EFFECT OF FEED STRUCTURE ON NUTRIENT DIGESTIBILITY, GROWTH PERFORMANCE, AND GASTROINTESTINAL TRACT OF PIGS – A REVIEW

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Abstract

The objective of this manuscript has been to analyse published data on the effect of feed structure (coarse/fine, meal/pelleted) on some parameters of the nutritional value of feed, performance of pigs and their gastrointestinal tract. The papers reporting mean geometric particle size or distribution of particles on sieves for the feeds used, were mainly considered. The literature data have indicated that finely ground feeds have a higher ileal digestibility of crude protein and amino acids and higher faecal digestibility of nutrients. They also contain more digestible and metabolisable energy than coarser ground feeds. Reduction of feed particle size has a stronger impact on the gain/feed ratio increase than on the daily gain of pigs. However, coarser feed structure and roller milling are efficient in maintaining the health of stomach. Lactic bacteria, stomach pH, short chain fatty acids in the gastrointestinal tract (GIT), as well as the volume and character of mucins positively responded to coarser and to non-pelleted feeds. Less intensively ground feeds, especially before pelleting, are also better at protecting the GIT of pigs against microbial infection by *Salmonella enterica*. Based on the references, some recommendations of grinding intensity have also been included.

Key words: particle size, digestibility, performance, gastrointestinal tract, pigs

Grinding is the most popular way of preparing animal feeds. It is particularly important in swine feeding because pigs do not comminute ingested feeds very well. Unlike birds, they do not have a gizzard for reduction of feed particles, neither do they chew feeds with teeth as meticulously as horses. Smaller particles of feeds mean a larger surface area exposed to digestive enzymes (Mavromichalis et al., 2000). With smaller particles, it is also possible to obtain better homogeneity while mixing

feeds, to prevent segregation (formation of layers) during transport of bulk feeds and to achieve a higher degree of starch gelatinization while pelleting feeds (Svihus et al., 2004). Smaller particles also improve pellet durability (Wondra et al., 1995 b; Svihus et al., 2004) and make it easier to add fat to feed mixes.

Feeds are disintegrated using hammer mills, roller mills or by crimping. In feed manufacturing plants, hammer mills are used most often for preparation of feeds for swine. Hammer mills are also suitable for grinding fibrous feeds (barley and oats grain, bran, grass meal, hulls). The particle size of feed materials and complete feed mixture is determined by the sieve method, that is by dry- or wet-sieve analysis. The results are given as the percentage distribution of particles on particular sieves or as a mean geometric diameter (MGD) particle size, in microns (μm) or millimeters. From the point of view of nutrition or technology, feeds disintegrated with hammer mills have a poorer distribution of particles than feeds ground by roller mills because they contain more fines (Wondra et al., 1995 c).

Effect of particle size on digestibility of nutrients and energy concentration

It is important to note that grinding intensity of feed influences nutrient digestibility. Measures of ileal digestibility are used routinely as estimates of amino acid bio-availability in pig feeds (Stein et al., 2007). The effects of particle size of cereal used in pig diets or particle size of feed mixtures on the ileal digestibility of amino acids (apparent, standardized or real) are presented in Table 1. Decreasing the particle size of cereal grains has increased the ileal digestibility of crude protein (N) and essential amino acids (AAs) in growing pigs (Wünsche et al., 1997; Fuller et al., 1994; Lahaye et al., 2008). Results of Kim et al. (2009) have shown that the fine grinding of lupin seeds (567 vs 1198 μm) considerably increased ileal digestibility of lysine (by 15%) and threonine (by 24%). Decreasing the particle size of complete feed mixtures from about 1000 to 600 μm (Oryschak et al., 2002) or to 500 μm (Lahaye et al., 2004, 2007) raised the digestibility of N by 7 to 10%, lysine by 10%, methionine by 4%, and threonine by 7 to 11%. For wheat-pea diets, very fine grinding (200 vs 500 μm) was beneficial (Lahaye et al., 2003). In very young piglets, the ileal digestibility of protein and AAs in a diet with fine ground maize (400 μm) appeared even lower ($P>0.05$) than in a diet with coarse ground maize (900 μm) (Chae et al., 2000).

