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Fermented liquid feed for pigs: a review

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Abstract

Since the announcement of the ban on the use of antibiotics as antimicrobial growth promoters in the feed of pigs in 2006 the investigation towards alternative feed additives has augmented considerably. Although fermented liquid feed is not an additive, but a feeding strategy, the experimental work examining its possible advantages also saw a rise. The use of fermented liquid feed (FLF) has two main advantages, namely the simultaneous provision of feed and water which may result in an alleviation of the transition from the sow milk to solid feed and may also reduce the time spent to find both sources of nutrients. Secondly, offering FLF with a low pH may strengthen the potential of the stomach as first line of defense against possible pathogenic infections. Because of these two advantages FLF is often stated as an ideal feed for weaned piglets, the results obtained so far are rather variable, but in general show a better body weight gain and worse feed/gain ratio for the piglets. However, for growing-finishing pigs on average a better feed/gain ratio is found compared to pigs fed dry feed. This better performance is mostly associated with a less harmful microbiota and a better gut morphology. This review provides an overview of the current knowledge of FLF for pigs, dealing with the FLF itself and its effect on the gastro-intestinal tract and animal performance.

Keywords: fermented liquid feed, pig, gastro-intestinal tract, microbiota

1. Introduction

The use of microbial fermentation to conserve or improve food is not new. For thousands of years fermented foods and beverages contributed significantly to the diet of humans and animals. Even in the Bible there are references to the use of yoghurt (e.g. Genesis 18:8). Most fermented foods owe their origin to the fact that processes used in their production are inhibitory to many microorganisms. As a result, fermented products generally have a longer shelf life than their original substrate (Adams and Mitchell, 2002). This inhibitory action is also one of the positive things associated with the use of fermented liquid feed (FLF) in pigs.

The interest in fermentation of feed for improving the performance of piglets and pigs had a surge after the announcement of the planned ban in the EU on the use of antibiotics as antimicrobial growth promoter (AMGP) in the feed of pigs. In three recent reviews the potential of FLF, as an alternative for the use of growth-promoting antibiotics in the piglet feed, is discussed (Brooks, 2008; Niba et al. 2009; Plumed-Ferrer and Von Wright, 2009). In this

literature review the current knowledge about the use of fermented liquid feed in pigs will be given. Although the use of co-products in FLF is also of importance, this subject will only be briefly discussed (for review see Scholten et al. 1999b).

2. Definition of fermented liquid feed

It is important to define liquid feeding and differentiate it from other feeding systems. Liquid feeding involves the use of a diet prepared either from a mixture of liquid food industry by-products and conventional dry materials, or from dry raw materials mixed with water. A liquid feed should not be confused with wet/dry feeder systems where water and feed are kept separate up to the point of delivery to the pig (Brooks et al. 2003a).

By definition FLF is feed mixed with water, at a ratio of 1:1.5 to 1:4 and fermented for a period long enough to reach steady state conditions (Chae, 2000; Brooks, 2003; Brooks et al. 2003a). It is usually prepared by spontaneous fermentation (spontaneous fermented liquid feed; SFLF) or inclusion of the feed mixture with a culture of lactic acid bacteria (LAB) as inocula (controlled or inoculated fermented liquid feed; IFLF). If there is almost no time between mixing and feeding or the period for fermentation is too short to reach steady state conditions, the term liquid feed (LF) or non-fermented liquid feed (NFLF) is used (Canibe and Jensen, 2003; Plumed-Ferrer and Von Wright, 2009; Brooks, 2008).

3. Desired properties of FLF

From the moment that feed and water are mixed, there is a possibility that fermentation will begin. According to Canibe and Jensen (2003), the initial phase of fermentation is characterized by low levels of LAB, yeasts, and lactic acid, high pH, and, importantly, a blooming of enterobacteria. This phase is followed by a second phase, in which a steady state is reached, and

which is characterised by high levels of lactic acid bacteria, yeasts, and lactic acid, low pH, and low enterobacteria counts.

Recently Brooks (2008) further subdivided the initial phase in a phase 1 in which the high pH allows the proliferation of coliform bacteria and a phase 2 in which growth and fermentation by LAB inhibits pathogenic and spoilage organisms by the production of organic acids (particularly lactic acid), hydrogen peroxide and bacteriocins, as well as by lowering the pH and redox potential. In phase 3, the steady state phase, the LAB population and pH stabilizes, but over time, the yeast concentration of the feed can continue to increase. These phases are represented in Figure 1.

Van Winsen *et al*. (2000) pointed out that lactic acid concentration is the main responsible for the antimicrobial effect of FLF. Hence, strains to be used as inoculant for FLF production should have a high capacity for lactic acid production and should be active against enteric pathogens. According to Van Winsen *et al*. (2001) the desirable characteristics for FLF include (1) a pH below 4.5, (2) LAB concentration above 9 $\log_{10}$ CFU/ml, (3) lactic acid concentration above 150 mmol/l and (4) acetic acid and ethanol concentration below 40 and 0.8 mmol/l, respectively. Beal et al. (2002) stated that to prevent the growth of *Salmonella* spp., liquid feed needs to contain at least 75 mmol/l lactic acid. Beal et al. (2002) and Brooks et al. (2003b) stated that to reduce the concentration of enterobacteria, the concentration of lactic acid should be higher than 100 mmol/l. This concentration of lactic acid can have a beneficial effect on feed intake, daily gain and F/G ratio (Roth and Kirchgessner, 1998). The D-configuration of lactic acid seems to be equally metabolized, although at a slower rate, as the L-lactic acid (Everts et al. 2000).

Acetic acid can cause a loss of palatability and although Van Winsen et al. (2001) set the limit at 40 mmol/l, other authors indicated that a concentration of acetic acid above 30 mmol/l could already negatively affect the palatability of the FLF (Brooks 2003, 2008; Brooks et al.

2003b). Not only yeasts produce acetic acid, but also heterofermentative LAB can produce acetic acid to a high degree and cause loss of palatability of the feed.

When the fermentation is dominated by yeasts, this can have either a negative or a positive effect dependent on the strains present. A drawback can be the production of 'off-flavours' and ethanol, which might diminish the palatability as well as dry matter (DM) and energy content of the feed (Jensen and Mikkelsen, 1998). In fact, Jensen and Mikkelsen (1998) indicated that carbon dioxide loss can be as high as 3.1 % DM. In contrast, these authors also pointed out that the presence of yeasts in the FLF feed might benefit the health status of the gastro-intestinal tract (GIT) of the pigs. Yeasts have the ability of binding enterobacteria to their surface, thereby blocking the binding of these bacteria to the gut epithelium (Mul and Perry, 1994). Jensen and Mikkelsen (1998) found an inverse relationship between the concentration of yeast and enterobacteria in the GIT of pigs. Therefore, high concentrations of yeasts in the FLF may be beneficial. However, the population diversity of yeasts present in FLF is very high and deserves further investigation (Olstorpe et al. 2008).

4. Possible advantages and disadvantages of FLF

One of the main advantages, besides the enteropathogen reducing effect, of the use of FLF is the fact that it is a cost effective feeding strategy to replace AMGP. Probiotics, organic acids and yeast cell walls, often suggested as alternatives to the use of AMGP, are relatively high priced. Combined with the relatively high concentrations in which those products are needed in the feed to have a significant effect, makes their use financially questionable in practical pig production. The use of FLF may solve this problem, because it is characterised by high numbers of LAB and yeast, a low pH and high concentration of lactic acid (Jensen and Mikkelsen, 1998).

