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Influence of dietary fibre level and pelleting on the digestibility of energy and nutrients in growing pigs and adult sows

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Two experiments were carried out to investigate the effect of pelleting on the apparent total tract digestibility (ATTD) of energy and nutrients according to the dietary fibre (DF) level in growing pigs (experiment 1) and in adult sows (experiment 2). Four diets based on wheat, barley, maize and soybean meal and supplemented with increased contents of a mixture of wheat bran, maize bran, soybean hulls and sugar beet pulp (116, 192, 268 and 344 g NDF/kg dry matter (DM) in diets 1 to 4) were tested. In experiment 1, 32 growing pigs (62 kg average BW), in two replicates and according to a factorial design, were fed one of the four diets, either as mash or as pellets. The digestibility of energy, organic matter (OM) and all nutrients decreased with DF increasing for both feed forms; the reduction was about 1% for each 1% NDF increase in the diet ($P < 0.001$*). Pelleting improved moderately the digestibility of energy and OM (+1.5% and +1.0%, respectively;* $P < 0.05$*) in connection with greater DF (+5%;* $P < 0.05$*) and fat digestibility (+25%). Thus, pelleting improved the digestible energy content of diets on average by 0.3 MJ/kg of feed DM (*$P < 0.01$*). In experiment 2, four adult dry sows (235 kg average BW) were used in a 4 × 4 Latin square design and fed the four diets used in experiment 1 as pellets. The digestibility of energy, OM and macronutrients also decreased with DF increase (*$P < 0.001$*; −0.4% per 1% increase of dietary NDF for energy) while the digestibility of DF (i.e. crude fibre (CF) or ADF) increased (*$P < 0.001$*) or remained at a high level. In conclusion, increasing DF in diets decreases the digestibility of nutrients and energy in pigs and in sows. Although positive, the pelleting impact is minor on the energy and nutrients digestibility of fibre-rich diets in growing pigs, even in high-DF diets.*

Keywords: dietary fibre, digestibility, growing pig, pellet, sow

Introduction

Dietary fibre (DF) is defined as the dietary components resistant to degradation by mammalian enzymes but degradable by microbial fermentation (Bach Knudsen, 2001). It is a component of organic matter (OM) in most ingredients and constitutes a major fraction in co-products from the vegetable food and agro industries and, more recently, from the production of bio fuels. From an economical and sustainability point of view, promoting fibre-rich materials in pig feeds may limit the competition for plant foods between animal and human. However, the presence of DF in diets decreases the apparent total tract digestibility (ATTD) of dietary energy and nutrients (Le Goff and Noblet, 2001) due to the low digestibility of DF and possible negative interactions with other nutrients. The extent of the effect of DF has been largely studied and depends on the characteristics of DF (Chabeauti *et al.*, 1991; Noblet and Bach Knudsen, 1997) and on production factors such as body weight (Noblet and Shi, 1994), physiological stage (Noblet and Le Goff, 2001) and genotype (Morales *et al.*, 2002; Len *et al.*, 2007). In addition, most feeds are processed before feeding (Benhke, 1996) and treatments such as extrusion, toasting, or pelleting may affect the digestibility of nutrients. Pelleting is used in animal feeding because it decreases segregation by animals, facilitates the handling of feeds, limits feed wastage and reduces the level of dust in pig houses. Pelleting treatment involves a mechanical pressure coupled with moderate temperatures over a very short time. Also, the passage through diet may reduce the particle size and disrupt cell walls and structures (Saunders *et al.*, 1969). Consequently, intracellular nutrient contents are released, thus improving OM digestibility. Depending on the heat treatment intensity associated with pelleting treatment, significant improvements in digestibility were found for CP (Wondra *et al.*, 1995; Lahaye *et al.*, 2004), fat (Skiba *et al.*, 2002; Noblet and

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Champion, 2003; Xing *et al.*, 2004) or starch (Bengala-Freire *et al.*, 1991), whereas pelleting did not modify the ATTD of NDF and ADF (Stein and Bohlke, 2007). However, to our knowledge, few studies have been carried out to determine the impact of pelleting on the ATTD of nutrients and energy of fibre-rich diets. This question is important since the DF content of pig diets is expected to increase markedly in the near future. In particular, studies carried out in adult sows fed fibrous-rich diets have rarely been reported with pelleted diets. Based on the literature, we hypothesized that the ATTD of nutrients and the energy of fiber-rich diets may be improved after pelleting.

