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INFLUENCE OF FEED PROCESSING TECHNOLOGY ON PIG PERFORMANCE

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Abstract

Feed processing technology is essential in the concept of *sustainable precision livestock farming.* This concept aims to optimize productivity and efficiency in pig production by an integrated approach taking into account as many relevant factors dealing with feed, animal, microbiota, farm and their interactions, as well as customer, consumer and societal demands. In this chapter relevant aspects are presented with the aim of identifying new opportunities. The focus is on feed manufacturing rather than processing of feed ingredients, both on an industrial and farm level.

Physical treatments have been studied most intensively. Particle size reduction has shown to be of importance and results in more consistent effects than particle size uniformity. Nevertheless, the best strategy remains difficult to prescribe as the results indicate an optimum between 600 and 900 μm, depending on several other factors involved. Correct mixing is also of importance but does not seem to be a critical factor in practice for at least fattening pigs and sows. Further processing of meal into pellets has proven to increase growth rate and feed efficiency under controlled pelleting conditions on average by 6 and 6-7%, respectively. The impact of other pellet characteristics on pig performance, such as diameter and the quality in terms of hardness and durability, is often unclear although the presence of fines in the pelletized feed has been proved to be undesirable.

Relatively new are studies on microbiological treatments, such as fermentation. The concept of fermented liquid feed seems to be promising and several studies have shown beneficial effects such as improved gastrointestinal health and growth performance, and reduced mortality and morbidity in both piglets and fattening

pigs. Unfortunately palatability, health and nutritional value can be affected by uncontrolled fermentation and amino acid degradation.

In conclusion, feed processing technology is important both for minimizing feed production costs and optimizing pig health and performance. Although it offers many opportunities, more research is necessary for optimization of existing and development of new technologies. A potential bottleneck for innovation is the fact that implementation in practice often requires relatively large investments. Therefore, it is necessary to have better estimates and more quantitative data of the effects of feed processing technology on pig performance.

Introduction

Crucial in the development of modern pig production is the concept of *sustainable precision livestock farming*. This concept aims to optimize productivity and efficiency by an integrated approach taking into account as many relevant factors dealing with feed, animal, microbiota, farm and their interactions, as well as customer, consumer and societal demands. Several indicators demonstrate that optimising productivity and efficiency in pig production is still potentially possible. The genetic potential is only partially utilized, the utilization of most nutrients appears to be low and there is a huge variation in pig performance among farms and within farms (Den Hartog, 2009).

As feed usually contributes to more than 0.60 of the total costs, it has received most attention. In particular nutrition in terms of nutrient requirements and nutrient supply has been given a high priority in many research groups. However, feed processing technology does play an important role in improving productivity and efficiency as well, not only with respect to minimizing feed production costs but also optimizing pig performance. Feed processing technology is therefore essential in the context of *sustainable precision livestock farming* and may offer new opportunities in optimizing the balance between nutrient requirements and supply, improving animal welfare and health status, and reducing emissions. Traditionally, the focus in research was on physical aspects, such as particle size, the type of milling, mixing and pellet quality. Curently, other aspects do receive attention as well such as chemical, biochemical and microbiological treatment of raw materials and feed. In this chapter an overview of some of the aspects is presented with the aim of identifying new opportunities from the perspective of improving pig performance. The focus is on feed manufacturing rather than processing of feed ingredients, both on an industrial and farm level.

Grinding

Most of the feed ingredients used in feed manufacturing are ground for technological and nutritional reasons. The benefits from particle size reduction are related to the handling and mixing characteristics of ingredients, pelleting efficiency and quality, and digestibility. Both hammer mills and roller mills are commonly used in the production of pig feeds. With a hammer mill, there may be a wide distribution of particle sizes around the geometric mean, whereas with a roller mill, particles tend to be more uniform in size (i.e., lower standard deviation, or s_{gw}, of the mean particle size; Koch, 2002). Therefore both particle size reduction and particle size uniformity have been studied intensively.