Also the fact that co-products from the human food industry (Scholten et al. 1999a, b, 2001a, b) can be used, may contribute to the reduction in feed cost (Brooks et al. 2003a). Liquid

168 co-products of many sorts are used for pig feeding around the world. In European pig nutrition,
169 recycling of liquid co-products from human food industries has increased in particular, the starch
170 and sugar rich by-products: liquid wheat starch, potato steam peel and cheese whey. In 1996,
171 about 300,000 tonnes of products of the dairy industry were used in pig farms in The
172 Netherlands (Scholten et al. 1999b). Detailed data such as in The Netherlands are not available
173 from other countries, but using information from trade sources it could be estimated at least 30%
174 of all pigs in the EU are fed liquid diets and a majority of these incorporate at least some dairy
175 by-products (Table 1; EFSA, 2006).

176 Another benefit associated with feeding diets in a liquid form is the fact that piglets are
177 provided with water and feed simultaneously (Brooks et al. 2001; Brooks and Tsourgiannis,
178 2003; Russell et al. 1996; Brooks et al. 2003a; Brooks, 2008). In this way, the piglets do not need
179 separate trainings for feeding and drinking (Partridge and Gill, 1993; Russell et al. 1996). Barber
180 (1992) indicated that while some pigs in a group may find a drinker within a few minutes of
181 entering a pen, other pigs may take more than 24 h, long enough to induce symptoms of
182 dehydration. Providing the food in a liquid form most often results in a higher feed intake after
183 weaning (Russell et al. 1996). Also the feed digestion can be improved when presenting the food
184 in a liquid form (Gill et al. 1987; Barber et al. 1991). Barber et al. (1991) demonstrated that there
185 was a linear improvement in both DM and energy digestibility as the feed to water ratio
186 increased from 1:2 to 1:4. Jensen and Mikkelsen (1998) also concluded that feeding the diets as
187 LF or FLF improves growth performances and DM intake, but that the feed/gain ratio (F/G) was
188 only improved in growing-finishing pigs fed LF compared to DF.

189 Although a reduction in loss as dust during handling and feeding may occur (Forbes and
190 Walker, 1968), and improve the pigs environment and health due to the reduction of dust in the
191 atmosphere (Kneale, 1972; Brooks et al. 2003a), other authors have however observed a higher
192 feed wastage. Russell et al. (1996) pointed out that the trough design was one of the possible

193 reasons for the lesser performance of the piglets on FLF in their trial. More feed wastage was
194 noted by FLF fed piglets compared to dry fed piglets. After changing the trough design, the
195 piglets fed FLF performed better, but still worse than the piglets on the dry feed. A higher feed
196 wastage by piglets on FLF was also seen by Plumed-Ferrer and Von Wright (2009).

197 According to Brooks *et al*. (2003a) and Brooks (1999) other possible advantages linked
198 to the use of liquid feed are:

199 • Improved intakes at high ambient temperatures;
200 • Improved materials handling (system can act both as a feed mixing and distribution
201 system);
202 • Increased accuracy of rationing (computer control brings a degree of accuracy to the
203 system that it is difficult to emulate with dry feeding systems), also when using co-
204 products with different properties (DM-content) from batch to batch;
205 • Reduction in nitrogen loading through the easy adoption of "step" and "phase feeding";
206 • Reduction in phosphate loading through activation of endogenous phytase in cereal
207 grains and/or the addition of exogenous enzymes to diets. This was also investigated by
208 Carlson and Poulsen (2003) and Nitrayová et al. (2009);
209 • Improved enzyme activity by a possible reduction in particle size of the feed used, which
210 in turn reduces separation of materials in the trough and ensures the pig receiving a more
211 homogenous diet. However, attention should be paid not to use too small particle sizes, as
212 this is a predisposing factor for the development of gastric ulcers.
213
214 A very actual research issue nowadays is reduction of enteropathogens, such as
215 *Salmonella* spp. and *E. coli*, in the pig production. FLF, by excluding pathogens from the feed,
216 seems to be an excellent feeding strategy to achieve this. From surveillance studies it was clear
217 that liquid feeding had a positive effect on gut health and reduced the incidence of *Salmonella*
218 spp. (Tielen et al. 1997; Lo Fo Wong et al. 2004). However, Van der Wolf et al. (1999) showed
219 that when trough feeding was applied, in which the feed and water are left to soak for several
220 hours, the risk on *Salmonella* infections was increased. They hypothesised that this soaking
221 period allowed the proliferation of enteropathogens . This proliferation was indeed seen in the
222 NFLF in the study of Canibe and Jensen (2003). According to Van der Wolf et al. (1999, 2001)
223 this was not the case when complete diets with fermented co-products were fed and this feeding
224 strategy lowered the prevalence of *Salmonella* in finishing pig units. Feeding FLF also does not

always give a reduction in the incidence of diarrhoea, as could be seen in the challenge experiment performed by Amezcua et al. (2007) with *Escherichia coli* (*E. coli O149:K91:F4*).

Another aspect, that can regain interest nowadays, is the fact that feeding LF or FLF rather than dry feed can change the microbial conversion of tryptophan in the hind gut toward indole at the expense of skatole (boar taint) resulting in a lower skatole and a higher indole deposition in the back fat of fattening pigs and thus reduce boar taint (Kjeldsen, 1993). However, Hansen et al. (2000) found that giving FLF to pigs had no effects on skatole concentration in caecum, colon, blood and backfat and boar odour attributes, whereas administration of FLF plus 50 mg/kg of zinc bacitracin for the last week before slaughter decreased the corresponding skatole concentrations and the typical boar odours (pig and manure odour). However, meat from the two groups of pigs given FLF, either with or without zinc bacitracin, was significantly worse in terms of the scores for three flavour attributes (pig flavour, rancid flavour and total off-flavour) compared with meat from pigs given dry food.

Liquid feeding of diets is sometimes associated with the development of diseases like haemorrhagic bowel syndrome, gastrointestinal tympany, gastric torsion or gastric ulcers (Brooks, 2008; Plumed-Ferrer et al. 2005). A direct link is not easily found, because these diseases are mostly caused by a multifactorial condition. In the experiment of Plumed-Ferrer et al. (2005) the incidence of gastric ulceration was remarkably low, although two main predisposing risk factors, feeding FLF and feeding more than three times a day, were present.

The fermentation process can cause a loss of essential nutrients from the feed, such as vitamins and amino acids (AA), especially the free synthetic AA added to the feed (Canibe and Jensen, 2003; Niven et al. 2006). For example, the production of biogenic amines, such as cadaverine from L-lysine, can occur (Pedersen, 2001; Pedersen et al. 2002a, b; Brooks et al. 2003b; Niven et al. 2006; Canibe et al. 2007b, c, 2008). Biogenic amine formation causes an irreversible loss of AA for the pig, because it is caused by a decarboxylation rather than a

desamination (Dierick et al. 1986a, b). This is why some authors advocate the fermentation of only the grain fraction instead of the complete feed (Pedersen et al. 2002c; Scholten et al. 2002; Brooks et al. 2003b; Moran et al. 2006; Brooks, 2008; Canibe et al. 2007a; Canibe and Jensen, 2007).

Pigs often eat more DM when fed LF or FLF than when fed dry diets, so when formulating diets to be fed as FLF, care should be taken to formulate them on the basis of realistic estimations of DM intake per day. Otherwise the piglets will consume too much of some nutrients. Like proteins, which can depress feed utilisation and ultimately depress DM intake (Brooks et al. 2001) or cause protein-induced diarrhoea (Brooks, 2008). Brooks (2008) also pointed out that the fermentation of nutritionally balanced liquid feed will improve performance only if it increases feed intake or improves gut health. If the intake would be unaffected, it could be that the biochemical changes produced by fermentation will produce a diet that is less balanced.

