



Effects of Particle Size of Barley on Intestinal Morphology, Growth Performance and Nutrient Digestibility in Pigs

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ABSTRACT : A growth trial and a digestibility trial were conducted to examine the effect of feed particle size on the performance, nutrient digestibility, gastric ulceration and intestinal morphology in pigs fed barley-based diets. Barley was processed through a hammer mill to achieve four diets varying in particle size (average particle size \pm standard deviation): coarse (1,100 \pm 2.19 μ m), medium (785 \pm 2.23 μ m), fine (434 \pm 1.70 μ m) and mixed (1/3 of coarse, medium and fine) (789 \pm 2.45 μ m). Sixty-four entire male pigs were used in the growth trial and the diets were fed *ad libitum* between 31 kg and 87 kg live weight. Following slaughter, stomach and ileal tissues were scored for integrity (ulceration or damage) and histological measurements taken. Twenty-four entire male pigs were used in the digestibility trial, which involved total faecal collection. Over the entire growth phase, there were no differences ($p>0.05$) in average daily gain and feed conversion ratio between pigs fed diets of different particle size. Pigs fed the coarse and medium diets had lower ($p<0.05$) stomach ulceration scores (0.20 and 0.25, respectively, on a scale from 0 to 3) than those fed the mixed (0.69) or the fine diets (1.87). The stomachs of all animals fed the fine diet had lesions and stomach ulcerations were present only in this group. Pigs fed the fine diet had thicker ($p<0.001$) ileal epithelial cell layer with no differences ($p>0.05$) being observed for villous height or crypt depth. Faecal digestibility coefficients of neutral and acid detergent fibre were the highest ($p<0.05$) for the mixed diet, intermediate for the fine and coarse diets and the lowest for the medium diet. A similar numerical trend ($p = 0.103$) was observed for the apparent faecal energy digestibility coefficient. It is concluded that, with barley based diets, a variation in average particle size between 400 μ m and 1,100 μ m had no effect on pig performance but the fine dietary particle size affected the integrity of the stomach, as well as the structure of the small intestine, thus compromising overall gut health. Our data also demonstrate that changes in particle size distribution during the digestion process, rather than average particle size or particle size variation, are related to apparent faecal digestibility. (**Key Words :** Pig, Particle Size, Intestinal Morphology, Barley)

INTRODUCTION

Traditionally pig feeds are characterised by their ingredients, chemical composition, nutritive value, and form of presentation (meal, pellets, dry, wet). Many steps are involved in the processing of pigs diets (weighing, grinding, mixing, pelleting, etc.) and each of these steps can have an impact on both the nutritive value of the feed and the performance of the animal.

Cereal grains are milled before being incorporated into pig diets, and different milling protocols will result in diets of different average particle size and particle size distribution. Particle size has been reported to influence nutrient digestibility, growth rate, feed intake, feed conversion ratio and gut health, especially in terms of

gastric ulceration (Healy et al., 1994; Wondra et al., 1995a, b, c, d, e; Mavromichalis et al., 2000; Kim et al., 2002; Oryschak and Zijlstra, 2002; Lawrence et al., 2003; Choct et al., 2004). In New Zealand, barley is the main cereal grain used in pig diet. The aim of this experiment was to examine the effect of barley particle size on the growth performance, nutrient digestibility and gastric ulceration in pigs fed barley-based diets. In addition, the effects of dietary particle size on intestinal morphology were investigated as data in this area are scarce.

MATERIALS AND METHODS

Diet preparation

The experimental diets (grower and finisher) were based on barley grain, soybean meal, and animal by-products (Table 1).

