ADG of sows fed diets with different dietary CP level. However, such effect was transient as at the fourth phase (days 28–36), the piglets raised by sows fed normal dietary CP level had greater ADG than those from sows fed low dietary CP level. Probably, these results were due to the fixed equal amount of creep feed supplement in all dietary treatments. After all, the reduction of piglets' ADG from sows fed low CP diets did not have deleterious effects on the coefficient of variation of litter LW at the end of each lactation phase.

Moreover, Laspiur et al. (2009) suggested that the imbalances due to excesses or deficiencies in dietary amino acids reduce the efficiency of the dietary nitrogen utilization by the animal, limiting milk protein synthesis. The order of limiting amino acids for lactating sows varies according to body tissue mobilization level (Kim et al., 2009). In this study, the *ad libitum* feed supply may support a low level of sow LW losses. In this situation, sows without body protein loss need more dietary valine relative to lysine, and thereby, the most limiting amino acids are lysine, valine and threonine. Although an attempt was made to attain an ideal amino acid pattern on the basis of lysine, methionine, threonine and tryptophan requirements, the effective valine supply did not met the actual estimated requirements according to NRC (2012) and it would have been necessary to supplement the diet with crystalline valine, especially to the LP diets.

The reduction of dietary CP had no impact on the sow apparent total tract digestibility of most nutrients but only a slightly lower total tract digestibility of dietary CP, as previously found in growing pigs when reducing dietary CP from 18% to 12.3% (Le Bellego et al., 2001).

Faecal dry matter content was only increased during phase 1 (days 1–9) of lactation in sows fed low dietary CP levels. Tabeling et al. (2003) show that parturition leads to a higher DM content in faeces and reduced defecation frequency. In our study, greater DM content in faeces and lower manure production was noticeable in the first days post-partum of sows fed low dietary CP, although it could not be associated with lower water disappearance.

In the present study, the reduction of dietary CP did not produce significant differences in manure composition but only a lower pH. Some previous reports found that low CP diets consistently decreased manure ammonium content (Kerr et al., 2006; Ziemer et al., 2009). This discrepancy may be probably due to the fact that both dietary CP levels evaluated in the current study were rather low (12% vs. 14% of CP), and thus, the potential to decrease the nitrogen excreted may have reached a threshold.

Effect of increasing dietary NDF on sow and litter performance, apparent total tract digestibility and manure composition

The increase of dietary NDF did not affect negatively either sow feed intake, LW or backfat thickness. High-fibre diets are normally used during pregnancy to induce satiety and prevent constipation, and they are also recommended during, at least, the days around farrowing to improve colostrum composition and therefore to reduce piglet mortality (Loisel et al., 2013). However, their use is restricted during lactation so that feed energy density is not impaired. In this study, vegetable fat sources (sunflower oil) were used to balance the energy content of high NDF diets, which were consumed at a similar amount to normal NDF diets.

Feed intake decreases as the dietary energy concentration increases, and as a result, total lysine intake may decline when formulating high-fibre diets for lactating sows at a certain lysine percentage of the diet. Hence, it is recommended to use the SID lysine to ME ratio as the optimum method of expressing the lysine requirement (Xue et al., 2012). Although NRC (2012) requirements for lactation sows are based on greater ME and SID lysine content than in the present study (3.3 Mcal/kg vs. 7.2–8.7 g/kg respectively), the *ad libitum* feeding pattern allowed meeting most of the estimated nutrient requirements of sows on a daily basis. However, according to the above-mentioned order or limiting amino acids (lysine, valine and threonine) when sow LW losses are reduced (Kim et al., 2009), the increase of dietary NDF (22% vs. 18% NDF) allowed greater valine-to-lysine ratio (59% vs. 49%) and greater threonine-to-lysine ratio (60% vs. 54%) compared to normal NDF diets.

The dietary NDF levels of sows had only mild effects on litter performance. The piglets raised by sows fed dietary high NDF only showed greater ADG at the end of lactation (phase 4, days 28–36) compared to their counterparts raised by dams fed normal NDF. This outcome is in agreement with Renaudeau et al. (2003), who found that litter LW gain was greater in lactating sows fed high NDF diets (22% NDF vs. 19% NDF) during a 28-day lactation. Although the estimated milk yield during phases 1 and 2 (days 1 to 18 of lactation) based on piglets' ADG (Noblet and Etienne, 1989) did not differ between sow dietary NDF levels, there might be subsequent differences in milk yield, its nutrient composition or lactation curve persistency between sows fed high and normal NDF diets.

Despite the lack of differences in sow productive performance, the nutrient digestion was highly affected by increasing dietary NDF. Even though diets were formulated to be isoenergetic, the apparent total tract digestibility coefficients of OM, DM, CHO and CP were decreased while EE digestibility was increased by using high NDF diets. This may be due to the increased flow of OM, DM and CHO to the terminal ileum as a consequence of a lower digestibility of non-starch polysaccharides (Schulze et al., 1994; Serena et al., 2008). The reduction of the apparent total tract digestibility of CP may be due to increased endogenous amino acid losses when feeding high-fibre diets because of increased production of mucin (Mosenthin et al., 1994; Schulze et al., 1994).