5. Fermentation variables

The use of LF was already advocated by Henderson in 1814, but it was Smith (1976) who first pointed to the fact that when feed was soaked in water for a certain length of time, prior to feeding, that lactic acid bacteria and yeast naturally present on grains proliferate and produce lactic acid, acetic acid and ethanol and then reduce the pH of the feed. Generally, the LAB dominate fermentations in liquid feed. However, at low operating temperatures and particularly when co-products from brewing and ethanol production are used, yeasts can dominate the fermentations (Brooks et al. 2003b).

Fermentation can be influenced by several factors. In Figure 2 the most important factors playing a role in this are given. The LAB naturally present on the different feed components or LAB added to the feed determine, together with the fermentation parameters, the degree of acid

276 production (primarily lactic acid). The faster this production, the faster the drop in pH and the
277 faster pathogenic bacteria, such as *Salmonella* spp. or *E. coli*, are reduced. Also strains
278 originating from the air can influence the fermentation profile. An acid environment does not
279 exclude the possible growth of yeasts and fungi present on the feed or in the air. These can
280 produce "off-flavours" and taints that make the feed less palatable (Moran, 2001; Brooks et al.
281 2003b). In the past few years some studies also investigated the population diversity of LAB or
282 yeasts in FLF and its changes (Plumed-Ferrer et al. 2004; Pedersen et al. 2004; Canibe et al.
283 2007a; Olstorpe et al. 2008) and they found a wide range of variation in the populations of the
284 feeds. Other parameters such as environmental temperature or fermentation temperature, interval
285 between and degree of backslopping (partial replacement of FLF by fresh LF in continuous
286 fermentation) and the actual feed:water ratio of the FLF, can have an effect on the actual
287 fermentation characteristics of the FLF (Choct et al. 2004a).
288
289 ***5.1. Spontaneous versus inoculated fermentations***
290
291 In the FLF the fermentation may happen spontaneously or it may be induced. The induced
292 fermentation can be achieved either by backslopping or inoculation of the feed with a LAB strain
293 (Plumed-Ferrer and Von Wright, 2009). Beal et al. (2005) pointed out, that spontaneous
294 fermentation is not a reliable system to obtain a safe and palatable final product. They fermented
295 56 samples of wheat and 44 of barley. Only a few spontaneous fermentations reached the
296 threshold of 100 mmol/l lactic acid needed to eliminate *Salmonella* spp. (20% after 72 h
297 fermentation at 30°C). Other studies have shown as well that uncontrolled/spontaneous
298 fermentations result in higher concentrations of both acetic acid and biogenic amines, which
299 adversely affect the palatability and intake of liquid diets (Brooks et al. 2003b; Niven et al.
300 2006).

Brooks et al. (2003b) stated that to benefit from the use of FLF, fermentation needs to be controlled. In this view, spontaneous fermentations seem to be too variable. This problem can be diminished by the inoculation of the liquid feed with LAB that produce high concentrations of lactic acid rapidly (Jensen and Mikkelsen, 1998; Brooks et al. 2003b). In the literature there are already many LAB species used to produce FLF. *Lactobacillus plantarum* is often used to inoculate liquid feed to produce FLF (Van Winsen et al. 2000; Demečková et al. 2002; Heres et al. 2003; Plumed-Ferrer et al. 2005; Niven et al. 2006; Missotten et al. 2007). Also, *Pediococcus spp*. are often used to inoculate liquid feed (Geary et al. 1999; Beal et al. 2002; Niven et al. 2006; Missotten et al. 2007). In fact, combinations of these two strains have been used to produce FLF (Jensen and Mikkelsen, 1998; Moran, 2001; Moran et al. 2006). An overview of all LAB species found in literature to produce FLF are given in Table 2.

In a recent study, Olstorpe et al. (2008) demonstrated that the species composition in fermented liquid feed may vary considerably. They showed that *Pediococcus pentosaceus* was the dominant population at the beginning of a spontaneous fermentation, but that after 3 days of continuous fermentation the *Lactobacillus plantarum* population had become the dominant population. This was also observed in inoculated FLF, where the LAB strain used to inoculate the feed did not stay the dominant LAB strain in the FLF (Geary et al. 1999; Missotten, 2010). To maintain the possible probiotic effect of the added strain, the use of batch fermentation may thus be more suitable (Brooks, 2008).

5.2 Complete feed or grain fraction

Fermenting the whole feed is the easiest way to produce FLF, but it can bring along some problems, like the use of essential nutrients from the feed by the microorganisms (Brooks et al. 2003b; Brooks, 2008). To eliminate this possibility it is often suggested to only ferment the grain fraction. This grain fraction may then be used to make a range of diets, so that “step” or “phase

feeding" can be implemented using the same fermented grain. A grain is also a more consistent product to ferment, compared to a complete feed, consisting out of multiple nutrients (Brooks et al. 2003b). However, Beal et al. (2005) reported that spontaneous fermentation of grain is often not sufficient to produce FLF with desirable characteristics. So inoculation with a LAB strain is necessary, particularly considering that fermentation will have to produce more lactic acid to compensate for the dilution and buffering effects of the other feed components when the complete feed is produced (Brooks, 2008).

5.3. Continuous or batch fermentations

5.3.1. Continuous fermentations

For FLF the term continuous fermentation is actually not the exact term to be used, because the fermentation is not continuously renewed with a fresh feed mixture, but at regular time intervals (usually coinciding with feeding times). This is known as 'backslopping' (Salovaara, 1998). In practice, backslopping can involve the retention of a specified quantity of previously fermented product in the tank and mixing in fresh substrate or the addition of a portion of the fermented product to a fresh tank of substrate to act as an inoculum (Nout et al. 1989). In this way, a portion of a previous successful fermentation is retained as an inoculum for the next batch (Moran et al. 2006). This allows for the gradual selection of LAB and an accelerated fermentation (Nout et al. 1989), although Brooks (2008) also pointed out the possibility that this may result in the development of a microflora dominated by yeasts, which may compromise the palatability and nutritional value of the feed. As mentioned before however, high concentrations of yeasts in the FLF may be beneficial as well.

In their study, Jensen and Mikkelsen (1998) stated that a fermentation period of 8 hours would be most practical for the farmers, since they feed their pigs three times a day. They investigated whether 8 hours would suffice to ferment a new mix in the fermentation vessel, with an as low as possible residue from the previous fermentation. They concluded that to ensure an efficient fermentation, half of the previous feed has to remain in the tank between fermentations, although it took 3-5 days to reach steady state conditions.

Plumed-Ferrer et al. (2005) showed that maintaining 25% in the tank to inoculate the fresh added LF to the tank (backslopping at 8:00 a.m. and 14:00 p.m. every day), was sufficient to maintain a proper fermentation. Moran et al. (2006) found that there was no advantage in keeping more than 20% of the fermented wheat (backslopped after 24 h) when performing fermentation. So although a retention of 50% is mostly used, it seems that a lower proportion can be used with 20% being the lowest percentage still ensuring the exclusion of coliforms.