The barley was ground by either a Nielsen 50HP

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Table 1. Diet specification, ingredient composition and analytical composition of experimental diets on an as-fed basis

Ingredient (g/kg)	Grower				Finisher			
Barley	705				806.5			
Blood meal	30				0			
Fish meal	20				0			
Meat and bone meal	130				110			
Soybean meal	65				45			
Tallow	45				20			
Lysin	0				3			
Methionine	2				2			
Threonine	0.5				2			
Vitamin+mineral premix	2.5				2.5			
Dicalcium phosphate	0				8			
Sodium chloride	0				1			
Composition (g/kg)	Fine	Medium	Coarse	Mixed	Fine	Medium	Coarse	Mixed
DE (MJ/kg) ^a	13.86				13.00			
Lys/DE (g/MJ) ^a	0.70				0.63			
Dry matter ^b	898	911	912	906	884	897	895	887
Crude protein ^b	217	217	203	206	164	166	169	175
Crude fat ^b	67	105	69	69	39	46	52	49
Neutral detergent fibre ^b	192	173	164	192	187	199	193	190
Acid detergent fibre ^b	53	51	45	47	58	52	62	58

^a Calculated based on Morel et al. (1999). ^b Determined values.

hammer mill (4 mm and 7 mm for the medium and coarse grind, respectively) or a 3 KW hammer mill equipped with a 1 mm screen for the fine grind. Micro ingredients were mixed with 20 kg of barley in a Hobart mixer for 5 min to produce a basal mixture. The basal mixture was added to the barley and other major ingredients and mixed for 10 min in a vertical auger mixer to produce 500 kg diet batches. Two batches of each diet were manufactured. Four diets were produced: fine, medium, coarse, and mixed grind. The mixed grind diet was a blend of equal proportion of fine, medium and coarse ground barley.

Particle size measurement

For the determination of particle size, the diets were sampled before the addition of tallow. Particle size was determined in duplicate with 150 g samples from each batch of diet. A set of sieves of size 2,800 µm, 2,000 µm, 1,600 µm, 1,400 µm, 1,000 µm, 500 µm, 250 µm and 106 µm (Endocot, London, UK) were mounted on an Endecot sieve shaker and the sample agitated for 2 min.

The average particle size (d_i) of the material retained on a sieve was calculated as the geometric mean of the diameter opening in two adjacent sieves (d_u and d_o).

$$d_i = (d_u \times d_o)^{0.5}$$

The weight of material retained in each sieve (W_i) is used to calculate the average particle size (d_{gw})

$$pw_i = W_i / \sum W_i$$

$$d_{gw} = \log^{-1} (\sum pw_i \log(d_i))$$

The particle size standard deviation (S_{gw}) was calculated as:

$$S_{gw} = \log^{-1} (\sum pw_i (\log d_i - \log d_{gw})^2)^{0.5}$$

Growth trial

A total of 64 entire male pigs (average±SD, 32.1±2.70 kg) were included in this experiment. The pigs were housed in pens of 8 pigs at the Massey University Pig Biology Unit and fed *ad libitum* with water available at all times. The pens were randomly allocated to one of four treatment groups (fine, medium, coarse or mixed diet) with two pens of 8 pigs per treatment. The grower diet was fed for five weeks to a liveweight (LW) of 61.1±5.6 kg, followed by the finisher diet to an average slaughter weight of 87.2±5.7 kg. The pigs were slaughtered at a commercial abattoir, and individual carcass weight and P2 backfat thickness were recorded.

Morphological measurement

After slaughter, the stomachs were opened, the contents expelled, and the tissue gently rinsed with water before being transported on ice to the Massey University post-mortem facility. The *pars-oesophagea* region of the stomach was scored for gastric ulceration by a trained veterinary pathologist using a four-point scale (Kavanagh, 1994), where:

0 = No lesion

- 1 = Hyperkeratisation
- 2 = Erosion
- 3 = Ulceration

Out of the 64 pigs slaughtered, 20 pigs (5 per dietary treatment) were selected for the histological measurements. The small intestine was clamped at the gastri pylorus and ileo-caecal valve, and a sample of tissue (5 cm in length) was collected from an area 75% along the tract. These samples were processed for histological examination (fixed in Bouin's fluid, embedded in paraffin wax, 5 µm sections cut and stained with alcian blue, haematoxylin and eosin). Measurement of villous height, crypt depth, villous tip to crypt base and epithelial cell thickness were made from 20 villi per animal using a light microscope (100× magnification) and SigmaScan computer software (Wu et al., 2004).