The effect of a particle size of feeds on the faecal digestibility of crude protein and energy in pigs was summarized by Guillou and Landeau (2000). They found that for each 100 μm reduction in a range of particle sizes from 1500 to 200 μm , the digestibility of crude protein increases by 0.847 ($P<0.001$), and of energy increases by 0.629 percentage points ($P<0.001$).

Another consequence of the grinding intensity of feeds concerning the digestibility of nutrients is a change in the nutritional value, expressed by the digestible energy (DE) or metabolisable energy (ME) concentration (Table 2). Decreasing the particle size of maize-based diets (430 vs 840 μm) resulted in an increased (by 3.5%) DE concentration in piglets (Albar et al., 2000), as well as in sows (by 5%) fed a diet with MGD of 478 μm instead of 907 μm (Wondra et al., 1995 a). Complete diets

formulated from barley ground to 610 µm instead of 929 µm (Flis et al., 2001), and barley grain with a particle size reduced from 900 to 400 µm (Nortey et al., 2003) also had higher concentrations of DE and ME (by 0.5 MJ/kg) in growing and finishing pigs. The findings of Montoya and Leterme (2011) showed that field pea for pigs should be intensively ground, which may increase the DE concentration by up to 15%. The results of the cited experiments demonstrate that medium and fine ground feeds in swine nutrition have higher digestibility of nitrogenous compounds, energy and higher energy concentration than coarsely ground feeds, especially ones with particles above 800 µm. Such more intensively ground feeds should result in better performance parameters.

Table 1. Effect of grain/complete feed particle size on nitrogen and some essential amino acids ileal digestibility in pigs

Assay ingredient/ diet	MGD µm	Pig category	Coefficient of ileal digestibility (%)					Reference
			N	lys	met	thr	ΣAA	
Barley	^c 1600	growing	[†] 74.6		[†] 72.6	[†] 69.6		Wünsche et al. (1987)
	700	35 kg	81.1		77.6	78.5		
	600	initial	86.0		83.6	84.5		
Wheat	^c 1000		84.9		80.2	77.4		
	600		85.7		87.5	78.9		
	500		90.3		87.8	83.8		
Barley	^d 4 mm	growing	^Δ 63	^Δ 62	^Δ 72	^Δ 49	^Δ 69	Fuller et al. (1994)
	2 mm		70	64	^Δ 73	62	75	
Wheat	904	growing	[§] 75.9	[§] 60.7	[§] 78.9	[§] 63.9	[§] 79.2	Lahaye et al. (2008)
	598	38 kg initial	78.6	58.3	80.1	66.0	81.2	
Lupin seeds	1198	growing	^Δ 64.5	[§] 72.4	[§] 70.3	[§] 65.6		Kim et al. (2009)
	955	47 kg	73.2	75.8	72.7	71.5		
	567		79.3	83.6	71.4	81.9		
Maize-based diets	900	piglets		[†] 92.5	[†] 83.8	[†] 85.4	^{c,†} 86.8	Chae et al. (2000)
	400	26 day old		89.2	82.2	86.8	85.4	
Barley-based diets	928	growing	^Δ 67.4 b					Oryschak et al. (2002)
	646	25 kg initial	73.6 a					
Wheat-pea diets	500	growing	[†] 76.6 b	[†] 75.7 b		[†] 76.6 b		Lahaye et al. (2003)
	200	35 kg initial	85.3 a	87.3 a		85.7 a		
Wheat- -sunflower diets	954	growing	[§] 74.2 b	[§] 64.7 b	[§] 83.1 b	[§] 68.6 b		Lahaye et al. (2004)
	462	38 kg initial	79.2 a	71.3 a	86.6 a	73.3 a		
Maize-soy- bean meal diets	1000	growing	[§] 63.3	[§] 63.7		[§] 58.4		Lahaye et al. (2007)
	500		69.5	69.8		65.0		

a, b – values are significantly different; ^c own calculation of MGD from given distribution of particles; ^d 2 or 4 mm screen size; ^e ΣEAA; [†] true digestibility; ^Δ apparent digestibility; [§] standardized digestibility.