The objectives of the current study were to first determine the impact of feed form (mash *v.* pellets) in growing pigs on the ATTD of energy and nutrients of diets over a large range of DF contents; second, to determine whether the level of DF affects nutrient digestibility in pelleted diets fed to adult sows; and third, to predict nutrients digestibility from DF content.

Material and methods

The experiments were carried at the French National Institute for Agricultural Research (INRA), Saint-Gilles, France. Experimental protocols for the care and use of animals were in accordance with the guidelines established by the French Ministry of Agriculture (authorization no. 04739 to Jean Noblet).

Experimental diets, animals and feeding

Four diets differing in NDF concentrations were formulated. The ingredients and the chemical composition of each diet are given in Table 1. The diets were based on wheat, maize, barley, soybean meal and a combination of fibrous ingredients (sugar beet pulp, wheat bran, maize bran and soybean hulls) at levels ranging from 0% (low fibre (LF)) to 21% (medium fibre (MF)), 42% (high fibre (HF)) and 63% (very high fibre (VHF)) in the diet. The corresponding NDF contents ranged from 116 g/kg in the LF diet to 192 g/kg in the MF diet, 268 g/kg in the HF diet and 344 g/kg in the VHF diet. All ingredients were ground through a 2.5-mm screen. The four diets were then processed as mash or as pellet. For pelleting, the temperature in the conditioner averaged 42°C and the pellets temperature after pelleting averaged 64°C; their diameter was 4.5 mm.

In experiment 1, 32 [Piétrain × (Large White × Landrace)] castrated male pigs (average BW of 62 kg) were assigned to the eight treatments in two successive replicates of 16 pigs (two pigs per treatment) and according to a factorial design including four diets (LF diet to VHF diet) and two types of feed form (mash *v.* pellets). The pigs' BW at the start of the adaptation period were balanced between treatments. Pigs were adapted to the diets and the metabolic cages for 8 to 10 days before total collection of faeces and urine for 10 days. The feeding level of each pig was progressively increased during the adaptation period in order to attain 2.0 kg of feed per day at the start of the collection of excreta, which is equivalent to a daily supply of about 2 MJ metabolisable energy (ME) per kg $BW^{0.60}$ for the LF diet (Sauvant *et al.*, 2004). It was increased up to 2.2 kg over the collection period and it was equalized between treatments. This feeding level represents for the lowest DF level approximately 85% of the *ad libitum* intake recorded in previous studies on similar pigs kept in the same conditions (Quiniou *et al.*, 1996). Pigs were provided *ad libitum* access to water.

In experiment 2, four Large White × Landrace sows (average BW of 235 kg) were assigned to the four dietary pelleted diets of experiment 1 according to a 4 × 4 Latin square design. Sows were ovariectomized in order to avoid any effect of cycling and oestrus on feed intake and digestibility measurements. Each sow received alternately one of the four experimental pelleted diets during four successive 20-day

Table 1 *Ingredients and chemical composition of the experimental diets*[1]

	Diet			
	LF	MF	HF	VHF
Ingredients (%)				
Wheat	35.37	27.69	20.02	12.34
Maize	35.38	27.70	20.02	12.34
Soybean meal	14.00	10.96	7.92	4.88
Barley	10.00	7.83	5.66	3.49
Wheat bran	0.00	6.00	12.00	18.00
Maize bran	0.00	6.00	12.00	18.00
Soybean hulls	0.00	6.00	12.00	18.00
Sugar beet pulp	0.00	3.00	6.00	9.00
Molasses	2.00	1.57	1.13	0.70
Dicalcium phosphate	1.20	1.20	1.20	1.20
Calcium carbonate	1.10	1.10	1.10	1.10
Sodium chloride	0.45	0.45	0.45	0.45
Vitamins and minerals mixture[2]	0.50	0.50	0.50	0.50
Nutrients levels (analyzed; % DM)				
DM (%)	84.2	88.5	88.9	89.2
Ash	5.6	6.1	6.3	6.8
CP	16.8	16.5	15.6	15.0
Starch	53.5	46.7	36.5	31.2
Ether extract	2.5	2.5	2.6	2.6
Crude fibre	2.6	5.9	9.5	12.3
Sugars (calculated)[4]	3.7	3.7	3.7	3.8
Carbohydrates[3]	75.1	75.0	75.5	75.6
NDF	13.1	22.0	28.1	34.4
ADF	3.1	5.6	8.8	11.8
TDF	12.6	21.4	30.5	38.2
Gross energy (MJ/kg DM)	18.10	18.05	18.06	17.92
Lysine (%; calculated)	0.62	0.58	0.54	0.51

LF=low fibre; MF=medium fibre; HF=high fibre; VHF=very high fibre; DM=dry matter; TDF=total dietary fibre.