Digestibility trial

Classical total collection method was used for the determination of apparent faecal digestibility of energy, and the faecal digestibility of neutral detergent fibre and acid detergent fibre. Twenty-four entire male pigs, (34.3±2.4 kg) were randomly allocated to one of the four dietary treatments. The pigs were housed individually in metabolism crates at the Massey Animal Physiology Unit. The pigs were fed the grower diets twice daily at a restricted level (daily feed allowance = 0.10×metabolic bodyweight, $W^{0.75}$) for 10 days. Water was freely available at all times. Feed intake was recorded daily and samples of the diets were taken at each feeding time. Feed refusals and faeces were collected and weighed daily over the last five days and kept frozen.

At the end of the collection period, the bulked faeces and refusals were thawed, thoroughly mixed, and sub-sampled. One sub-sample of faeces and the feed refusal samples were frozen, freeze-dried, finely ground and analysed in duplicate for moisture (convection oven 105°C, AOAC 930.15, 925.10) (AOAC, 2000), ash (furnace 550°C, AOAC 942.05) (AOAC, 2000), gross energy content (adiabatic bomb calorimeter, Gallenkamp and Co. Ltd., London) and for neutral detergent fibre (NDF) and acid detergent fibre (ADF) by the method of Robertson and van Soest (1981). Feed samples were also analysed for protein by the total combustion method (Leco, AOAC 986.06), and crude fat (Sontec extraction, AOAC 920.39) (AOAC, 2000).

A second frozen sub-sample of the faeces were analysed for particle size by the wet sieving procedures described by Waghorn (1986). The faecal samples were thawed, weight and wet sieved in a set of Endocot (London, UK) sieves of size 2,000, 1,000, 500, 250, 106, 75 µm. Each sample was then washed through the sieves and the contents of each of the sieves subsequently washed onto a dried, pre-weighed

filter paper. Samples of elute were retained for determination of soluble matter. Filter papers and samples of elute were then dried for 24 h in a forced draft oven at 80°C before re-weighing. The masses of particles from each sieve were expressed as percent of total dry matter recovered including the solubles. The mean of two replicates per sample was used in all subsequent calculations.

Statistical data analysis

A normality test was carried out, and the data transformed as appropriate. The effect of dietary particle size on live weight, daily growth rate, carcass weight, and backfat thickness were statistically analysed on an individual animal basis using simple analysis of variance (PROC GLM, SAS 2003). Daily feed intake and feed conversion ratio were analysed similarly, but at the pen level. Stomach scores were analysed with a categorical data modelling procedure (PROC GENMOD, SAS 2003). The effect of dietary particle size on histological parameters was statistically analysed with a general linear model with diet as a fixed effect and using pig within diet as the error term (PROC GLM, SAS 2003). The digestibility coefficients for gross energy (DEc), neutral detergent fibre (NDFc) acid detergent fibre (ADFc) were calculated based on the determined GE, NDF and ADF values and the total feed intake and faecal outputs. Faecal particle sizes were statistically analysed by simple analysis of variance (PROC GLM, SAS 2003). A principal component analysis was conducted using PROC FACTOR (SAS 2003).

RESULTS

Diets characteristics

The ingredient composition and the chemical analysis of the experimental diets are presented in Table 1.

The target dietary average particle sizes (d_{gw}) were 1,000, 700, and 400 µm for the coarse, medium and fine diets, respectively. The actual particle size averages and standard deviation ($d_{gw} \pm S_{gw}$), for the four grower and finisher diets were: coarse (1,026±2.3 µm, 1,175±2.1 µm, medium (716±2.3 µm, 854±2.1 µm), fine (390±1.7 µm, 479±1.7 µm) and mixed (880±2.6 µm, 698±2.3 µm).