Table 2. Effect of particle size on energy concentration in diets

Main dietary grain	Diet MGD μm	Pig category	Energy concentration (MJ/kg)		Reference
			digestible	metabolisable	
Maize	907	sows	15.33 b	14.9 b	Wondra et al. (1995 a)
	478		16.13 a (+5.1%)	15.7 a (+4.8%)	
Maize	840	piglets 13.5 kg	^d 15.36 b		Albar et al. (2000)
	430		15.91 a (+3.5%)		
Barley	830		14.69		
	440		14.89 (+1.4%)		
Barley	^e 929	growing		11.93	Flis et al. (2001)
	610	53 kg		12.43 (+4.2%)	
	929	finishing		12.24	
	610	78 kg		12.70 (+3.8%)	
Barley	^f 900	growing	^f 11.99 b		Nortey et al. (2003)
	650		12.10 b		
	400		12.50 a (+4.2%)		
Field pea seeds ^g	1035	growing	13.96 c		Montoya and Leterme (2011)
	649	28 kg	14.71 b (+8%)		
	156		16.05 a (+15%)		

a, b, c – values are significantly different; ^d MJ/kg dry matter; ^e MGD particles of barley used for formulation of the diets; ^f MGD particles and DE content for barley grain; ^g MGD particles and DE content for field pea seeds.

The effect of grinding intensity on growth performance of pigs

Table 3 juxtaposes results of some studies on the effect of dietary particle size on the growth performance of pigs. Most investigations have shown that smaller particles of feeds for weaned piglets, mainly achieved by decreasing the particle size of grains used in diet formulation, increase the average daily gain (ADG) and feed conversion (G/F) ratio, i.e. gain of body weight from 1 kg of ingested feed. Decreasing a dietary particle size from very coarse (1430 μm) to medium (680 μm) markedly increased the ADG (by 9.7%) and G/F ratio (by 11.6%), but further reduction of the particle size (to 450 μm) did not cause a larger increase of the ADG (Mavromichalis et al., 2000). In a study of Albar et al. (2000), a decrease in the MGD in diets from 710–840 μm to 430–550 μm raised the ADG by 3.1–5.7% and the G/F ratio by 2.1–6.9%, depending on the supplied cereal (wheat, barley, maize). In addition, decreasing the particle size in feeds for growing or for finishing fatteners also frequently increases the performance parameters (Wondra et al., 1995 b, c; Mavromichalis et al., 2000; Callan et al., 2007; Millet et al., 2012 b). The findings reported from most of the investigations showed that pigs fed finely ground diets more frequently demonstrated a greater improvement of G/F ratio than improvement of ADG. This was often associated with a lower feed intake of finely than coarsely ground feeds (Wondra et al., 1995 b, c; Mavromichalis et al., 2000; Callan et al., 2007; Grosse Liesner et al., 2009; Millet et al., 2012 b). Another explanation could be the higher nutritional value of finely ground feeds, i.e. higher amino acid digestibility and energy concentration.

Table 3. Effect of dietary particle size on growth performance parameters in pigs