When using pipeline-feeding systems, a spontaneous fermentation of the LF occurs in the pipes, and residues of feed in the pipes can thus be seen as a special form of backslopping (Royer et al. 2004a, 2004b, 2005). Hansen and Mortensen (1989) pointed out that it was detrimental to sterilize pipeline-feeding systems as this removed the LAB and increased the pH of the feed by 1.5-2.0 units. This allowed coliform bacteria to proliferate, causing outbreaks of diarrhoea, until the LAB re-established themselves after 3 to 5 days and lowered the pH again. This growth of *Enterobacteriaceae* can also occur when the fresh feed mix is added to the fermentation vessel when applying backslopping, because of the dilution effect the pH can go above the growth inhibiting level of 4.5 (Brooks, 2008).

5.3.2. Batch fermentation

This type of fermentation, where the feed and water mixture is fermented in a vessel without replacements of a part of the FLF, is most often used in *in vitro* experiments. Sometimes batch

fermentations of the feed or the grain fraction are used to produce FLF for *in vivo* experiments (Scholten et al. 2002), because they are easier to control and if undesirable fermentation occurs it is only within one batch (Brooks, 2003; Brooks et al. 2003b). Recently Brooks (2008) also suggested that batch fermentations may be more suitable for preserving the probiotic effect of added strains than the backslopping technique.

5.4. Temperature

Jensen and Mikkelsen (1998) investigated whether fermentations at different temperatures would give a different result. This was the case, but they found that fermenting the feed at temperatures above 20°C did not give major advantages to the FLF compared with the FLF produced at 20°C (Figure 3). At 20°C the coliform count was just above the detection limit of 3 $\log_{10}$ CFU/g FLF. They did stress the fact that the temperature needs to be at least 20°C if the required pH at feeding has to be lower than 4.5. Enteric pathogens, such as *E. coli* and *Salmonella* spp., do not tolerate pH values below 4.5 (Merrell and Camilli, 2002)

Later Beal et al. (2002) investigated the effect of fermentation on the exclusion of *Salmonella* Typhimurium. They found that the reduction time was much shorter at 30°C versus 20°C. So although the minimal temperature for getting optimal FLF is a temperature of 20°C, a temperature of 30°C is preferable since it allows a fast production of lactic acid and a fast exclusion of enteropathogens (Brooks, 2003).

It should also be avoided with backslopping to add cold water to the system. For example adding water immediately from the tap (5-7°C) will cold-shock the system. This could cause the induction of cold-shock protein formation in enteropathogens, which can protect them and allow them to persist longer in the feed (Brooks et al. 2001, Beal et al. 2002). Furthermore it disturbs the growth of the LAB and it allows the yeasts to become dominant (Brooks et al. 2001).

Not only the temperature of the fermentation vessel is important, also the environmental temperature is of importance. Niba et al. (2009) stated that FLF may contribute considerably to the African agriculture, especially in semi-arid and hot areas. In such areas, ambient temperatures (± 30°C) could support efficient lactic acid fermentation of feeds.

5.5. Feed:water ratio

By definition, the feed to water ratio of LF or FLF can fluctuate between 1:1.5 and 1:4. Barber et al. (1991) demonstrated that there was a linear improvement in both DM and energy digestibility as the feed to water ratio increased from 1:2 to 1:4, while Gill (1989) demonstrated that there was an improvement of the F/G ratio as the feed to water ratio increased from 1:2 to 1:3.5. The same was observed by Hurst (2002) and Hurst et al. (2008) for a feed to water ratio from 1:1.5 to 1:3. Although the intake of solid food by newly weaned pigs is generally low, the results obtained by Russell et al. (1996) demonstrated that the dry matter feed intake of the newly weaned pig can be increased by providing it with FLF, even though that this implied a consumption of a greater volume of material. When piglets are offered FLF with different DM percentages (14.5 – 25.5%), they maintain their DM intake in the lowest DM group by increasing their total volumetric intake. The dietary DM concentration also had no effect on weight gain or F/G ratio (Geary et al. 1996). All these studies support the theory that the pig will limit intake of water not originating from LF or FLF, e.g. from nipple drinkers, to maximise feed intake (Yang et al. 1981). Hence the total volumetric intake will be comparable when the same diet is fed in liquid or dry form (Geary et al. 1996).

Although, a wide range of ratios can be used, it becomes clear from the overview given in Plumed-Ferrer and Von Wright (2009) and Niba et al. (2009) that the slurry is most of the time given to pigs in a feed to water ratio between 1:2 and 1:3. In batch fermentations in the lab sometimes higher ratio’s are being used for experimental purposes.

6. Effect on GIT health

The concept of gut health is complex and, at present, an ill-defined notion. Conway (1994) proposed that there are three major components of 'gut health', namely the diet, the intestine and its commensal microbiota. The intestine is an important compartment, being a major site of digestion, nutrient absorption and hydro-mineral exchange homeostasis, harbouring a complex microbiota and a highly evolved mucosal immune system (Lallès et al. 2007). Post-weaning GIT disorders in pigs result not only from alterations in GIT architecture and function but also from major changes in the adapting enteric microbiota (Konstantinov et al . 2004) and immune responses (Stokes et al. 2004; Baily et al. 2005). Undoubtedly all these aspects of GIT physiology, microbiology and immunology contribute interactively to the so-called gut health balance (Lallès et al. 2007). In this part the effect of feeding FLF on GIT pH, microbial population and GIT morpho-histology will be discussed.

6.1. Effect on GIT pH

A lowering of the gastric pH in piglets fed FLF compared to DF or LF piglets is often seen (Mikkelsen and Jensen, 1998; Jensen and Mikkelsen, 1998; Canibe and Jensen, 2003). The pH in the small intestine of FLF fed piglets is however often higher than in piglets fed DF or LF (Mikkelsen and Jensen, 1998 and 2000; Jensen and Mikkelsen, 1998; Canibe and Jensen, 2003). This may be related to an increased secretion of pancreatic juice, stimulated by the low pH and high lactic acid concentrations in the FLF (Jensen and Mikkelsen, 1998; Plumed-Ferrer and Von

454 Wright, 2009). In Table 3 the results obtained in the study of Canibe and Jensen (2003) are given
455 as a good example of pH in the different GIT segments when pigs are fed FLF, LF or DF.
456 Radecki et al. (1988) suggested that the improved growth of pigs fed on diets containing
457 organic acids may be related to a lower gastric pH, allowing a better proteolytic activity in the
458 stomach and inhibiting the growth of undesirable pathogenic bacteria. This can also be the case
459 when feeding FLF. The stomach is indeed an important barrier against pathogens (Lallès et al.
460 2007) and lowering the pH may improve this barrier and prevent coliform scours (Easter, 1993),
461 especially in newly weaned piglets which are often not capable of producing enough gastric acid
462 (HCl) themselves yet (Partridge and Gill, 1993).
463
464 ***6.2. Effect on GIT microbial population***
465
466 The use of FLF can influence the microbial population in the GIT. Canibe and Jensen (2003)
467 found no differences among the different types of feeding in the number of LAB grown at 37°C
468 from the distal small intestine (Table 4). At an incubation temperature of 20°C however, the
469 proportion of LAB able to grow was significantly higher in pigs fed FLF compared to the DF or
470 LF fed piglets. This indicated that the LAB population in the GIT of the two groups was
471 different. They also found that the proportion of yeast was, almost in all GIT compartments,
472 significantly higher in the FLF fed group (Table 4). In contrast, all segments of the FLF fed
473 piglets showed less coliform bacteria (Table 4). This was also apparent in the study of Moran
474 (2001) in which he found that the ratio of LAB to coliform bacteria in the lower gut of the pigs
475 weaned with FLF was shifted in favour of the LAB, while in piglets fed dry feed, this ratio was
476 shifted in favour of the coliforms.
477 Demečková et al. (2002) showed that it is possible through feeding the sows FLF that the
478 bacterial gut population of their offspring can be influenced. The newborn pig usually has a
479 sterile gut at birth and acquires its characteristic flora through contact with its mother and its

surroundings. Th most significant contributor of bacteria to the piglet's surroundings is the sow. Demečková et al. (2002) reasoned that if the gut microflora of the sow could be manipulated this would impact on the development of the piglet's gut microflora. The piglets from sows fed FLF indeed showed lower coliform counts in their faeces compared to piglets from sows fed NFLF or dry diets. Also the LAB population was augmented in the faeces of the piglets from sows fed FLF compared to the other piglets.