The average particle size of the grower diets were within 3% of the target, but the finisher diets were 20% coarser than the target. Both the grower and finisher mixed diets displayed the greatest variations in particle size as measured by the standard deviation (S_{gw}).

Growth performance

During the grower phase (LW 31-61 kg), pigs fed the medium and mixed diets had higher ($p < 0.01$) average daily gain (ADG), than those feed the fine and coarse diets (882

Table 2. Least-square means for average daily gain (ADG), daily feed intake (DFI), feed conversion ratio (FCR), P2 backfat thickness (BF) and dressing percentage (DP) for pigs fed diets of different particle size

	Diet				SE
	Fine	Medium	Coarse	Mixed	
Grower ADG (g/d)	794 ^a	882 ^b	803 ^a	923 ^b	29
DFI (kg/d)	1.74	1.76	1.66	1.83	0.052
FCR (kg/kg)	2.19	2.00	2.07	1.99	0.092
Finisher ADG (g/d)	1,149	1,092	1,101	1,113	39
DFI (kg/d)	2.81	2.62	2.67	2.76	0.082
FCR (kg/kg)	2.46	2.44	2.45	2.53	0.076
Overall ADG (g/d)	940	964	937	994	24
DFI (kg/d)	2.18 ^b	2.09 ^a	2.10 ^a	2.20 ^b	0.012
FCR (kg/kg)	2.33	2.19	2.26	2.33	0.050
BF (mm)	10.7	10.9	10.2	10.9	0.59
DP (%)	77.2 ^b	76.2 ^{ab}	75.3 ^a	76.0 ^a	0.38

^{a, b, c} Values within a row with different superscripts are different (LSD, $p < 0.05$).

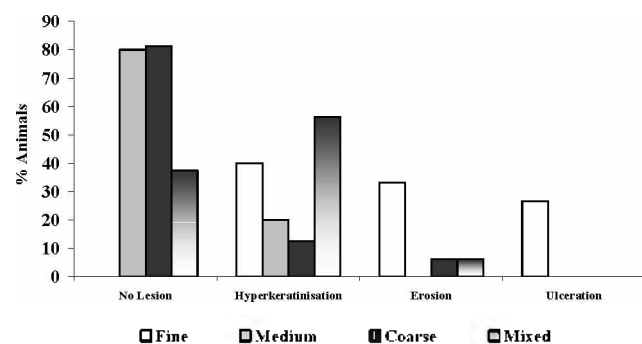
Table 3. Stomach ulceration scores and histological measurements of a section of distal ileum of pigs fed diets of different particle size

	Diet				SE
	Fine	Medium	Coarse	Mixed	
Stomach ulceration score	1.87 ^z	0.20 ^x	0.25 ^x	0.69 ^y	0.156
Ileal measurements (μm)					
Villous tip - crypt base	772	795	819	719	36
Villous height	348	397	413	356	36
Crypt depth	428	397	410	368	22
Epithelial thickness (log)	1.43 ^c	1.29 ^{bc}	1.15 ^{ba}	1.01 ^a	0.057
(back-transformed value) ¹	(26.9)	(19.5)	(14.0)	(10.2)	

^{x, y, z} Values within a row with different superscripts are different (Chi², $p < 0.05$).

^{a, b, c} Values within a row with different superscripts are different (LSD, $p < 0.05$).

¹ Back-transformed value: $10^{\text{Epithelial thickness}}$ i.e. $10^{1.43} = 26.9$.