PARTICLE SIZE REDUCTION

Optimal particle size of pig diets seems to be dependent on several factors, including the type of ingredient, the complexity of diet composition, further processing such as pelleting and animal-related physiological factors. In theory, particle size reduction increases the surface area of ingredients, allowing for greater interaction with digestive enzymes and as a result improving performance (Goodband *et al.*, 1995). Feed efficiency rather than body weight gain were indeed improved when reducing particle size of cereal grains for piglets (Ohh *et al.*, 1983; Healy *et al.*, 1994), fattening pigs (Ivan *et al.*, 1974; Owsley *et al.*, 1981; Giesemann *et al.*, 1990; Cabrera *et al.*, 1994), and lactating sows (Wondra *et al.*, 1995a,b). On average, feed efficiency is improved by 1 to 1.5% for each 100 μm mean geometric diameter particle size reduction in the range from 400 to 1000 μm. However, there seems to be an optimal mean geometric diameter of cereal particles between 500-700 μm as below 300 μm both feed intake, body weight gain and feed efficiency tend to deteriorate (Healy *et al.*, 1994). This has been demonstrated for maize, sorghum and barley. Wheat seems to have a higher particle size optimum, i.e. between 800-900 μm. This is probably related to the tendency of this cereal to become sticky and pasty in the buccal cavity because of its high gluten content. If ground too fine, wheat can reduce feed intake. Roller mills with a differential drive produce a uniform particle size and fewer fines and may be more suitable for processing wheat in pig diets (Goodband *et al.*, 1995).

Fewer studies have been carried out with other single feed ingredients. Fastinger and Mahan (2003) recently evaluated the effects of solvent-extracted soyabean meal particle size (900 to 150 μm) on amino acid (AA) and energy digestibility. Apparent digestibility of the average of the 10 essential AA increased as particle size decreased, but energy digestibility and the average of the non-essential AA digestibilities was not affected. The largest improvement in AA digestibility was observed when particle size of the solvent-extracted soyabean meal decreased from 900 to 600 µm. However, Lawrence *et al.* (2003) did not observe any effect of soyabean meal particle size on piglet growth performance.

Mixed grinding of ingredients resulted in similar effects as reported for single grinding of cereals, including the presence of an optimum. Although most information comes from field trials, feed efficiency seems to be improved to a similar degree as reported in studies for single grinding of cereals, i.e. by 1 to 1.5% for each 100 µm mean geometric diameter particle size reduction in the range from 600 to 1000 µm. In particular pig performance on fibre-rich feeds seems to benefit from particle size reduction. Real digestibilities of amino acids in pigs were increased when particle size was reduced in wheat-sunflower meal (Lahaye *et al.*, 2004) and in wheat-rapeseed meal diets (Lahaye *et al.*, 2008). The latter also reported that coefficients of ileal digestibility for dietary energy, OM, and DM were improved when wheat particle size in a wheat-rapeseed meal diet was reduced from 1,000 to 500 µm.

Several studies have indicated that the negative effects of too fine grinding of cereal grains are related to a higher incidence of gastric mucosal alterations, such as keratinisation of the stomach and gastric ulcers. Similar mucosal changes have been reported for pelleted diets, irrespective of the original grinding intensity before pelleting (Grosse Liesner *et al.*, 2009). Finely ground feed is more fluid when mixed with the digestive secretions of the pig's stomach compared to a more coarsely ground feed (Regina *et al.*, 1999). As a result, the acids in the stomach have a greater chance of coming into contact with and irritating the oesophageal region of the stomach. The frequency of keratinisation and ulceration increases when particle size drops below 500 µm. This was demonstrated in piglets (Healy *et al.*, 1994), fattening pigs (Cabrera *et al.*, 1994; Wondra *et al.*, 1995a,b), and lactating sows (Wondra *et al.*, 1995c). Under practical conditions, gastric ulcers seem to be more important in gestating and lactating sows than in fattening pigs. Therefore the greatest potential for fine grinding or rolling to improve feed efficiency will be for fattening pigs and to a lesser degree for piglets. It appears that piglets do a better job of chewing feed than fattening pigs. Ayles *et al.* (1996) suggested that to change occasionally (e.g., when pigs are moved or sorted) from fine-ground to coarse-ground, and then back to fine-ground diets could be an effective measure to prevent ulcers in pigs while capturing most of the benefits in efficiency of growth when fine grinding.