Main dietary grain	Diet MGD μm	Pig category	Growth performance parameters			Reference
			ADFI (kg)	ADG (g)	G/F (g)	
Wheat	1430	weaned (21 d)	0.55	410 (100%)	750 (100%)	Mavromichalis et al. (2000)
	680	piglets	0.52	450 (+9.7%)	870 (+11.6%)	
	450		0.51	430 (+4.9%)	840 (+11.2%)	
Wheat	710	piglets	0.799	552 (100%)	676 (100%)	Albar et al. (2000)
	530	(8–26 kg)	0.814	566 (+2.5%)	676	
	450		0.812	576 (+4.3%)	694 (+2.7%)	
Barley	830	piglets	0.729	474 b (100%)	653 (100%)	Albar et al. (2000)
	740	(8–26 kg)	0.753	498 a (+5.1%)	662 (+1.4%)	
	550		0.742	501 a (+5.7%)	671 (+2.7%)	
	440		0.748	498 a (+5.1%)	667 (+2.1%)	
Maize	840	piglets	0.805	518 b (100%)	641 b (100%)	Albar et al. (2000)
	660	(8–26 kg)	0.810	545 a (+5.2%)	667 ab (+4%)	
	430		0.776	534 ab (+3.1%)	685 a (+6.9%)	
Wheat-barley	^{c,d} 930	piglets	1.30	708	546	Grosse Liesner et al. (2009)
	^{c,e} 860	(7–12 weeks)	1.33	771	581 (100%)	
	^{c,e} 560		1.20	692	578	
	^{c,e} 490		1.27	753	595 (+2.4%)	
	^{c,e} 470		1.09	689	633 (+9%)	
Wheat	^f coarse	weaners	^h 0.98	543 b (100%)	ⁱ 552 b (100%)	Rasmussen et al. (2012)
	^g fine	8–30 kg	0.99	561 a (+3.3%)	568 a (+2.9%)	
Maize	1017	finishing	3.25 a	960 (100%)	295 (100%)	Wondra et al. (1995 b)
	886	55–114 kg	3.21 a	940	293	
	705		3.26 a	950	291	
	507		3.16 b	980 (+2%)	310 (+5%)	
Maize	806	finishing	3.282 a	931 (100%)	284 b (100%)	Wondra et al. (1995 c)
	558	55–113 kg	3.134 b	964 (+3.5%)	308 a (+8.4%)	
Wheat (Exp. 2)	1250	finishing	3.11	880 (100%)	280 (100%)	Mavromichalis et al. (2000)
	670	67–114 kg	3.05	890 (+1%)	290 (+3.6%)	
Wheat (Exp. 3)	660	finishing	2.91	900 (100%)	310 (100%)	Mavromichalis et al. (2000)
	440	63–115 kg	2.84	910 (+1%)	320 (+3.2%)	
Complex diets	^c 900	finishing	2.55 a	920 (100%)	357 b (100%)	Callan et al. (2007)
	^c 640	48 kg+56 days	2.47 b	955 (+3.8%)	382 a (+7%)	
Corn-barley-wheat	700-LF ^j	growing-	1.98	776	392 b	Millet et al. (2012 b)
	500-LF	-finishing	1.96	771	393 b	
	700-HF ^j	24–107 kg	1.95	766	392 b (100%)	
	500-HF		1.87	771	411 a (+4.8%)	

a, b – values are significantly different; ^c own calculation of MGD from data distribution of particles; ^d meal form; ^e pelleted; ^f 60% dietary particles above 1 mm; ^g 35% dietary particles above 1 mm; ^h daily intake in feed units for grower pigs (FUGp); ⁱ gram of body weight gain/1 FUGp; ^j LF and HF diets contained 4 and 9% of crude fibre, respectively.

Effect of feed structure on the gastrointestinal tract

In swine production, the gastrointestinal tract (GIT) health and resistance to bacterial infections are also important, as they affect the costs of veterinary care and also animal welfare.

Table 4. Effect of diet particle size on stomach morphology score in pigs

Main dietary grain	Pig category	Diet MGD (μ m) and form	Stomach score ^a			Reference
			keratinization	ulceration	mean score	
Maize	weaned piglets	712 – HM ^b , pelleted	^c 1.0	^c 1.0		Healy et al. (1994)
		418 – HM, pelleted	1.75	1.0		
Maize	finishing 55–114 kg	1017 – HM, meal	^d 1.4	^d 1.1		Wondra et al. (1995 b)
		1017 – HM, pelleted	2.0	1.2		
		517 – HM, meal	3.2	1.8		
		517 – HM, pelleted	3.4	1.9		
Maize	finishing 55–113 kg	460 – HM, meal	^d 3.0	^d 1.6		Wondra et al. (1995 c)
		460 – HM, pelleted	2.8	2.3		
		491 – RM ^e , meal	2.0	1.2		
		491 – RM, pelleted	2.6	1.6		
Barley	growing-finish 25–97 kg	860 – RM, meal			^f 0.8	Nielsen and Ingvarsten (2000)
		860 – RM, pelleted			1.3	
		480 – HM, meal			2.1	
		480 – HM, pelleted			3.7	
Wheat		900 – RM, meal			0.6	
		900 – RM, pelleted			4.3	
		510 – HM, meal			3.5	
		510 – HM, pelleted			4.9	
Triticale	growing-finish 26–94 kg	1300 ^g – RM, meal			^d 0.8	Flis et al. (2003)
		900 ^g – HM, meal			1.1	
		550 ^g – HM, meal			1.5	
Barley	growing-finish 31–87 kg	1105 – HM, meal			^e 0.25	Morel and Cottam (2007)
		785 – HM, meal			0.20	
		434 – HM, meal			1.87	
Barley-wheat	growing-finish 9–110 kg	890 – meal			ⁱ 0.70	Millet et al. (2012 a)
		720 – crumbled ^h			2.81	