[1]Values correspond to the means of chemical characteristics obtained from mash and pelleted diets.

[2]Supplied per kilogram of feed: retinyl palmitate, 2.7 mg; cholecalciferol, 25 μg; DL-α-tocopherol acetate, 20.0 mg; thiamine, 2.0 mg; riboflavin, 4.0 mg; pyridoxine, 1.0 mg; cobalamin, 20 μg; niacin, 15 μg; D-panthotenate, 9.9 mg; biotin, 200 μg; folic acid, 1 mg; menadione, 2.0 mg; choline chloride, 500 mg; Zn, 80.5 mg (as ZnO); Cu, 4.0 mg (as $CuSO_4$); Mn, 28.6 mg (as MnO4); Fe, 38.5 mg (as $FeCO_3$); I, 131 μg (as CaI_2); Co, 38.0 μg (as $CoSO_4$) and Se, 38.5 μg (as Na_2SeO_3).

[3]Carbohydrates = 100 − (ash + CP + ether extract).

[4]Calculations were done according to Sauvant *et al.* (2004).

periods. During each period, sows were adapted to the diet for 12 days before total collection of faeces and urine for 8 days; the four sows were kept continuously in metabolic cages. Feeding level of each sow was adjusted for each period to provide the same daily estimated (Sauvant *et al*., 2004) ME/kg metabolic BW (500 kJ/kg $BW^{0.75}$ per day). During excreta collection, sows were housed in respiration chambers for heat production measurements; these latter data will not be presented in the present paper.

Sows and pigs were weighed at the beginning and the end of the excreta collection period. For each diet and for each animal, a sample of diet was collected in each replicate for experiment 1 and in each period for experiment 2, and analysed for their dry matter (DM) content; the dietary samples of replicates were pooled per diet and per experiment for subsequent chemical analyses. Feed refusals were collected daily and measured for their DM content. Faeces were collected daily, stored at 4°C and weighed, homogenized by a Stephan homogenizer (Stephan and Sympac France, Lognes, France) and subsampled at the end of the period. Then, faeces samples, for each collection period, were freeze-dried (Froilabo, Froilabo-Firlabo, Emerainville, France) for further chemical analyses. Urines were also collected daily and daily aliquots were pooled for each animal.

Analytical methods

For feed samples, moisture, ash, CP (N $\times$ 6.25), Weende crude fibre (CF), and ether extract (EE) were analysed according to AOAC 777 (1990). Gross energy (GE) content was measured using an adiabatic bomb calorimeter (IKA, Staufen, Germany). DF (NDF, ADF and ADL) was determined according to the methods of Van Soest and Wine (1967) using a sequential procedure with prior amylolytic treatment. Total DF (TDF) contents were also quantified according to the method of Prosky *et al*. (1988). Starch content was determined using Ewer's polarimetric method (European Economic Community, 1972). Moisture, ash, CP, DF and GE analyses were also carried out on each faecal sample. In addition, EE was measured on pooled faecal samples (one per diet and per treatment) using an automated extractor (Soxtec, Foss, France) after HCl hydrolysis. Nitrogen in urine was analysed on fresh material whereas GE content was obtained after freeze-drying approximately 30 ml of urine in polyethylene bags. Analyses on feed samples were performed in triplicates, while analyses on excreta were performed in duplicates.

Calculations and statistical analyses

ATTD coefficients of OM, nutrients, and GE, and digestible energy (DE), and ME contents were calculated according to Noblet *et al*. (1989). The ME value was calculated as the difference between DE value and energy losses in urine. According to Graham *et al*. (1986) and Bach Knudsen and Hansen (1991), starch and sugars are assumed to be 100% digestible at the faecal level.