**Figure 1.** Stomach lesion distributions for pigs fed diets of different particle size characteristics.

and 923 g/d vs. 794 and 803 g/d, respectively) (Table 2). No significant differences ($p > 0.05$) were observed in ADG during the finisher phase. Over the entire trial period, the ranking of treatments within ADG was similar to that during the grower phase (mixed and medium > coarse and fine), but the differences were not statistically significant. No treatment differences in backfat thickness were observed. Dressing percentage increased significantly ($p = 0.013$) as the average particle size of the diet decreased. No differences in feed conversion ratio were found between treatment groups. Over the entire trial, pigs fed the medium

and coarse had a lower feed intake than those fed the fine and mixed diets (Table 2).

Morphological measurements

Pigs fed the medium and coarse diets had lower stomach ulceration scores (0.20 and 0.25, respectively) than those fed the mixed diet (0.69). The highest score was recorded for pigs fed the fine diet (1.87; Table 3). All the stomachs of the animals fed the fine diets had lesions, and ulcerations were present only in this group (Figure 1). Approximately 80% of the animals fed the medium and coarse diet had stomachs with no lesions. There were no significant differences between the treatment groups for the villous tip-crypt base, villous height, or crypt depth (Table 3). Epithelial thickness was significantly thinner ($p < 0.01$) in the coarse diet and even thinner in the mixed diet ($p < 0.01$) than in the fine diet group.

Digestibility coefficients

Faecal neutral and acid detergent fibres digestibility coefficients were the highest for the mixed diets, intermediate for the fine and coarse diet and the lowest for the medium diet ($p < 0.05$). A similar numerical trend was observed for the apparent faecal energy digestibility coefficients ($p = 0.103$) (Table 4).

Table 4. Faecal digestibility coefficients for energy (DEc), neutral detergent fibre (NDFc) and acid detergent fibre (ADFc) as influenced by feed particle size

	Fine	Medium	Coarse	Mixed	SE
DEc	0.817	0.789	0.812	0.821	0.093
NDFc	0.609 ^b	0.552 ^a	0.622 ^b	0.689 ^c	0.014
ADFc	0.259 ^{ab}	0.188 ^a	0.275 ^{bc}	0.352 ^c	0.028

^{a,b,c} Values within a row with different superscripts are different (LSD, $p < 0.05$).

Particle size

No difference in the distribution of particle size in the faeces was observed between the mixed and medium diets (Table 5). The coarse diet had the largest ($p < 0.05$) proportion of particles over 2,000 μm and the fine diet the largest ($p < 0.05$) proportion of particles between 106 and 1,000 μm . The change in particle size distribution between the diet and the faeces was calculated for each animal, and a principal component analysis was conducted with those values. The results of this analysis show that the change in particle size distribution allows a clear distinction between animals fed different diets (Figure 2). The first principal component function explained 54% of the variance and the

Table 6. Principal component analysis functions for changes in particle size distribution between diet and faeces

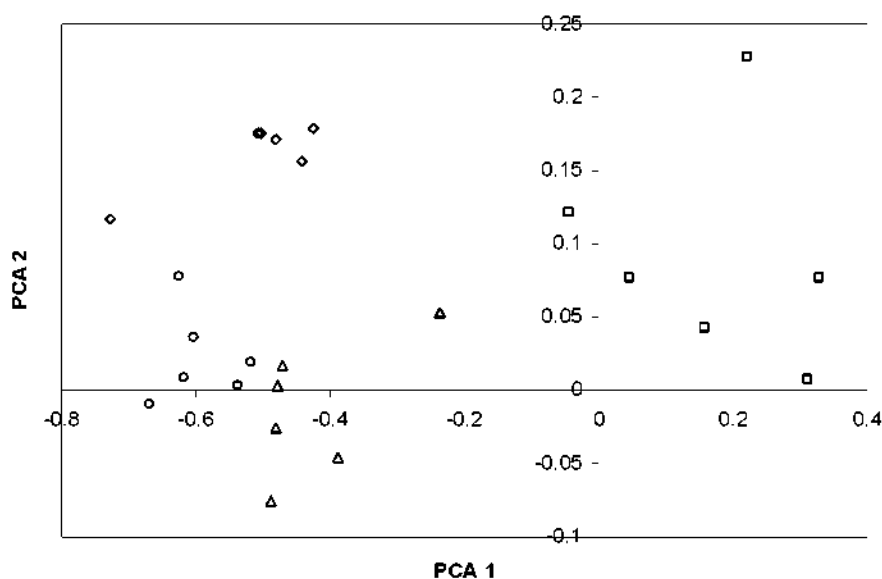
Particle size class	Function 1	Function 2
>2,000 μm	0.1073	-0.8862
1,000-2,000 μm	-0.9659	-0.1433
500-1,000 μm	-0.6678	0.5935
250-500 μm	0.7565	0.3259
106-250 μm	0.9049	0.1112
<106 μm	0.6945	0.0084
% variance	54.4	21.3