Feeding FLF to pigs reduced the microbial activity (ATP concentration) in the GIT, significantly in the stomach and small intestine, of piglets compared to piglets fed NFLF (Jensen and Mikkelsen, 1998). This is also seen when feeding AMGP (Jensen, 1988). In Canibe and Jensen (2003) this reduction in ATP concentration in the GIT was not found, although the microbial population from the caecum and colon of the piglets fed with FLF showed a reduced fermentation capacity (Højberg et al. 2003).

6.3. Effect on GIT morpho-histology

The transition from liquid milk to solid feed is often accompanied with a reduced feed intake and growth check (Brooks and Tsourgiannis, 2003). This results in shortening of villi and crypt deepening in the small intestine, which is generally associated with a reduced digestive capacity (Pluske et al. 1997; Montagne et al. 2007). Liquid feed, either fresh or fermented, is stated to help overcome this reduced feed intake (Scholten et al. 1999b). Pluske et al. (1997) and Vente-Spreeuwenberg and Beynen (2003) stated that it iss mainly due to a higher nutrient intake that villus architecture can be maintained. So it would seem that feeding the diet in a liquid form is positive because it reduces the transition gap from milk to the weaner diet (Russell et al. 1996; Brooks et al. 2001).

Most studies conducted until now included a comparison between DF and LF (Deprez et al. 1987; da Silva et al. 2001; Hurst, 2002). In most studies, an improvement is seen in the

morphology of the pigs fed with LF. Moran (2001) however included also FLF in his experiment (Table 5). From these results an improvement in villus length/crypt depth ratio could not be seen for the piglets fed LF or FLF, as the villus length was reduced compared to feeding DF. Moran (2001) however found a correlation between the dry matter intake and mucosal integrity.

Scholten et al. (2002) found that pigs fed diets containing 45% fermented liquid grain (wheat) had improved villus architecture compared to piglets fed a fresh liquid diet (without fermented grain). In the first section of the small intestine, pigs had significantly greater villus length and a greater villus/crypt ratio. Bruininx et al. (2010) found that the supernatants of diets containing either prefermented cereals or their fermentation end-products (organic acids and ethanol) clearly modulated cellular growth and metabolism of enterocyte-like Caco-2 cells, although these effects were not observed in the *in vivo* characteristics (villus length, crypth depth and brush-border enzyme activities) measured in a section of the jejunum of weanling pigs.In the first two conducted experiments comparing piglets fed FLF with piglets fed DF Missotten (2010) found comparable results to those of Moran (2001). In these experiments it was observed that the piglets fed FLF took up proportional more water and less DM from the FLF because of a fast sedimentation of the solids in the FLF. In a third experiment however, this sedimentation was hindered by adding sepiolite (SPLF®, Grupo Tolsa S.A., Spain) to the feed. In this third experiment the piglets fed FLF had larger villi than the piglets fed the dry feed in which the same LAB strain, used to inoculate the FLF, was present.

7. Growth promotion

According to the review of Jensen and Mikkelsen (1998) several investigations have shown that feeding either LF or FLF improves feed intake and growth performance of pigs. In piglets

however this is not accompanied by a better F/G ratio, while for slaughter pigs the F/G was improved on average by 6.9 % (Table 6; Jensen and Mikkelsen, 1998).

Plumed-Ferrer and Von Wright (2009) also gave an overview of *in vivo* trials performed and their effect on the pigs. However, focus in that review was put on fermentation parameters and not all performance data were given and some studies discussed are not that relevant for comparing dry feeding (DF) to LF or FLF. For example, Vente-Spreeuwenberg et al. (2003) compared three liquid diets with different carbohydrate sources or the study of Kim et al. (2001) was an experiment comparing a pelleted feed versus a milk formula for early weaned piglets. In Table 7 and 8 all the relevant performance data found in the literature, for piglets and growing-finishing pigs respectively are presented. Challenge experiments like Amezcua et al. (2007) and Canibe et al. (2008) were excluded as they are less representative for normal commercial situations.

In Table 9, additional studies that did not fit into the structure of Tables 7 and 8 are presented. It should be noted however, that differences measured for the types of feeding may be due to different levels of wastage rather than different efficiencies of feed utilisation. This wastage does not allow to calculate the F/G ratio with the actual feed consumption (Brooks et al. 2003a). Russell et al. (1996) found that this wastage was partly responsible for the lesser performance of the piglets on FLF. This lower F/G ratio was ameliorated by altering the through design, but not completely eliminated. In the three experiments conducted by Missotten (2010) the F/G ratio of the piglets was improved by reducing the sedimentation of the solids in the feed slurry. In the third experiment, where sepiolite was used to reduce this sedimentation, the piglets fed FLF showed a better F/G ratio than the control (dry) fed group (1.33 vs 1.52 respectively).

For slaughter pigs, from 20 kg to slaughter, Smith (1976) also performed a test comparing LF to FLF, but no advantage was observed in offering the LF fermented compared to offering it fresh. The study of Scholten et al. (2002) is included in Table 7, but it has to be

555 stressed that these piglets were restricted fed and that their performance was very poor. The
556 objective of that study was not to determine the growth performance, but the effect on the GIT
557 morphology. Most trials however used *ad libitum* feeding.

558 Since the review of Jensen and Mikkelsen (1998) more feeding trials with FLF have been
559 performed as can be seen in Tables 7 to 9, but the conclusion made by these authors is still valid.
560 These authors concluded that feeding LF or FLF results in an improved feed intake and growth
561 performance, but that the F/G ratio was on average not improved for piglets, while for growing-
562 finishing pigs on average a better F/G ratio is found compared to pigs fed DF. Recently however,
563 Missotten (2010) showed that the F/G ratio can be improved by feeding piglets with FLF in
564 which the sedimentation of the solids is controlled.

565

566 **8. Conclusion**
567

568 Although care has to be taken that undesirable fermentation does not occur during FLF
569 production, its utilisation in pig feeding seems to ameliorate growth performance, provided that
570 sedimentation of the solids in the liquid slurry is hindered. Preventing this mal-fermentation is
571 usually performed by adding LAB strains to the feed under controlled fermentation parameters.
572 Until now not one strain has been found that also remains the dominant strain in the FLF. So
573 further investigation is warranted in this field, because spontaneous fermentations are not reliable
574 and inoculation is needed to initiate a consistent fermentation process. The application of
575 fermenting only the grain fraction of the feed can also be applied. This prevents some problems
576 with fermenting complete diets (e.g. loss of essential nutrients), but other problems such as the
577 need for an even higher lactic acid production arise. Furthermore, the use of batch or
578 backslopping fermentation is still under debate. The choice of the type of fermentation will
579 largely depend on the discovery of a good inoculant for producing FLF.