Data were subjected to ANOVA analysis of Statistical Analysis Systems Institute (SAS) (SAS Institute Inc., Cary, NC, USA). Linear and quadratic effects of diet composition on digestibility coefficients and nitrogen balance were analysed using a contrast statement. The proc GLM with a level of significance of $P < 0.05$ was used. In experiment 1, the model consisted of replicate ($n_i = 2$), diet ($n_j = 4$) and feed form ($n_k = 2$) as the main effects, and the interaction between diet and feed form (*jk*). The experimental unit was the animal and the error term was the residual error of the model. In experiment 2, sow data were analysed according to a latin square design with diet ($n = 4$), period ($n = 4$) and sow ($n = 4$) as the main effects. The experimental unit was the animal and the error term was the residual error of the model.

In order to analyse the effect of DF content on the ATTD of nutrients and energy, regression equations were calculated for each experiment with NDF as an indicator of DF level; in experiment 1, the effect of feed form and the interaction between feed form and diet were also tested according to a covariance model.

Results

The four experimental diets were formulated to provide different levels of DF (Table 1). To raise the DF level in diets, wheat, maize, barley and soybean meal were partly substituted by sugar beet pulps, wheat bran, maize bran and soybean hulls. Therefore, concomitant with increasing DF levels, diets contained decreasing contents of ST and CP. The chemical composition of each diet was identical for both feed forms and values used in the calculations were averaged for each diet.

All animals remained healthy throughout the duration of the experiment. In experiment 1, according to the experimental design, growing pigs were fed a constant amount of feed, which resulted in DE intakes that were lower when feeding diets with higher DF contents. No refusals were observed. Pigs grew at an average rate of 760 g/day and, concomitant with the DE intake reduction, their average daily gain (ADG) decreased with DF increase ($P < 0.05$; Table 2); feed form did not affect ADG. In experiment 2, according to the experimental design, adult sows were fed the same ME level during the experimental period. Since the energy intake was above their requirements (data not presented), their growth was positive (450 g/day) but not affected by diet composition (Table 4).

Effect of DF level on digestibility of energy and nutrients in growing pigs (experiment 1)

As indicated in Table 2, the digestibility of OM and energy decreased linearly with DF increase ($P < 0.001$); the decrease averaged about one percentage point per percentage point NDF for OM, nutrients and energy (E) (Table 3). The DF levels decreased (quadratic; $P < 0.05$) the digestibility of DF (i.e. CF, NDF, ADF or TDF) with the highest values obtained with MF diet. The DF levels did not affect the ME/DE ratio. According to the negative effects of DF on energy digestibility, increasing DF reduced DE and ME values (linear and

Table 2 *Effects of dietary fibre level and pelleting on performance, nitrogen balance and nutrients and energy digestibility in growing pigs*