second 21% (Table 6).

DISCUSSION

Growth performance

In the present study, diets containing at least 70% barley ground at different average particle sizes (coarse, medium and fine) were fed to pigs between 31 and 86 kg live weight. Pigs fed the medium diets had higher ADG during the grower phase than those fed the fine and coarse diets. They also had a lower DFI than those fed the fine diet. Over the entire growth phase, there was a trend for pigs fed the

**Figure 2.** Graph of first and second principal component functions (PCA1 and PCA2) for changes in particle size distribution between diet and faeces, (\square = fine, \diamond = medium, \circ = coarse, Δ = mixed).**Table 5.** Particle size proportion in the faeces

Particle size class	Fine	Medium	Coarse	Mixed	SE
>2,000 μm	0.058 ^a	0.161 ^b	0.221 ^c	0.166 ^b	0.015
1,000-2,000 μm	0.151	0.152	0.162	0.156	0.012
500-1,000 μm	0.299 ^b	0.144 ^a	0.134 ^a	0.135 ^a	0.020
250-500 μm	0.220 ^b	0.120 ^a	0.120 ^a	0.114 ^a	0.017
106-250 μm	0.110 ^b	0.088 ^a	0.083 ^a	0.090 ^a	0.006
72-106 μm	0.037	0.039	0.039	0.038	0.003
Solubles	0.126 ^a	0.296 ^b	0.241 ^b	0.302 ^b	0.032

^{a,b,c} Values within a row with different superscript are different (LSD, $p < 0.05$).

medium size diet to eat less, grow faster, and have better feed conversion ratios than those fed either the coarsely or finely ground diets. Nielsen and Ingvarlsen (2000) did not find any differences in ADG, AFI, FCR and percent lean when pigs were fed diets containing 70% barley ground to 480 or 860 μm between 25 and 95 kg live weight. Lawrence (1970) did not find any effect of particle size on growth performances when pigs were fed barley-based diets milled with 1.56 mm, 4.68 mm and 9.36 mm screens. Also, Seerley et al. (1988) found no differences in performance with corn and wheat-based diets with particle sizes between 910 μm and 1,780 μm . No differences in DFI, ADG, or FCR were observed by Laurinen et al. (2000) between pigs fed barley ground with a hammer mill equipped with 3 or 5 mm screens. Guillou and Landau (2000) reviewed 23 trials conducted in France and showed that with barley-based diets, a curvilinear relationship exists between particle size and both ADG and FCR. Average daily gain was highest and FCR lowest where diets had a particle size around 700 μm . The differences observed in the dressing percentage suggest that both the size of the gastrointestinal tract and its contents were larger for pigs fed coarsely ground diets.

In summary, growth performance is optimised where the particle size of a barley-based diet fed as a meal is between 700 and 800 μm .

A comparison of the medium and mixed diets allows assessment of the impact of increased particle size variation (S_{gw}) within diets of a similar average particle size. The S_{gw} was larger in the mixed versus the medium diet (2.6 vs. 2.3 μm , and 2.3 vs. 2.1 μm in the grower and finisher diets, respectively). Increased particle size variation had no effect on ADG, DFI, or FCR during either of the grower or finisher phases. Similarly, Wondra et al. (1995c) did not find an effect of corn-based diet particle size variation (2.5 vs. 2.3 vs. 2.0) on pig performance.