In contrast, the apparent total tract digestibility of EE was increased by using high NDF diets. Noblet and Shi (1993) reported a curvilinear relationship between dietary EE and the apparent total tract digestibility of EE, which is reduced when the fibre content of the diet rises above 200 g NDF/kg. In this study, the feed NDF content surpassed that threshold but the fat digestibility was not impaired. The current results are in agreement with Le Goff et al. (2002), who found that moderate increases of dietary fibre (inclusion of 235 g/kg of maize bran that yielded 197 g NDF/kg of diet) reduced the apparent total tract digestibility of nutrients in growing pigs but did not affect heat production when data were adjusted for a similar ME intake.

The faecal DM content of sows was not affected by dietary NDF. These results are not in agreement with Tabeling et al. (2003), who observed that faeces became markedly softer with higher contents of crude fibre in sow diets. This difference could be attributed to the dietary fibre sources used, as in the present study, they were mainly sugar-beet pulp and a minimum of cereal straw, whereas in that case they were provided through oat and soybean hulls. The increase of dietary NDF showed a concomitant reduction of manure density together with an increase manure produced by sows on a dry matter basis (kg DM/day), as evidenced in growing pigs (Moeser and van Kempen, 2002; Morazán et al., 2015).

The organic nitrogen content of manure did not differ between dietary NDF treatments, but there was tendency for lower ammonium nitrogen content in manure from lactating sows fed high NDF diets. It has been hypothesized that increasing dietary NDF level by sugar-beet pulp addition may alter N excretion by reducing urinary N excretion in favour of faecal N excretion (Canh et al., 1997), but this response may only be noticeable at high dietary CP levels (Lynch et al., 2008). This could trigger lower ammonia emissions from manure because N excreted as urine is mainly in the form of urea, which is converted into ammonia and carbonate by the urease enzyme present in faeces (Van der Peet-Schwering et al., 1999).

Although no differences were found in the coefficient of total tract apparent digestibility of phosphorus, the content of this mineral in manure was reduced when increasing dietary NDF level. Phosphorus is essential for gastrointestinal bacteria due to its function as a constituent of primary cell metabolites (Metzler and Mosenthin, 2008). Thus, we hypothesized that certain microbiota present in manure might have partially consumed phosphorus after excretion. Accordingly, these authors suggested that high fibre feed benefits the growth of certain microbial population that can consume undigested phosphorus.

Effect of marker used to estimate apparent total tract digestibility

The coefficients of apparent total tract digestibility of the present study were in line with results reported by Noblet and Shi (1993) for adult sows. However, the recorded values may differ between external markers (as chromic oxide, Cr_2O_3) and internal feed marker (as AIA). The greater total tract digestibility measurements when using AIA compared to Cr_2O_3 were independent of diet, as there were no interactions between the marker and dietary CP or NDF level. The main differences arouse in the coefficient of apparent total tract digestibility of the least digestible nutrients (NDF, 37.2% higher estimate in AIA than in Cr_2O_3; and EE, 45.0% higher estimate in AIA than in Cr_2O_3). Similar results were described by Moughan et al. (1991) in growing pigs when comparing the nutrient digestibility calculated by these two methods.

The present results could be due to the fact that recovery rates of AIA are higher than that of Cr_2O_3. A review from Sales and Janssens (2003) revealed a recovery range of AIA (as an indigestible marker) from 84 to 192%. On the contrary, Cr_2O_3 has shown an incomplete recovery range in faeces from 75 to 87% (Moore, 1957; McCarthy et al., 1974). Furthermore, Clawson et al. (1955) suggested that the recovery of Cr_2O_3 is affected by a diurnal excretion pattern. Therefore, its recovery rate may be incomplete, and it would underestimate the digestibility coefficients of nutrients.

Even though Cr_2O_3 has been widely used as a reference marker to determine total tract digestibility in several species, including pigs (Ishikawa, 1966; Ishikawa and Sugimura, 1973), it has several drawbacks. Apart from incomplete recovery, it has major disadvantages due to carcinogenicity associated to analytical procedures for its determination (Delagarde et al., 2010), and it involves difficulties to handle and mix accurately in feed at low dosage levels. In lactating sows, AIA may be an effective marker to estimate the total tract apparent digestibility of those nutrients that are greatly digested throughout the gastrointestinal tract (e.g. carbohydrates).

In conclusion, the reduction of dietary CP level in lactating sows had no effect on either LW or backfat thickness or apparent total tract digestibility of nutrients. However, the piglets' ADG was reduced in low dietary CP diets, which suggests that sows reduced milk production due to an underestimation of certain essential amino acid requirements (e.g. valine). The increase of dietary NDF level did not affect sow and litter performance, but the total tract apparent digestibility of OM, CP and carbohydrates was reduced and EE digestion was increased in high NDF compared to normal NDF diets equally balanced for ME and lysine content. Finally, The coefficients of total tract apparent digestibility of nutrients in lactating sows were greater when using AIA compared to Cr_2O_3 marker, regardless of dietary CP or NDF level, but their coefficients of variation were lower in the former than in the latter.

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