^a higher values indicate greater pathogenic changes; ^bhammer-milled grain used in diet; ^c1–3 point scale; ^d1–4 point scale; ^e roller-milled grain used in diet; ^f 0–10 point scale; ^gparticle size of grain used for diet formulation; ^hpelleted and crumbled; ⁱ 0–5 point scale.

Ulceration of the stomach is a common disorder in swine herds (Melnichouk, 2002; Friendship, 2003), which awaits full clarification. The following are implied as possible causes: genetic traits, various stress factors present in pig production, infection with *Helicobacter suis*, pre-slaughter handling operations as well as feed structure (Friendship, 2003; Haesebrouck et al., 2009). Fine grinding of ingredients of complete feeds, which improves digestibility of nutrients, energy concentration and often the performance parameters, is not beneficial for the GIT health of pigs. It has been demonstrated that finely ground feeds cause damage to the stomach mucosa

in the non-glandular region surrounding the esophageal opening (*pars oesophagea*). Several degrees of the loss of integrity are distinguished: parakeratosis, erosive lesions and ulcers, and the scoring system of the integrity of stomach mucosa facilitates interpretation of results.

The data summarized in Table 4 indicate that a coarser feed structure is efficient in maintaining the integrity of gastric mucosa. Decreasing the dietary particle size from about 700 to about 400 μm by using finely ground maize raised the stomach keratinization score from 1.0 to 1.75 in weaned piglets (Healy et al., 1994). Also, decreasing the particle size of finisher maize-based meal diet from 1017 to 517 μm increased keratinization (from 1.4 to 3.2) and ulceration (from 1.1 to 1.8) score (Wondra et al., 1995 b). Pigs fed barley-, wheat- or triticale-based finely ground feeds had more pathogenic changes in the stomach than the ones fed coarsely ground feed (Nielsen and Ingvarsten, 2000; Flis et al., 2003; Morel and Cottam, 2007). Applied as meal (non-pelleted), coarse diets (860, 900 μm) formulated from roller-milled barley and wheat significantly increased stomach health compared to diets containing fine (480, 510 μm) hammer-milled grain (Nielsen and Ingvarsten, 2000). A diet containing roller-milled grain, even when having a similar particle size (491 μm) as a diet with hammer-milled grain (460 μm), had better influence on the stomach health (keratinization score 2.0 vs 3.0 and ulceration score 1.2 vs 1.6) (Wondra et al., 1995 c).

The mechanism responsible for the beneficial effect of a coarser ground feed on the integrity of stomach mucosa is still unclear. It has been proven that pigs fed a coarse meal feed had firmer (solid) stomach content because of higher dry matter concentrations than pigs fed a fine meal diet, which had more watery stomach ingesta (Nielsen and Ingvarsten, 2000; Mikkelsen et al., 2004). It has been proven that high firmness of stomach content coincided with a low score of gastric lesions (Nielsen and Ingvarsten, 2000). Mösseler et al. (2010) found that also the pH of gastric ingesta from the esophageal region of pigs fed coarsely ground meal diet was higher than of pigs fed finely ground meal diet (4.94 vs 4.47; $P < 0.05$).

Pelleted diets, produced from both coarse ground and fine ground feeds, increased incidence and severity of keratinization, erosion and ulcerations of stomach (Wondra et al., 1995 b, c; Nielsen and Ingvarsten, 2000) (Table 4). Pelleted diets, confronted with non-pelleted ones, raised the incidence and severity of the damage of stomach mucosal integrity of finisher pigs (Wondra et al., 1995 b, c) and grower-finisher pigs (Nielsen and Ingvarsten, 2000; Millet et al., 2012 a) to a greater extent in pigs fed with wheat-based diets than in pigs fed with barley-based diets (Nielsen and Ingvarsten, 2000). In a study of Grosse Liesner et al. (2009), the use of coarsely ground meal diet (25% particles > 2 mm, 29% < 0.4 mm) had hardly any negative effect on the gastric wall, whereas the use of coarsely ground and pelleted diet (9% particles > 2 mm, 51% < 0.4 mm) increased macroscopic stomach score from 0 to 110 ($P < 0.05$), and histological score from 5.4 to 50.2. The pelleted diet (made from finely or coarsely ground feeds) resulted in higher fluidity of the stomach content and significantly higher CL-concentration at the *pars non glandularis* compared with meal diets (Mösseler et al., 2010). A possible explanation could be the reduction of the size of feed particles during pelleting. It was suggested that, in