Morphological measurements

The influence of fine milling on the increase in stomach ulceration has been reported by many authors (Wondra et al. 1995b; Dirkzwager et al. 1998; Eisemann and Argenzio, 1999). In the present experiment, all pigs fed the finely milled barley diet ($d_{\text{gw}} < 500 \mu\text{m}$) had some sort of lesion in the *pars oesophagea* region of the stomach and, consequently, had the highest stomach ulceration score (1.87 on a four-point scale). This was also found by Cole et al. (2002) who noted progressive erosive damage to the *pars oesophageal* region of the stomach after feeding fine diets for 7-days, and increases in ulcerative damage after 24 or 48 h of feed withdrawal. In the present study, pigs fed the medium and coarse diets ($d_{\text{gw}} > 700 \mu\text{m}$ and $< 1,200 \mu\text{m}$) had the lowest scores (0.20 and 0.25, respectively), and none of them displayed stomach ulceration. These findings are in agreement to those of Nielsen and Ingvarlsen (2000), where

stomach score (on a scale of 1 to 10) increased from 2.1 to 3.1 when particle size was reduced from 860 to 480 μm , and those of Ayles et al. (1999) where no change in stomach ulceration score (1.23 vs. 1.41, on a scale from 0 to 3) was recorded for diets having average particle sizes of 763 and 953 μm .

Pigs fed the mixed diet, which contains one third of the fine particle size diet, had an intermediate ulceration score (0.69), and the majority of the pigs in this group had hyperkeratisation in the stomach. This suggests that an increase in particle size variation in diets of similar average particle size (i.e. mixed vs. medium diet, $S_{\text{gw}} = 2.6$ vs. 2.3 μm , and 2.3 vs. 2.1 μm in grower and finisher diets, respectively) had a negative influence on gastric ulceration (0.20 for medium vs. 0.69 for mixed). Such a trend was also observed by Wondra et al. (1995c), who reported an increase in keratinisation score from 1.7 to 2.3 (on a scale of 1 to 4), where S_{gw} increased from 2.0 to 2.5.

Brunsgaard (1998) showed that feed particle size (coarse or fine) rather than the type of cereal (wheat or barley) had an effect on morphological characteristics and epithelial cell proliferation in the caecum and colon of pigs. Pig fed coarse barley (75% of particles greater than 1,000 μm) had larger crypt depth and volume than those fed the fine barley (17% of particles $> 1,000 \mu\text{m}$). Hedemann et al. (2005) did not find any effects of particle size on villous height and crypt depth in the small intestine, but Brunsgaard (1998) did observe that the crypt depth in the colon was significantly lower in the fine diet compared with the coarse diet (420 ± 12 vs. $449 \pm 12 \mu\text{m}$). In our study, similarly to Hedemann et al. (2005), no difference in crypt depth and villi height were observed in the small intestine. However, pigs fed the coarse diet (64% of particles greater than 1,000 μm) tends ($p > 0.05$) to have a larger distance from villous tip to crypt base and have a finer epithelium thickness ($p < 0.05$) than those fed the fine diet (9% of particles greater than 1,000 μm). As epithelial thickness is an indication of cell repairs our results show that more morphological damage of the villi are present with fine diet than with coarse diet in the small intestine. These changes in intestinal morphology are similar to those observed after weaning (Dong and Pluske, 2007). It can be expected that, as in weaned piglets, the morphological damage caused by the fine diet will reduce nutrient absorption and that the production and composition of the mucin will be affected thus impacting on gut health in the small intestine.