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927

928 Table 1. Pig numbers and estimated market shares of liquid feeding (dairy and other products) in
929 some European countries (EFSA, 2006)

		The share of liquid feeding	
Country	**Pig numbers x 10^6**	**All pig categories % fed**	**Sows % fed**
Iceland	-	70	0
Denmark	13.4	60	30
Finland	1.4	60	20
Switzerland	-	50-60	30
The Netherlands	11.1	50	15
Ireland	1.8	40-50	20
Italy	8.9	40	5-10
Sweden	1.9	30	10
France	15.3	30	5-10
Austria	3.1	30	5-10
Germany	26.3	30	3-5
Norway	-	25-30	2
UK	4.8	20	10
Belgium	6.3	10	2
Greece	0.994	10	2
Spain	25.4	1	0
Portugal	2.348	0	0
EU-25	151.6	30	

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Table 2. Lactic acid bacteria strains used in studies, related to pigs, for producing fermented liquid feed either for *in vitro* or for *in vivo* experiments

Strain(s)	Experiment type	Study
Lactobacillus plantarum	*In vivo*	Van Winsen et al. (2001); Van Winsen et al. (2002)
Lactobacillus plantarum	*In vitro*	Van Winsen et al. (2000); Christensen et al. (2007); Moran (2001)
Lactobacillus plantarum PC-81-11-02	*In vivo*	Moran (2001); Demečková et al. (2002)
Lactobacillus plantarum REB1-Rif^{R}	*In vivo*	Plumed-Ferrer et al. 2005
Lactobacillus plantarum VTT E-78076	*In vitro and In vivo*	Canibe et al. (2001); Canibe et al. (2008)
Lactobacillus plantarum LQ80	*In vitro*	Kobashi et al. (2008)
Lactobacillus plantarum 23E13, 98L11 and 2P22	*In vivo (whey)*	Amezcua et al. (2007)
Lactobacillus plantarum + *Pediococcus* spp.	*In vitro*	Jensen and Mikkelsen (1998); Moran (2001; with *Pediococcus pentosaceus*) and Moran et al. (2006)
Lactobacillus plantarum CNCM I-840 + *Streptococcus infantarius* CNCM I-841 (Adjulact Pro®)	*In vitro*	Missotten et al. (2007)
Pediococcus acidilactici CNCM MA 18/5M (Bactocell®)	*In vitro*	Niven et al. (2006); Missotten et al. (2007)
Pediococcus acidilactici	*In vitro* and *In vivo*	Moran (2001); Geary et al. (1999)
Pediococcus pentosaceus	*In vitro*	Moran (2001); Beal et al. (2002)
Lactobacillus bavaricus + *Pediococcus acidilactici*+ *Streptococcus bavarius*	*In vitro*	Jensen and Mikkelsen (1998)
Lactobacillus alimentarius	*In vitro*	Jensen and Mikkelsen (1998)
Lactobacillus lactis subsp. *cremoris* 303	*In vivo*	Lawlor et al. (2002)
Lactobacillus rhamnosus LC 705 + *Propionibacterium freudenreichii* spp. *shermanii* JS (Bioprofit®)	*In vitro*	Canibe et al. (2001)
Lactobacillus brevis	*In vitro*	Moran (2001)
Lactobacillus amylophilus	*In vitro*	Moran (2001)
Lactobacillus curvatus	*In vitro*	Moran (2001)

935 Table 3. The pH along the gastrointestinal tract of pigs fed either dry feed (DF), non fermented
936 liquid feed (NFLF) and fermented liquid feed (FLF; feed to water ratio 1:2.5, backslopping with
937 50% retention at 20°C) (n = 5; Canibe and Jensen, 2003)

	Diet			
Segment	**DF**	**LF**	**FLF**	***P*-value**
Stomach	4.4[a]	4.6[a]	4.0[b]	0.003
Proximal small intestine	5.9	5.8	5.7	0.48
Mid small intestine	6.0[a]	5.8[b]	6.1[a]	0.008
Distal small intestine	6.4[a]	5.7[b]	6.1[ab]	0.02
Caecum	5.7	5.5	5.7	0.17
Proximal colon	5.9	5.8	5.8	0.72
Mid colon	6.1	6.0	6.1	0.54
Distal colon	6.4[ab]	6.2[a]	6.5[b]	0.04

938 [a,b]: means within rows with a different superscript differ significantly ($p<0.05$)
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941 Table 4. Microbial counts [$\log_{10}$ CFU/g sample] along the gastrointestinal tract of pigs fed either
942 dry feed (DF), non fermented liquid feed (NFLF) and fermented liquid feed (FLF; feed to water
943 ratio 1:2.5, backslopping with 50% retention at 20°C) (n = 5; Canibe and Jensen, 2003)

	Diet			
Segment	**DF**	**NFLF**	**FLF**	***P*-value**
LAB (20°C)				
Stomach	<5.4(3)[a]	7.9[b]	9.0[c]	<0.001
Distal small intestine	<6.3(5)[a]	<6.5(3)[a]	7.2[b]	0.01
Caecum	<6.0(5)	<6.2(2)	<6.6(2)	0.21
Mid colon	<6.1(5)	<6.3(3)	<6.3(4)	0.34
LAB (37°C)				
Stomach	8.8	8.7	8.9	0.35
Distal small intestine	8.2	8.6	8.4	0.41
Caecum	8.7[ab]	9.0[a]	8.3[b]	0.04
Mid colon	9.2[a]	9.2[a]	8.5[b]	0.01
Enterobacteria				
Stomach	3.8[a]	5.7[b]	<3.2(4)[c]	<0.001
Distal small intestine	5.5[a]	6.6[b]	<4.1(3)[c]	<0.001
Caecum	5.9[a]	6.3[a]	5.0[b]	0.02
Mid colon	6.2[a]	6.6[a]	4.7[b]	0.004
Yeasts (20°C				
Stomach	<3.4(2)[a]	3.7[a]	5.4[b]	0.001
Distal small intestine	<3.4(3)[a]	3.9[b]	7.0[c]	<0.001
Caecum	<3.2(2)	<3.3(1)	<5.1(1)	0.07
Mid colon	<3.2(3)[a]	<3.3(1)[a]	<4.6(1)[b]	0.03
Yeasts (37°C)				
Stomach	<3.3(4)[a]	<3.6(2)[a]	4.2[b]	0.03
Distal small intestine	<4.0(3)	3.6	4.5	0.08
Caecum	<3.9(2)	<3.4(3)	<3.6(3)	0.59
Mid colon	<3.7(3)	<3.3(4)	<3.4(2)	0.69

944 Values in brackets indicate the number of samples with values below detection levels. The approximate detection
945 levels ($\log_{10}$ cfu/g) were as follows: stomach: LAB, 5; enterobacteria, 3; yeasts, 3. Small intestine, caecum
946 and colon: LAB, 6; enterobacteria, 4; yeasts, 3. "<" indicates that some observation from which the mean
947 was calculated had values below detection levels. When no colonies were detected, the detection limit was
948 applied to make the calculations. Therefore some values are lower than actually reported
949 [a,b,c]: means within rows with a different superscript differ significantly ($p<0.05$)

Table 5. Mean villus length (V) and crypt depth (C) en V/C ratio in different sections of the small intestine of piglets killed 14 days post-weaning. Piglets were either fed dry feed (DF), non fermented liquid feed (NFLF), fermented liquid feed (FLF) or suckled further. The liquid feeds were supplied every hour (1), every 4 hours (4) or every 12 hours (12) (adapted from Moran, 2001)