	Mash diets				Pelleted diets					Main effects, *P*-value			
Item	LF	MF	HF	VHF	LF	MF	HF	VHF	s.e.	Replicate	Diet[1]	Feed form	Diet × feed form
Performance													
BW (kg)	62.4^{ab}	64.1^{a}	62.5^{ab}	60.3^{b}	63.8^{a}	64.4^{a}	62.1^{ab}	60.8^{b}	1.5	<0.001	0.079	0.657	0.936
Daily BW gain (g/day)	850^{a}	740^{b}	685^{b}	698^{b}	855^{a}	890^{a}	677^{b}	683^{b}	38	0.392	<0.001	0.205	0.101
DM intake (g/day)	1928	1934	1946	1942	1938	1943	1950	1954	2	NA	NA	NA	NA
Digestibility coefficient (%)													
Dry matter	87.1^{a}	81.3^{b}	74.8^{c}	66.2^{d}	87.3^{a}	84.3^{e}	74.1^{c}	68.1^{f}	0.6	0.003	<0.001[2]	0.019	0.031
Organic matter	89.3^{a}	83.5^{b}	76.8^{c}	68.4^{d}	89.5^{a}	86.5^{e}	76.2^{c}	70.2^{f}	0.6	0.004	<0.001[2]	0.016	0.035
Nitrogen	86.1^{a}	77.8^{b}	70.8^{c}	61.5^{d}	85.0^{a}	81.0^{e}	69.7^{c}	62.9^{d}	1.1	0.007	<0.001	0.456	0.133
Ether extract	37.8	35.2	39.8	33.4	69.8	64.7	62.0	47.3	1.6	NA	NA[3]	NA	NA
Carbohydrates[4]	91.8^{a}	85.3^{b}	77.5^{c}	70.3^{d}	90.9^{a}	86.0^{b}	76.4^{c}	70.6^{d}	0.9	0.080	<0.001	0.717	0.662
Crude fibre	35.4^{a}	46.2^{b}	44.6^{c}	32.3^{c}	32.8^{a}	62.6^{bc}	47.8^{c}	38.8^{c}	5.1	0.113	0.852[2]	0.098	0.318
NDF	60.8^{ac}	63.3^{a}	59.1^{ad}	50.7^{d}	66.7^{ab}	73.5^{b}	60.6^{ae}	54.2^{cde}	3.1	0.050	<0.001[2]	0.016	0.095
ADF	66.6^{ab}	58.8^{ac}	59.4^{ac}	50.8^{c}	57.2^{ac}	72.1^{b}	60.5^{ac}	57.7^{ac}	4.2	0.406	0.035	0.302	0.059
TDF	52.1^{a}	56.3^{b}	53.6^{c}	47.7^{d}	53.1^{a}	65.3^{bc}	60.1^{d}	52.9^{e}	5.1	0.754	0.002[2]	0.004	0.484
Energy	86.9^{a}	80.5^{b}	73.7^{c}	65.1^{d}	87.6^{a}	84.2^{e}	73.6^{c}	67.1^{f}	0.7	0.003	<0.001[2]	0.001	0.034
ME/DE[5] (%)	96.7	96.6	96.4	96.7	96.8	96.7	96.5	96.5	0.1	0.006	0.142	0.456	0.561
Energy values (MJ/kg of DM)													
DE	15.72^{a}	14.57^{b}	13.30^{c}	11.72^{d}	15.87^{a}	15.23^{e}	13.27^{c}	12.01^{f}	0.12	0.003	<0.001	0.001	0.033
ME	15.20^{a}	14.08^{b}	12.83^{c}	11.28^{d}	15.38^{a}	14.42^{a}	12.81^{c}	11.66^{f}	0.11	0.030	<0.001	0.010	0.282
Nitrogen balance (g/day)													
Intake	51.5	50.8	48.6	46.7	51.8	50.9	48.8	47.0	0.1	0.298	<0.001	<0.001	0.185
Faecal	7.2^{a}	11.3^{b}	14.2^{c}	18.0^{d}	7.8^{a}	9.7^{e}	14.8^{c}	17.4^{f}	0.3	0.005	<0.001	0.498	0.124
Urinary	21.5^{a}	19.1^{bc}	16.0^{d}	12.0^{e}	20.9^{ab}	18.1^{c}	15.6^{d}	12.5^{e}	0.4	<0.001	<0.001	0.493	0.750
Retained	22.9^{a}	20.4^{b}	18.4^{c}	16.7^{c}	23.1^{a}	23.2^{a}	18.3^{c}	17.1^{c}	0.7	0.016	<0.001	0.113	0.191

LF = low fibre; MF = medium fibre; HF = high fibre; VHF = very high fibre; DM = dry matter; TDF = total dietary fibre.
[1]*P*-value is that of the linear contrast.
[2]Quadratic contrast, *P*-value < 0.05.
[3]NA: not applicable: ether extract of faeces was measured on samples pooled per diet and per feed form; digestibility coefficients could not be calculated for each pig.
[4]Carbohydrates = 100 − (ash + CP + ether extract).
[5]Metabolisable energy/digestible energy ratio.
A value followed by different superscript letter was statically different ($P < 0.05$).

Table 3 *Effect of dietary NDF level (g/kg) on apparent total tract digestibility (%) of organic matter (ATTD OM), crude protein (ATTD CP) and energy (ATTD E) according to diet form (mash and pellet) in growing pigs*

Feed form	Equation[a]	R^2	RSD[b]	NDF	Feed form
Mash or pellet	ATTD OM = 103.8 (±1.3) − 0.98 (±0.05) × NDF	0.92	2.3	<0.001	0.162
Mash or pellet	ATTD CP = 101.9 (±1.6) − 1.13 (±0.06) × NDF	0.91	2.8	<0.001	0.572
Mash	ATTD E = 101.6 (±1.3) − 1.03 (±0.05) × NDF	0.93	2.3	<0.001	0.054
Pellet	ATTD E = 103.1 (±1.3) − 1.03 (±0.05) × NDF				