Other factors explaining the mechanism of action of particle size reduction may also play a role. Feed particle size directly affects the time needed to mix feed adequately, the segregation of ingredients during handling, and feed flow ability. Moreover, Anguita *et al.* (2007) and Solà-Oriol *et al.* (2007) observed a relationship between particle size of the cereal grain fraction in the feed and voluntary feed intake which might be independent from a better digestibility due to an increase of surface area or improved homogeneity related to mixing and handling during production. In contrast to above mentioned effects, other studies failed to observe any effect of particle size on voluntary feed intake, performance or digestibility of nutrients (Gipp *et al.*, 1995).

It should be noted that particle size should always be seen in relation to the size of the screen. Small kernel cereals such as sorghum may fall through the opening intact when using screens with a bigger diameter. This may affect digestibility. The latter is in particular the case for full fat rapeseed, which is hardly digestible when not ground. However, the relation between size of the screen and optimal particle size is complex as other factors, such as hammer mill revolutions per minute, tip speed and the numbers of hammers are also of importance.

PARTICLE SIZE UNIFORMITY

In contrast to the effects of particle size, effects of particle size uniformity on pig performance do not seem to be consistent. Choct *et al.* (2004) analysed processing (hammer mill vs. roller mill), particle size, and feeding method (liquid vs. dry) for wheat-based diets fed to weaned piglets. They observed that piglets fed hammer-milled diets consistently consumed more feed and grew faster. Thacker (2006) found that digestibility coefficients for DM, CP, and energy with a particle size similar in mean geometric diameter were greater for pigs fed hammer-milled oats vs. roller-milled oats. This was attributed to the larger small particle size fraction for hammer-milled oats. In contrast, Wondra *et al.* (1995b) reported positive effects of roller-milled feed on the digestibility of DM, N and GE of a maize-based diet but their results suggested an effect of mill type separate from any s_{gw} effect. Reece *et al.* (1985) described particles of hammer milled maize as more spherical in shape with more uniform edges than particles of roller milled maize. They hypothesized that a spherical shape would reduce susceptibility to attack by digestive enzymes, thus decreasing digestibility of nutrients in hammer-milled maize. However, effects on performance may also be attributed to differences in flow ability characteristics and as a consequence differences in homogeneity of the feeds. Flowability appears to be influenced more strongly by variation in particle size than by the shapes of particles (Groesbeck *et al.*, 2007).

Particle size uniformity is also of relevance for preventing keratinisation of the stomach and gastric ulcers. An upper level of fine particles seems to be reasonable, as a minimum level of coarse particles is not ulceroprotective. Grosse Liesner *et* *al.* (2009) showed that a higher proportion of particles < 400 μm of 0.30 resulted in increasing frequency/intensity of gastric mucosal alterations in reared piglets, i.e. higher risks for ulcerations.

Mixing

From the feed manufacturing point of view, the optimum mixing procedure would require minimal inputs of time, energy, and labour. However, for optimal pig performance adequate mix uniformity is required. Recommendations for mix uniformity, usually expressed as coefficient of variation (CV) for the distribution of some nutrient or marker within the feed, refer to values less than 10% (Beumer, 1991; Lindley, 1991). The accuracy of such recommendations is questionable both due to methodological problems when using markers and the absence of a clear relationship between mix uniformity and nutritional value of the feed. The ideal marker has not been identified yet and in practice a pragmatic choice is often made, taking into account accuracy and costs of analysis, distribution characteristics and raw material composition.

It can be argued whether improper mixing of one batch of feed would cause serious problems in pigs because of the relatively high amount of feed consumed per day and the fact that a single batch will usually be consumed in a short period of time. Traylor *et al.* (1994) demonstrated in finishing pigs that growth performance was not affected by reducing the CVs of the diet from nearly 54% (0 min. mixing time) to less than 10% (4 min. mixing time). Moreover, bone strength did not differ among pigs fed the various treatments, suggesting that minimal mixing of the diets did not create problems with Ca or P status of the pigs. In contrast, in a similar experiment with weanling piglets they did find a significantly improved body weight gain and feed efficiency. However, below a CV of 12% little response was observed. Groesbeck *et al.* (2007) also demonstrated that inadequate mixing (CV >12%) can reduce nursery pig performance. Therefore, it seems that fattening pigs are probably less sensitive to diet non-uniformity than piglets.