terms of the particle size, pellet processing is similar to the secondary grinding process (Wolf et al., 2010). Based on the results of Grosse Liesner et al. (2009) and Cappai et al. (2013), the proportion of fine particles (below 0.4 mm) is more important for prevention of gastric lesions, particularly in the case of pelleted complete feeds, than the share of particles over 1.0 mm.

Experimental results have shown that the feed structure (coarse/fine, meal/pelleted) can also affect the microflora, fermentation, morphology and functions of the GIT. Feeding a coarse ground meal diet increased the microbial diversity and stimulated the growth of total anaerobes and lactic acid bacteria in the stomach, compared with feeding fine ground meal and fine ground pelleted diets (Canibe et al., 2005; Mikkelsen et al., 2007). In addition, the number of *Helicobacter suis* bacteria per gram of gastric mucus was lower on meal than on pelleted and subsequently crumbled feed (Millet et al., 2012 a). It was shown that a coarsely ground feed also decreased the number of coliform bacteria in the distal small intestine, ceacum ($P < 0.05$) and midcolon ($P < 0.01$) compared with a finely ground feed (Mikkelsen et al., 2004). Regarding the GIT ecology of pigs, a coarsely ground diet acted similarly to a finely ground diet with addition of 1.8% of formic acid (Canibe et al., 2005) or with 1.2% potassium diformate (Pepenbrock et al., 2005). A higher number of total anaerobes and lactic acid bacteria increases the concentrations of lactic acid and reduces pH in the stomach of pigs fed a coarse non-pelleted diet compared to pigs fed a finely ground pelleted diet (Mikkelsen et al., 2004; Canibe et al., 2005). Thus, the stomach acts as a barrier preventing harmful bacteria from entering and proliferating in the lower part of the GIT (Mikkelsen et al., 2004).

A coarser feed increases the concentration of short chain fatty acids (SCFA) in distal sections of the GIT (Visscher et al., 2009) because more undigested starch flows from the small intestine to the caecum and large intestine (Kamphues et al., 2007). SCFA have a favourable influence on the gut morphology and function. Acetate increases colonic blood flow and enhances ileal motility. Butyrate has been shown to be a preferred energy substrate for the colonocyte and to be a potent differentiating agent in cell culture (Scheppach, 1994). Also, the invasion of intestinal epithelial cells by *Salmonella enterica* is hindered after exposure to butyric acid (Gantois et al., 2006).

The results of Callan et al. (2007) showed that a coarse ground diet (900 μm) increased (210 vs 150 mmol/l; $P < 0.05$) the total faecal SCFA concentration and molar proportions of propionic acid and butyric acid, while decreasing ($P < 0.05$) acetic acid compared to a fine ground diet (640 μm). In another experiment, pigs fed a crumbled diet which had 43% particles above 1 mm (with wet-sieve analysis) showed a higher concentration of propionate ($P < 0.0001$) and butyrate ($P < 0.01$) in the caecal content than those fed the same form of feed, but containing just 30.3% of particles above 1 mm (Visscher et al., 2009).