[a]Equations were obtained according to a covariance model with feed form as fixed effect and NDF as covariate.
[b]Residual standard deviation.
Separate equations are given when the intercepts differ ($P < 0.05$) between diet preparations; the interaction between NDF content and feed form was not significant ($P = 0.80$, 0.66 and 0.95 for OM, CP and energy, respectively).

quadratic effects for DE; $P < 0.01$): a decrease of 4 MJ/kg of DM was measured between LF diet and VHF diet. Increasing DF reduced N and energy intakes and retained N; more nitrogen was excreted in faeces and less in urines ($P < 0.001$).

Effect of pelleting on diets digestibility in growing pigs (experiment 1)

Pelleting of diets improved the digestibility of OM and energy by about one percentage point (80.6% *v.* 79.5% for OM and 78.1% *v.* 76.6% for energy; $P < 0.05$, Table 2). With regard to DF, pelleting improved digestibility of NDF ($P = 0.016$) or TDF ($P = 0.004$) and tended ($P = 0.098$) to improve CF digestibility. In the case of NDF, digestibility for pelleted diets (63.7% *v.* 58.5%) was five points greater than for mash diets. An unexpected interaction between diet characteristics and feed form was observed for digestibility coefficients of OM and energy (interaction, $P < 0.05$), which is mainly explained by the higher difference between mash and pellets forms for the MF diet, either for OM, energy or DF fractions. Even if it has not been statistically demonstrated, the digestibility of fat for the pelleted diets was numerically greater than the values obtained for the mash diets (61% *v.* 36%, s.e. = 1.6). The ME/DE ratio was not affected by feed form. In summary, pelleting increased DE and ME contents (+0.3 MJ/kg of DM; $P < 0.01$). The effect of NDF content on the digestibility of OM, N or E was not affected by pelleting (i.e. no significant interaction; Table 3); the intercept of the relationship was higher for pelleted diets but the difference was significant only for energy ($P = 0.054$; Table 3).

Effect of dietary fibre level on the digestibility of pelleted diets in adult sows (experiment 2)

As indicated in Table 4, the digestibility of OM and energy decreased linearly with DF increase ($P < 0.001$) while the digestibility of DF (i.e. CF or ADF) increased ($P < 0.001$) or remained at a high level (i.e. NDF) (quadratic, $P < 0.05$). The reduction averaged about 0.35, 0.70 and 0.40 percentage point per percentage point NDF for OM, N and energy, respectively (Table 5). The DF levels did not affect the ME/DE ratio. According to the negative effects of DF on energy digestibility, DF increase reduced DE and ME values ($P = 0.001$): a decrease of 1.5 MJ/kg of DM was measured between LF diet and VHF diet. Due to the greater dry matter intake and DE values slightly higher than expected with the high-DF diets, the DE intakes increased with increase of the DF level (Table 5). More nitrogen was excreted in faeces ($P < 0.001$) and less in urines when feeding diets with higher DF contents.

Discussion

Introduction of fibre in feeds for pigs

In agreement with literature data, increasing the DF content in the diets led to a reduction of the ATTD of nutrients and energy (Yin *et al.*, 2000; Le Goff and Noblet, 2001). The extent of this reduction depends on DF sources with more accentuated effects with lignified DF (straw for instance) and reduced effects with more digestible DF (soybean hulls or sugar beet pulp for instance) (Chabeauti *et al.*, 1991). The reduction of one percentage point of digestibility per one percentage point NDF increase in the diet observed in the present study with a mixture of DF sources is quite consistent with the reduction calculated by Noblet and Perez (1993) and Le Goff and Noblet (2001) on a large number of diets (50 to 70) prepared with different DF sources. The depressive effects of DF on OM and energy digestibilities and DE and ME values and their variations are caused firstly by the replacement of highly digestible nutrients such as CP or starch by partly undigestible cell wall materials (lignin, non-starch polysaccharides (Bach Knudsen *et al.*, 1993; Noblet and Shi, 1993)). Secondly, the presence of DF influences the digestion and absorption processes along the gastrointestinal tract (Cummings and Englyst, 1995). In the small intestine, soluble DF raises the luminal viscosity (Ellis *et al.*, 1995) and increases the water-binding capacity of digesta (Glitsø *et al.*, 1998). Depending on their physico-chemical properties such as viscosity (Larsen *et al.*, 1993) and water-holding capacity (Leterme *et al.*, 1996), the presence of DF increases protein endogenous losses due to excessive saliva, gastric and pancreatic secretions (Zebrowska and Low, 1987) and a mechanical erosion of mucosa with an important desquamation of cells (Montagne *et al.*, 2003); it also accelerates the rate of passage of digesta in the gut with reduced duration for fermentation in the hindgut (Le Goff *et al.*, 2002b; Wilfart *et al.*, 2007). The DF fermentation is also associated with a higher microbial activity in the large intestine (Wenk, 2001), which results in