Thermal processing & feed form

Although mixed feed ingredients are ready for use, pig feeds are often further processed for technological, nutritional and microbiological reasons. In particular pelleting is quite common but also other processing techniques such as extrusion, expansion and pressure cooking, either or not in combination with pelleting and crumbling, are used in practice. Most of those treatments require steam conditioning. Moreover, the temperature increases during the shaping process due to friction. Therefore shaping the feed is usually linked with effects of thermal processing and as a consequence the effects on pig performance are not easy to explain.

CONDITIONING AND PELLETING

Pelleting and other further processing techniques add considerable cost to manufacturing of pig diets. However, they may have certain advantages. For pelleting, improved rate of growth and feed efficiency are most prominent. On average, growth rate is increased by 6% and feed efficiency is improved by 6 to 7% by feeding pellets compared to meal (Hancock and Behnke, 2001). Why pelleting positively impacts growth performance has not been clearly demonstrated. Some research suggests that pelleting improves nutrient digestibility (Wondra *et al.*, 1995a). In particular starch gelatinization is often mentioned as a factor or relevance. Starch gelatinization is the rupture of starch granules, thereby allowing the linear and cyclic molecules to hydrate and become more available for enzymatic digestibility. This might be of relevance for piglets under stress conditions but is probably of less importance for older pigs. Even in studies with very young piglets, little effect of the degree of gelatinization of the cereal portion of the diet on piglet performance has been observed previously (Hongtrakul *et al.*, 1998; Medel *et al.*, 1999). Nevertheless, starch gelatinization is directly related to pellet quality and pellet quality affects the feed efficiency response. Stark *et al.* (1994) fed diets with varying levels of pellets and pellet fines, and found that as pellet fines increased in the diet, the benefits of pelleting were lost. Consequently, attention must be given to producing quality pellets in order for the benefits of pelleting to be realized.

Excessively high temperatures during pelleting or other thermal processing may be responsible for decreased performance of pigs fed diets containing specific protein sources (e.g. dried whey, fish meal, or spray-dried animal proteins) and micro-ingredients (e.g. vitamins and enzymes) compared with performance of pigs fed diets processed at lower temperatures (Traylor *et al.*, 1997; Hongtrakul *et al.*, 1998, Steidinger *et al.*, 2000). Normal pelleting conditioning temperatures of 85°C could potentially burn or scorch some of these specific ingredients and increase the potential for initiating the Maillard reaction, thereby decreasing their nutritional value.

It should be noted that pellet quality is also related to particle size and possibly particle size uniformity. Reimer (1992) indicated that fineness of grind may control 0.20 of pellet quality. Decreasing particle size from a coarse to a fine grind exposes more surface area per unit volume for absorption of condensing steam during the conditioning process. This results in a higher feed temperature and more water absorption, which together, within the time available, increases gelatinization of raw starch. Grinding can also improve pellet quality by reducing air spaces between particles, allowing closer surface to surface contact for a given volume of feed; i.e., it increases bulk density. Large pieces of any ingredient in a feed formula result in weak spots in the pellet, especially if these are fibrous.

Pelleting also contributes to an improved microbiological status of the feed, although recontamination always remains a challenge. However, a study using a pig intestine organ model showed that *Salmonella enterica* serovar Typhimurium DT12 adhered significantly less to the ileal tissue of pigs fed non-pelleted diets than to those fed pelleted diets. This is possibly related to the secretion of mucins that are capable of binding Salmonella and allowing for colonization. These results suggest that pigs fed non-pelleted feed are better protected than pigs fed a pelleted diet (Hedemann *et al.*, 2005). Pelleting also tends to increase scores for keratinisation and (or) ulceration in pigs (Wondra *et al.*, 1995a,b; Amornthewaphat *et al.*, 1999).

PELLET DIAMETER

Few data are available on the effects of pellet size or in particular changes in pellet size during the feeding period. Although one may expect effects in the pre- and post-weaning period, in particular taking into consideration effects reported in certain choice feeding experiments, pellet diameter does not seem to be a major contributor to the low feed intakes seen in the post-weaned piglet when the pellets are presented as in a commercial situation (i.e. not choice feeding) (Edge *et al.*, 2005). Similar results were reported by Traylor *et al.* (1996), showing that pellets up to 12 mm in diameter had no influence on post-weaning performance, as did the provision of a meal-based diet.