Digestibility coefficients and particle size

Pigs fed the mixed diet had the highest faecal digestibilities for neutral detergent fibre, acid detergent fibre and energy, while pigs fed the medium diet had the lowest, and those fed the fine and coarse diet had intermediate values. These differences were statistically

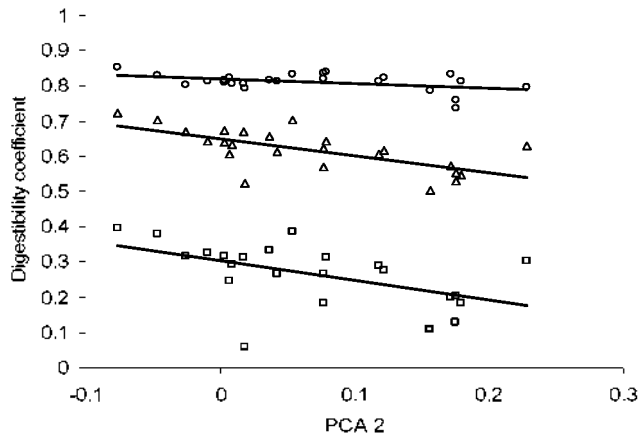


Figure 3. Relationships between principal component function 2 values and faecal digestibility coefficients for ADFc (\square), NDFc (Δ) and DEc (\circ).

significant ($p < 0.05$) for NDFc and ADFc but not for DEc. Similarly, Dirkzwager et al. (1998), Laurinen et al. (2000), and Albar et al. (2000) did not find significant differences in apparent faecal energy digestibility between finely and coarsely ground barley in weaner, grower, or finisher pigs. The ranking of the diets in terms of digestibility coefficients was medium < fine = coarse < mixed and do not match the average dietary particle size (fine < medium = mixed < coarse) or dietary particle size variation (fine = medium = coarse, mixed). Moreover, the particle size distribution in the faeces does not seem to be related to digestibility coefficients as the diet with the highest (mixed) and lowest (medium) values have a similar particle size distribution in the faeces. However, it is possible to discriminate between animals fed different diets when the changes in particle size distribution between the feed and the faeces are used. Such discrimination has been observed in chickens fed different types of wheat (Lentle et al., 2006). The ranking of the diet on the x-axis (principal component function 1, Figure 2) corresponds to the average dietary particle size (fine < medium = mixed < coarse) and the ranking on the y-axis (principal component function 2, Figure 2), match the ranking in digestibility (medium < fine = coarse < mixed). Figure 3 represents the relationships between the principal component function 2 values and DEc ($R^2 = 0.21$, $p < 0.05$), NDFc ($R^2 = 0.44$, $p < 0.001$) and ADFc ($R^2 = 0.28$, $p < 0.01$). This illustrates the fact that the digestibility coefficients are related to changes in particle size distribution during the digestion process, but it does not explain why pigs fed the mixed diet had higher digestibilities than those fed the medium diet.

In humans, starch from coarsely ground diets is physically less accessible for enzymatic digestion due to the presence of intact cell wall (Livesey et al., 1995). However, undigested starch will contribute to increased fermentation in the hind gut thus increasing the production of short-chain

fatty acids (Livesey, 1991). In our study no difference in DEc between the fine and the coarse diets was observed. It can be expected that starch digestion in the small intestine will be greater for the fine diet than the coarse diet and that fermentation in the hindgut will be higher for the coarse diet, thus resulting in similar apparent faecal DEc values. Similarly, it can be postulated that the highest digestibility coefficients observed for the mixed diet are caused by a higher starch digestibility in the small intestine and higher hindgut fermentation.

CONCLUSIONS

It is concluded that, with barley based diets, a variation in average particle size between 400 μm and 1,100 μm had no effect on pig performance but fine dietary particle size affected the integrity of the stomach, as well as the structure of the small intestine, thus compromising overall gut health. Our data also demonstrate that changes in particle size distribution during the digestion process, rather than average particle size or particle size variation per se, are related to apparent faecal digestibility.

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