Table 4 *Effects of dietary fibre level on energy and nutrients digestibility in adult sows*

	Diet					Main effects, *P*-value[1]			
	LF	MF	HF	VHF	s.e.	Period	Diet, linear effect	Diet quadratic effect	Sow
Performance									
BW (kg)	230	231	233	238	1	0.019	0.004	–	<0.001
Daily BW gain (g/day)	267	326	444	782	156	0.590	0.405	0.054	0.093
DM intake (g/day)	1977	2098	2255	2441	15	0.071	<0.001	0.075	<0.001
Digestibility coefficient (%)									
Dry matter	89.7	87.0	84.3	82.5	0.2	0.009	<0.001	0.062	0.019
Organic matter	92.5	89.8	87.1	85.2	0.2	0.026	<0.001	0.057	0.018
Nitrogen	88.2	83.2	77.8	73.9	0.4	0.019	<0.001	0.248	0.051
Ether extract	68.1	60.7	58.9	50.7	1.3	NA[1]	NA	NA	NA
Carbohydrates[2]	94.0	92.2	89.6	88.0	0.8	0.061	<0.001	0.76	0.293
Crude fibre	57.9	77.6	79.5	83.8	2.1	0.451	<0.001	0.011	0.106
NDF	83.9	82.5	80.2	84.9	1.0	0.952	0.070	0.88	0.089
ADF	66.8	78.6	79.8	85.0	1.0	0.036	<0.001	0.015	0.089
Energy	91.1	87.8	84.7	82.4	0.3	0.455	<0.001	0.092	0.038
ME/DE[3] (%)	95.8	96.2	96.1	95.8	0.4	0.782	0.98	0.30	0.071
Energy values (MJ/kg of DM)									
DE	16.52	15.93	15.09	14.90	0.13	0.870	<0.001	0.18	0.150
ME	15.82	15.33	14.50	14.28	0.16	0.780	0.001	0.43	0.112
Nitrogen balance (g/day)									
Intake	52.2	54.8	56.6	59.1	0.4	0.10	0.004	0.89	<0.001
Faecal	6.2	9.2	12.6	15.5	0.3	0.006	<0.001	0.67	0.003
Urinary	34.4	30.1	27.8	28.2	1.7	0.51	0.033	0.22	0.993
Retained	11.6	15.4	16.2	15.5	1.7	0.50	0.0147	0.22	0.211

LF = low fibre; MF = medium fibre; HF = high fibre; VHF = very high fibre; DM = dry matter.
[1]NA: not applicable: ether extract of faeces was measured on samples pooled per diet, and digestibility coefficients could not be calculated for each pig.
[2]Carbohydrates = 100 − (ash + CP + ether extract).
[3]Metabolisable energy/digestible energy ratio.

Table 5 *Effect of dietary NDF level (g/kg) on apparent total tract digestibility (%) of organic matter (ATTD OM), crude protein (ATTD CP) and energy (ATTD E) of diets in adult sows*

Equation[a]	R^2	RSD[b]	NDF
ATTD OM = 97.2 (±0.6) − 0.35 (±0.02) × NDF	0.94	0.77	<0.001
ATTD CP = 97.4 (±1.3) − 0.68 (±0.05) × NDF	0.93	1.58	<0.001
ATTD E = 96.7 (±0.7) − 0.41 (±0.03) × NDF	0.94	0.88	<0.001

[a]Equations were obtained according to a covariance model with sow as fixed effect and NDF as covariate.
[b]Residual standard deviation.

a transfer of urinary N to faecal microbial proteins (Le Goff *et al.*, 2002a). Finally, the quadratic response of DF digestibility with DF increase observed in our study would suggest that the growing pig has limited capacities for DF degradation at high levels of inclusion.