Nevertheless, feeding behaviour seems to be affected by pellet diameter. Edge *et al.* (2005) demonstrated that the total time spent at the trough pre-weaning seems to be increased with bigger pellet diameters. However, this did not result in higher feed intake and the effect disappeared post-weaning. A'Ness *et al.* (1997) in a preliminary study found that, when suckling piglets were offered supplementary solid feed in the form of sow rolls (pellets with a very large diameter), they spent longer periods of time engaged in trough-directed behaviour than those piglets offered feed in a typical commercial pellet size (2-3 mm diameter). However, feed intake and body weight gain were not measured. It is hypothesised that, in this experiment, a larger pellet diameter will provide the incentive the piglet needs both to approach the trough and to ingest solid feed.

Liquid feed

The concept of liquid feed is widely spread in pig production. Traditionally many pigs were fed on meal mixed in a bucket with whey or water. Increasing farm size and the need for automation encouraged a move to dry feeding but recent developments in computer-driven systems have led to a revival of liquid feeding.

Piglets are fed on liquid milk by their mothers until weaning and it is logical to continue to feed them on a liquid diet provided that it can be delivered by a reliable and hygienic system. There are many advantages of using liquid feeding systems compared to dry feeding in pig production. These include improved nutrient utilization, flexibility and control of feeding programs, and improved animal performance (Jensen and Mikkelsen, 1998; Russell *et al.*, 1996; Canibe and Jensen, 2003; Brooks *et al.*, 2001; Lawlor *et al.*, 2002). Liquid feeding may also enhance gut health, reduce the need for feed medications, and improve animal welfare (Brooks *et al.*, 2001; Canibe and Jensen, 2003). Liquid feed can provide the pig with its essential daily energy and nutrients at a lower cost, because it enables the use of relatively cheap, moisture-rich co-products from the food and, more recently, biofuel industry. Excellent performance in both fattening pigs and lactating sows has been achieved on liquid feed provided that the diet is formulated correctly and proper hygiene control is maintained. In particular when highly variable, moisture-rich co-products are used, it is of utmost importance to estimate the nutritional value as precisely as possible.

Liquid feeding also creates opportunities for using digestibility-enhancing enzymes, which work more efficiently in a liquid than in a dry environment. However, effluent output can be higher when liquid feed is used, because of the extra volume of water consumed by the pigs. In addition, emissions can be higher in case of imbalances due to the variability of nutrient levels.

Fermented liquid feed

Relatively new is the concept of fermented liquid feed (FLF) either fermented with existing or introduced lactic acid bacteria. FLF is a mixture of water and starch containing feed ingredients or complete feed stored in a tank (ratio feed:water of 1: 2.5-2.75 wt/wt) at a certain temperature (20-25°C) and time (1 day) before feeding to the animals. Such compositions are characterized by a high level of lactic acid bacteria, yeast and lactic acid, low pH and low enterobacteriaceae counts. Several studies have shown beneficial effects in animals fed FLF compared to those fed with dry or liquid feed, such as improved gastrointestinal health and growth performance, and reduced mortality and morbidity in both piglets and fattening pigs (Geary *et al.*, 1999; Canibe and Jensen, 2003; Scholten *et al.*, 1999). These benefits appear to be the result of enhanced nutrient availability, and reduced growth and shedding of pathogenic bacteria such as Yersinia, Salmonella, and E. coli due to low pH (Geary *et al.*, 1999; Scholten *et al.*, 1999; van Winsen *et al.*, 2001; Demeckova *et al.*, 2002). Furthermore, pepsin activity is increased due to lower pH, resulting in improved protein digestion (Scholten *et al.*, 1999).

Various studies have shown that the effect of feeding FLF on growth performance and nutrient digestibility in both piglets and pigs can be inconsistent (Pedersen and Stein, 2009). Nevertheless, the use of FLF has gained recent interest also as an alternative strategy for reduction of the use of antibiotics in pig production. In addition, it has the potential of increasing the inclusion of co-products from the food and biofuel industry in animal diets to avoid wasteful disposal that can thus decrease costs and the environmental burden (Canibe and Jenssen, 2007, Canibe *et al.*, 2007).