	Section of intestine sampled*	**DF**	**Suckled**	**NFLF(1)**	**NFLF(4)**	**NFLF(12)**	**FLF(1)**	**FLF(4)**	**FLF(12)**
V [µm]	0.25	655^{a}	646^{a}	593^{ab}	621^{ab}	486^{b}	538^{ab}	565^{ab}	430^{b}
	0.50	650^{a}	596^{abc}	605^{ab}	570^{abc}	452^{ab}	598^{abc}	560^{abc}	487^{bc}
	0.75	578^{a}	515^{ab}	557^{a}	576^{a}	458^{ab}	518^{ab}	531^{ab}	406^{b}
C [µm]	0.25	244^{b}	306^{a}	251^{ab}	261^{ab}	268^{ab}	234^{b}	268^{ab}	230^{b}
	0.50	260^{ab}	308^{a}	262^{ab}	283^{ab}	250^{b}	249^{b}	290^{ab}	233^{b}
	0.75	249	282	238	245	241	240	280	243
V/C	0.25	2.68	2.11	2.36	2.37	1.81	2.29	2.10	1.87
	0.50	2.50	1.94	2.31	2.01	1.81	2.40	1.93	2.10
	0.75	2.32	1.83	2.34	2.35	1.90	2.15	1.90	1.67

* The small intestine was extended to its full length by cutting the mesentery. Sections were removed proportionately at 0.25, 0.50 and 0.75 intervals along the intestine.

^{a,b,c}:within rows, means with a different superscript differ significantly ($p<0.05$) (on V/C ratio no statistics were performed)

Table 6. Difference (% change relative to dry feed) in daily body weight gain (BWG) and feed/gain ratio (F/G) in experiments conducted to compare liquid vs dry feeding (Jensen and Mikkelsen, 1998)

		Daily BWG		F/G ratio	
	No. of trials*	**Av ± StDev**	**Min; Max**	**Av ± StDev**	**Min; Max**
Piglets					
LF vs DF	10	12.3 ± 9.4	(-7.5; 34.2)	-4.1 ± 11.8	(-32.6; 10.1)
FLF vs DF	4	22.3 ± 13.2	(9.2; 43.8)	-10.9 ± 19.7	(-44.3; 5.8)
FLF vs LF	3	13.4 ± 7.1	(5.7; 22.9)	-1.4 ± 2.4	(-4.8; 0.6)
Slaughter pigs					
LF vs DF	9	4.4 ± 5.4	(-2.6; 15.0)	6.9 ± 3.5	(1.9; 12.7)

*: according to the studies indicated in Tables 7 and 8 with §

DF: dry feed; LF: liquid feed; FLF: fermented liquid feed

962 Table 7. Effect of dry feeding (DF), liquid feeding (LF) or fermented liquid feeding (FLF) on growth performance of weaned piglets

Study	No of pigs/treat-ment	Weight range (kg)	Feeding strategy			Daily body weight gain [g]			Feed/gain ratio [kg/kg]		
			DF	LF	FLF	DF	LF	FLF	DF	LF	FLF
Kornegay et al. (1981)[§]	156	9-26	ad lib[$]	ad lib		430	400		2.40	2.54	
Kornegay et al. (1981)[§]	126	7-22	ad lib	ad lib		380	380		1.85	1.93	
Kornegay et al. (1981)[§]	186	8-21	ad lib	ad lib		360	380		1.77	1.84	
Nielsen et al. (1983)[§]	92	9-16				153[a]	179[a]	220[b]	2.07[a]	1.86[b]	1.95[b]
Nielsen et al. (1983)[§]	190	8-20				305	315	333	1.69	1.68	1.69
Van de Pas et al. (1989)	1754	8-23	ad lib	ad lib		446	417		1.61	1.72	
Van de Pas et al. (1989)	2138	8-24	ad lib	ad lib		427	431		1.54	1.68	
Van de Pas et al. (1989)	594	8-24	ad lib	ad lib		451	439		1.65	1.78	
Danish Pig federation (1991)[§]	520	7-32				438[a]	480[b]				
Danish Pig federation (1991)[§]	320	7-40				461[a]	527[b]				
Hansen and Jørgensen (1992)[§]	170	7-10				146[a]	196[b]		1.75	1.69	
Hansen and Jørgensen (1992)[§]	360	6-9				142[a]	171[b]		1.53[a]	2.03[b]	
Partridge et al. (1992)[§]	20	6-12				281[a]	312[b]		1.12	1.12	
Russell et al. (1996)[§]	24	3-7 weeks	ad lib		s/ad lib[$]	343[a]		428[b]	1.31[a]		1.89[b]
Russell et al. (1996)[§]	48	3-7 weeks	ad lib		s/ad lib	397[a]		454[b]	1.37[a]		1.44[b]
Mikkelsen and Jensen (1997)[§]	8	8-10					260	290		1.16	1.16
Mikkelsen and Jensen (1998)	10	8-20					468	440		1.11	1.14
Geary et al. (1999)	24	7 kg and then fed for 28 days		ad lib acidif. lact. acid (pH 4)	i/ad lib[$]		474	496		1.15	1.11
Pedersen (2001): trial 1	300	9-24.8	ad lib	ad lib	s/ad lib	387[a]	535[b]	392[a]	2.08[a]	1.71[b]	2.08[a]
Lawlor et al. (2002) (+AMGP)	192	8.4-16.8 4-8 weeks	ad lib	ad lib (res ad lib in week 1)[$]		338	286		1.13	1.68	
Lawlor et al. (2002) (+AMGP)	150	7.8-17.8 4-8 weeks	ad lib	ad lib (res ad lib in week 1)		391	352		1.17	1.56	
Lawlor et al. (2002) (+AMGP)	112	7.7-19 4-8 weeks	ad lib	1: fresh 2: acidif. lact. acid (pH 4)[$] ad lib (res in week 1)		408	1: 416 2: 433		1.16	1: 1.32 2: 1.27	

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964 Table 7 (continued). Effect of dry feeding (DF), liquid feeding (LF) or fermented liquid feeding (FLF) on growth performance of weaned piglets

Study	No of pigs/treat-ment	Weight range (kg)	Feeding strategy			Daily body weight gain [g]			Feed/gain ratio [kg/kg]		
			DF	LF	FLF	DF	LF	FLF	DF	LF	FLF
Lawlor et al. (2002) (-AMGP)	112	8-17.8 4-8 weeks	ad lib	acidif. lact. acid (pH 4) ad lib (res ad lib in w1)	i/ad lib (res ad lib in w1)	361	389	347	1.13	1.34	1.36
Scholten et al. (2002)	20 first 4 d 10 last 4 d	8 kg fed for 8 days	res		res 45% ferm wheat[$]	10		43			
Choct et al. (2004b) roller mill	12	8.35 kg fed for 21 days	medium fine ad lib		medium fine ad lib	365 414		365 389	1.64[a] 1.37[b]		0.98[c] 0.92[c]
Choct et al. (2004b) hammer mill	12	9 kg fed for 21 days	medium fine ad lib		medium fine ad lib	541 486		471 495	1.16 1.17		0.82 0.89
Pedersen et al (2005)	16	9.1-26	ad lib	1: fresh 2: with WWDG[*] res		547[a]	1: 453[b] 2: 433[b]		1.34[a]	1: 1.24[b] 2: 1.26[b]	
Canibe et al. (2007a)	40 at start and 32 after day 14	8 kg fed for 42 days	ad lib		res 1: ferm grain 2: s/FLF	399[a]		1: 312[b] 2: 282[b]	1.39		1: 1.55 2: 1.56
Missotten (2010)	6	7.4 fed for 8 days	ad lib		ad lib	133		46	1.62		3.66
Missotten (2010)	15	7.9-13.8	ad lib		ad lib	254		183	1.57		1.85
Missotten (2010)	15	6.3-11.9	1: ad lib 2: ad lib + probiotic		ad lib	1: 184[a] 2: 185[a]		253[b]	1: 1.52[a] 2: 1.48[a]		1.33[b]