Feed form: mash v. *pellets*

In agreement with literature data (Wondra *et al.*, 1995), pelleting the diet improved the ATTD of OM and energy, with the greatest impact on the MF and the VHF diets in our study in connection with a better digestibility of fat and some DF fractions. Although our results on fat digestibility need statistical approbation, the important numerical difference in fat digestibility between mash and pelleted diets is consistent with the positive effect of pelleting on fat digestibility in diets with full-fat rapeseed (Skiba *et al.*, 2002), high-oil corn (Noblet and Champion, 2003) or linseed (Noblet *et al.*, 2008). It is suggested that the thermal treatment associated with pelleting may change the physical structure of fat and improves its digestive utilization (Keogh and O'Kennedy, 1999). In contrast with some studies (Canibe, 1997; Stein and Bohlke, 2007), our study suggests that pelleting may improve the digestibility of some DF fractions. In some cases, pelleting would improve the nutrients solubility with a subsequent higher digestion by endogenous enzymes (Björck *et al.*, 1984). But that effect depends on diets composition (cereals, co-products and leguminous) and nutrients (fat, proteins, starch and DF) and the treatment conditions (temperature, moisture and particle size). Moreover and in contrast with our digestibility results, we have not observed any modification of DF fraction composition (NDF, ADF, etc.) for the four diets after pelleting; this effect requires confirmation in connection with the origin of DF, particle size and characteristics of the mechanical and thermal treatment. In agreement with other studies, pelleting treatment failed to improve faecal N digestibility (Vande Ginste and De Schrijver, 1998; Stein and Bohlke, 2007).

In summary, prediction equations of nutrients and energy digestibility according to the NDF concentration indicate that pelleting treatment increases the digestibility of nutrients such as fat and DF with a significant effect on energy digestibility and DE value independent of the DF level in the diet. However, this positive impact is not sufficient to compensate the negative effect of DF introduction in diets on energy digestibility and DE value.

Adult sows

The changes in apparent digestibility of nutrients and energy according to DF level obtained in our study with pelleted diets fed to adult sows are similar to those obtained on large sets of diets, usually given as mash (Le Goff and Noblet, 2001). Our study was not designed to test the effect of pelleting on nutrient digestibility for the adult sows, but we can speculate that this effect is smaller than in growing pigs and can therefore be ignored. The numerical comparison between adult sows and growing pigs indicates both higher average digestibility coefficients and a lower reduction of energy and nutrients digestibility with DF increase in adult sows. These results are in agreement with literature data obtained generally with mash feeds (Le Goff and Noblet, 2001). This difference is likely attributed to a more developed digestive tract with increased BW of animals (Noblet and Shi, 1994; Le Goff and Noblet, 2001) and a subsequently slower rate of passage of digesta (Le Goff *et al*., 2002b) in the hindgut compartment. The positive effect of BW is the highest when adult sows fed at maintenance level are compared to *ad libitum* growing pigs (Noblet and Shi, 1993); this situation combines the positive effects of a higher BW and of reduced feeding levels, which maximizes the retention time of digesta in the gut. However, the effect of feeding level in adult sows is rather negligible (Noblet, 2005) and the difference between restrictively fed adult sows and liberally fed growing pigs in our study is almost exclusively due to the direct effect of BW and associated development of the digestive tract. The variation of energy and nutrients digestibility with BW or physiological stage also depends on diet characteristics. Indeed, the improvement of energy and OM digestibilities is mostly associated with an improved degradation of the DF fractions (Le Goff and Noblet, 2001). Consequently, the difference between adult sows and growing pigs is as great as the DF content is increased. This is clearly illustrated in the present study with a depressive effect of NDF on energy digestibility, which is approximately 60% lower in adult sows than in growing pigs (Table 5).

In conclusion, results of the present study indicate that increasing DF in diets decreases the digestibility of all macronutrients and energy in both pigs and sows. But, in sows, the DF digestibility is maintained constant or increases with increasing DF in the diets while it decreases in growing pigs. Although a positive effect has been observed for some nutrients, the pelleting effect is minor on OM and energy digestibility in diets based on cereals and soybean meal and their high-DF by-products.

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