The inconsistency of effects on pig performance is partly related to the fact that spontaneous fermentation of liquid feed is unreliable. Maintaining a continuous fermentation by retaining a proportion of the feed each day can result in the development of a resident microflora dominated by yeasts. This may compromise both palatability and health, and reduce the nutritional value of the feed. Batch fermentation of the cereal portion of the diet using inoculants selected to generate high concentrations of lactic acid has the potential to produce more consistent results. This approach may enable the combination of preservative and probiotic effects of lactic acid bacteria, while also improving the availability of nutrients in the feed and reducing levels of anti-nutrients and mycotoxins (Brooks, 2008). Palatability and, as a result, feed intake are not only affected in a negative way. Both higher and lower feed intakes compared to feeding non-FLF or dry feed have been observed. With respect to reduced feed intakes, Canibe *et al.* (2009a) demonstrated that low pH and high acetic acid concentration in FLF (within the levels typically measured in FLF) do not profoundly affect feed intake in piglets by impairing palatability. In addition, Canibe *et al.* (2009b) could not demonstrate a relation between biochemical and microbiological variation in FLF samples and feed intake at farm level. Forty farms were classified in two groups, a 'low feed intake' group and a 'high feed intake' group. The biochemical characteristics and the microbiological composition to group level were determined and the characterization of lactic acid bacteria and yeasts to species level was carried out. The lactic acid bacteria isolates were identified by sequencing the 16S ribosomal DNA gene and the yeasts isolates by sequencing the D1/D2 domain of the large-subunit (26S) ribosomal DNA. In general, the results obtained indicated that there are no big differences in the biochemical characteristics measured and in the microflora composition at group level between the two farm groups. The data on diversity of lactic acid bacteria and yeasts showed that a few species dominate in all FLF-samples.

There are indications that fermentation of only the starch containing feed ingredients and mixing them with the other ones prior to feeding, results in better pig performance than fermentation of the complete diet. In addition, Canibe and Jensen (2007) found a higher density of yeasts, a higher concentration of ethanol in the GIT, a change of the bacterial population of the stomach and a tendency for higher feed intake and body weight gain compared to feeding of the complete fermented diet.

It was suggested that feeding liquid feed containing exclusively the fermented liquid cereal grains may avoid microbial degradation of free amino acids in the feed. In particular the microbial degradation of free lysine has been suggested as an important factor that contributes to the negative impact feeding FLF may have on growth performance. Besides the fact that E. coli strains are able to degrade free lysine in FLF and large amounts of lactic acid bacteria can prevent such losses (Niven *et al.*, 2006), not much is known on the factors affecting this process (Canibe and Jensen, 2009). Nevertheless, to minimize loss of synthetic amino acids, it is advised to add amino acids to liquid feeds after stable fermentation is achieved, when liquid feed contains more than 75 mMol lactic acid, or when the pH is less than 4.5 (Braun and de Lange, 2004).

Lysine can also be protected by pelleting the feed before fermentation. Canibe and Jenssen (2009) clearly showed that the disappearance of free lysine was much higher when non-pelleted, non-heated feed was fermented than when the same pelleted (83°C) feed was used. This was the case both during the initial hours (48 h) of incubation and in a more established FLF (after back slopping had been practiced for several days). This would also indicate that the first established microflora determines the extent of free lysine degradation more than the substrate added after the system has reached steady state.

Improved digestibility by fermentation is also dependent on the level of soluble, potentially fermentable non-starch polysaccharides in the feed ingredients. This explains the bigger effects of fermentation on digestibility of barley compared with wheat (Jorgensen *et al.*, 2009).

In addition to direct effects, FLF may also have indirect effects via sow milk and excreta. Demecková *et al.* (2002) showed that faeces excreted from sows fed FLF had lower numbers of coliforms, and piglets sucking from such sows excreted faeces higher in lactic acid bacteria and lower in coliforms than their counterparts sucking sows fed dry pellets. In addition, the mitogenic activity in the piglet blood lymphocytes was increased indicating a greater level of lymphocyte proliferation and possibly enhanced immune function.