The intestinal epithelium is protected against pathogens by overlying mucus. Before pathogens permeate into enterocytes, they must degrade the mucous layer (Betscher et al., 2010). Acidic mucins increase resistance of mucus against bacterial enzymes (Deplancke and Gaskins, 2001). Mucosal architecture, epithelial cell proliferation as well as synthesis and qualitative properties of mucins secreted by goblet

cells in the intestine are also affected by the physical form of feed (Brunsgaard, 1998; Hedemann et al., 2005; Morel and Cottam, 2007; Betscher et al., 2010). Feeding coarser feed mixtures increased ($P=0.05$) the crypt depth in the colon compared to feeding fine diets. The crypt depth was 420 and 449 μm in pigs fed finely and coarsely ground feed, respectively (Hedemann et al., 2005). Testing feeds ground to different coarseness (1100, 785, 434 μm) showed that pigs fed a fine ground feed had a thicker ($P<0.001$) ileal epithelial cell layer (Morel and Cottam, 2007). In another study (Brunsgaard, 1998), pigs received barley- or wheat-based diets made from coarsely rolled or from finely milled grain. Pigs fed the coarsely rolled grain had the greatest volume of mucin granules in crypts of the large intestine. The influence of the grinding intensity of feeds used in piglets on secretion patterns of mucins was evidenced by data reported by Betscher et al. (2010). A coarsely milled non-pelleted feed mixture significantly decreased the ratio of neutral to acidic mucins in the duodenum, jejunum, ileum, caecum and colon of weaned piglets compared to those fed a fine milled and pelleted feed mixture.

The results reported by Mikkelsen et al. (2004), Hedemann et al. (2005) and Papenbrock et al. (2005) suggest that coarser ground feeds, as well as feeds in the meal form (non-pelleted), are better at protecting pigs against microbial infection. Mikkelsen et al. (2004) examined the *in vitro* survival of *Salmonella enterica* serovar Typhimurium DT12 in the stomach and caecum of pigs fed coarse and fine feeds, both in the meal and pelleted form. They discovered a very strong killing effect on *Salmonella enterica* in stomach contents from pigs fed the coarsely ground meal feed. Also Hedemann et al. (2005), using a pig intestine organ culture model, demonstrated that *Salmonella* adhered less (by 60%; $P<0.05$) to the ileal tissue of pigs fed non-pelleted diets. Coarse feed structure (68.9% particles above 1 mm) analogously to potassium diformate supplement, could positively influence the intestinal flora and was capable of reducing *Salmonella* excretion of infected piglets (Papenbrock et al., 2005).

Recommendations about grinding intensity of feed for pigs

As has been shown, the feed structure has a significant impact on many parameters of pig production. Thus, the choice of an optimal structure and form of a feed is not only a challenge for nutritionists; it is also a question of veterinary clinical relevance and food safety (Kamphues, 2011). For prevention of gastrointestinal dysfunctions, feed manufactures use various types of feed additives. However, complete feeds made by farmers themselves (especially for fatteners and sows) from home-grown cereals and purchased protein concentrates, might be lacking such additives. Some recommendations about grinding intensity are addressed to feed manufactures and pig farmers. Leblanc et al. (2006) recommend feeds with the mean geometric diameter (MGD) of particles of 600 μm for piglets and fatteners (with acceptable variation of 500–700 μm) and 700 μm for sows (with acceptable variation of 600 μm for lactating sows and 850 μm for gestating sows). Concerning ulcer prevention, it is necessary to define the upper threshold level of fine particles. Taking into account the findings of Grosse Liesner et al. (2009) and Cappai et al. (2013), the “critical amount” of fine particles (<0.4 mm) in pelleted diets, determined by wet

sieve analysis after pelleting, is between 30% (almost no mucosal lesions) and 36% (early damage of mucosal integrity).

It can be suspected that if the welfare and health of the GIT is taken into consideration when selecting the particle size of feeds, a slight decrease in the feed conversion rate, i.e. body gain per kg of ingested feed, should be expected.

Conclusions

Comparison of the results of individual studies indicates that pigs respond to grinding intensity and to the form of feeds. Finely ground feeds have higher ileal crude protein and AA digestibility as well as higher energy concentrations compared with coarse or medium ground feeds. Finding a better G/F ratio in fine ground feeds, despite a poorer feed intake, is partly associated with the higher nutritional value of such feeds. Reduction of feed particles, particularly in pelleted diets, adversely affects the status of the GIT, i.e. number of lactic acid bacteria, stomach mucosa integrity, concentrations of SCFA, volume and character of mucins, as well as the ability to prevent and counteract microbial infections. Considering the ulcerogenic risk of feed particle size, all efforts should be taken to maintain the share of very fine particles (below 0.4 mm) in feeds, especially in pelleted ones, at a level of no more than 30%.

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