Impact, opportunities & challenges

The results presented in this chapter demonstrate that feed processing technology is of crucial importance for optimizing productivity and efficiency in pig production. However, the effects on pig performance are not always clear, mainly due to complex interactions. Nevertheless, most studies indicate that pig performance can be further improved by optimization of existing and introduction of new technologies.

Particle size reduction has been shown to be of importance and results in more consistent effects than particle size uniformity. Nevertheless, the best strategy remains difficult to prescribe as the results indicate an optimum between 600 and 900 μm, depending on several other factors involved. It could be hypothesized that protein sources require a finer grinding than carbohydrate sources in order to maximize the digestion of amino acids. In particular fibre-rich protein sources such as rapeseed and sunflower meal may benefit from this approach. However, gains in pig performance must outweigh production costs. The latter usually increases when feed ingredients need to be ground separately using different screens. Moreover, grinding to particle sizes less than 600 μm sharply increase costs due to higher energy consumption and lower feed mill capacity. In addition, fine grinding without pelleting may result in increased dustiness of the feed, as well as bridging problems in bulk bins and feeders.

Correct mixing is also of importance but does not seem to be a critical factor in practice. At least this appears to be the case for fattening pigs and sows, because of the relatively high amount of feed consumed per day and the fact that a single batch will usually be consumed in a short period of time.

Further processing of meal into pellets has been proved to increase growth rate and feed efficiency under controlled pelleting conditions on average by 6 and 6-7%, respectively. However, the mechanism of action is still not fully resolved and the processing conditions used in practice are usually based on the experience of the feed mill operator. This might result in suboptimal processing conditions, in particular when taking into account the instability of certain specialty protein sources and micro-ingredients. Moreover, pelleting may abolish the preventive effect of coarse grinding on gastric mucosal alterations and could even be a risk factor for colonization of the gut with Salmonella. The impact of other pellet characteristics, such as the quality in terms of hardness, durability and pellet diameter on pig performance is often unclear. The presence of fines in the pelletized feed has proven to be undesirable. However, with respect to the effects of pellet diameter, a parameter often highlighted in sales, there is hardly any scientific basis. As a consequence, optimization of the feed form and required thermal processing conditions should receive some more attention and may still offer opportunities in optimizing productivity and efficiency.

All processing technologies discussed so far apply to dry feed and feed ingredients. However, the use of moisture-rich co-products from the food and biofuel industry offers a lot of opportunities and such ingredients can easily be fed when making use of automated liquid feeding systems. Moisture-rich co-products are usually price competitive as they do not require expensive drying and can be fed directly at the farm without interference of a feed compounder. Moreover, they may be abundantly available in the neighbourhood of pig farms. Liquid feeding has proven to result in excellent pig performance, provided the circumstances are well controlled. In particular the estimation of the nutrient content of the moisture-rich co-products, the final diet formulation and hygiene conditions are important. Inclusion of liquid co-products from the food and biofuel industry in animal diets also avoids wasteful disposal and, as a result, can decrease the environmental burden.

Liquid feeding also offers the opportunity for fermentation. The concept of fermented liquid feed (FLF) seems to be promising and several studies have shown beneficial effects in animals fed FLF compared to those fed with dry or liquid feed, such as improved gastrointestinal health and growth performance, and reduced mortality and morbidity in both piglets and fattening pigs. These benefits appear to be the result of enhanced nutrient availability, and reduced growth and shedding of pathogenic bacteria due to the formation of organic acids resulting in low pH and the presence of bioactive, often antimicrobial substances. Therefore FLF could be an alternative strategy for reduction of the use of antibiotics in pig production. However, various studies have shown that the effect of FLF on pig performance can be inconsistent. Palatability, health and nutrition value could be affected by uncontrolled fermentation. In particular the prevention of free lysine degradation has received much attention. Nevertheless, FLF seems to be manageable and large scale implementation may follow soon.

In conclusion, feed processing technology is indeed important in the concept of *sustainable precision livestock farming* and certainly offers new opportunities in pig production. However, more research is necessary for optimization of existing and developing of new technologies. A potential bottleneck for innovation is the fact that implementation in practice often requires relatively large investments. Therefore, it is necessary to have better estimates and more quantitative data of the effects of feed processing technology on pig performance.

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