[a,b,c]: means within the same study with different superscripts are significantly different at $p<0.05$

[*] WWDG: wet wheat distillers grain

[$] ad lib: *ad libitum* fed; res: restrictedly fed; s/:spontaneous fermentation; i/: inoculated fermentation; acidif: acidified; lact. acid: lactic acid; ferm: fermented

[§]: study used in review of Jensen and Mikkelsen (1998)

Table 8. Effect of dry feeding (DF), liquid feeding (LF) or fermented liquid feeding (FLF) on growth performance of growing-finishing pigs

Study	No of pigs/treat-ment	Weight range (kg)	Feeding strategy			Daily weight gain [g]			Feed/gain ratio [kg/kg]		
			DF	LF	FLF	DF	LF	FLF	DF	LF	FLF
Forbes and Walker (1968)[§]	62	38-slaught	Res[$]	res		700	705		3.14	2.91	
Forbes and Walker (1968)[§]	36	35-slaught	res	res		764	777		3.34	3.07	
Forbes and Walker (1968)[§]	36	33-slaught	res	res		659	673		3.46	3.05	
Kneale (1972)[§]	30	25-slaught	res	ad lib[$]		665[a]	765[b]		3.38[a]	2.95[b]	
Smith (1976)[§]	6	25-slaught	res	res		629	635		3.14	3.08	
Smith (1976)[§]	64	20-slaught	res	res		552	574		3.50	3.32	
Nielsen and Madsen (1978)[§]	64	21-slaught	ad lib	ad lib		604	604		3.01	2.86	
Patterson (1989)[§]	48	34-slaught	res	res		758	738		2.92	2.85	
Smed (1994)[§]	1500	31-slaught	ad lib	ad lib		655[a]	735[b]		2.96	2.74	
Scholten et al. (1997)		25-112		ad lib	Ad lib with co-products		749	768		2.69	2.58
da Silva et al. (2002)	16	6.7-90	ad lib	ad lib		755	720		2.73	2.77	
Hurst (2002)	G: 65[$] B: 68[$]	42-86 41-87	ad lib	ad lib		G: 794[a] B: 831[a]	G: 895[b] B: 973[b]				
Hurst et al. (2008)	33	47-84.1	ad lib	ad lib		892	963		2.58	2.53	
Hurst (2002)	18 to 10 at slaughter	9.55-85.1	ad lib	ad lib		641[a]	796[b]		1.72	1.87	
Pedersen et al. (2002c)	1403	25-120		ad lib	ad lib ferm grain[$]		924	957		2.61[a]	2.46[b]
Meat and Livestock Commission (in Brooks et al. 2003a)		34-103	ad lib	ad lib		754[a]	796[b]		2.53[a]	2.20[b]	
Canibe and Jensen (2003)	20	31-101	res	res	res	961[ab]	995[a]	931[b]	Similar: between 2.11 - 2.15		
Xuang Dung et al. (2005)	5	27.4-80	res	res 1:Normal 2: acidif. lact. acid (pH 4)	res	552[a]	1: 541[a] 2: 601[b]	598[b]	3.79[a]	1: 3.76[a] 2: 3.41[ab]	3.09[b]

[a,b]: means within the same study with different superscripts are significantly different at $p<0.05$

[$] ad lib: *ad libitum* fed; res: restrictedly fed; acidif: acidified; lact. acid: lactic acid; ferm: fermented; G: gilts; B: boars

[§]: study used in review of Jensen and Mikkelsen (1998)

Table 9. Effect of dry feeding (DF), liquid feeding (LF) or fermented liquid feeding (FLF) on growth performance of piglets or growing-finsihing pigs reported in studies not included in Table 7 and 8

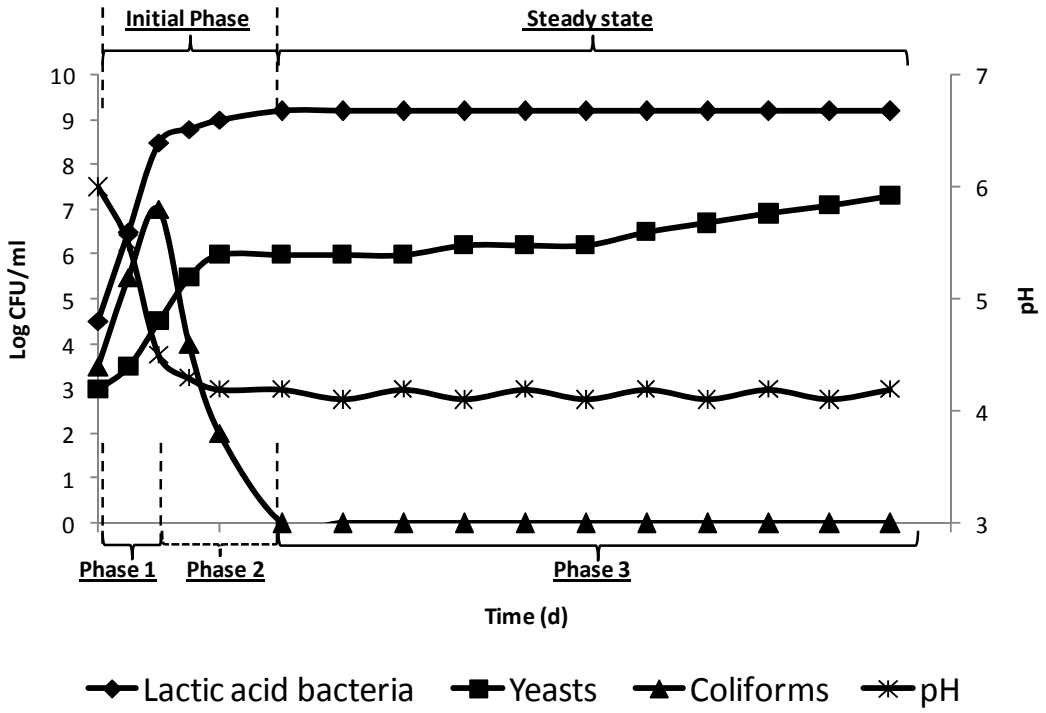
Study	Experimental groups	No of pigs/treat-ment	performance	
			Daily weight gain [g]	Feed/gain ratio [kg/kg]
Braude (1971)	Dry pellets	-	617[a]	3.31[a]
	Wet pellets	-	618[a]	3.29[a]
	Wet meal	-	633[b]	3.21[b]
Kim (1999)*	DF	-	774[a]	2.28
	LF	-	745[b]	2.27
Kim (1999)**	DF	-	763[a]	2.24
	LF	-	747[b]	2.26
Chae (2000)	DF	-	797[a]	3.38[a]
Growing-finishing pigs	LF	-	862[b]	3.32[a]
55-110 kg BW[$]	LF between 55-90 and DF between 90-110	-	852[b]	3.16[b]
Pedersen (2001): trial 2	DF	291	452	2.11
9.8-26.7 kg BW	Partly FLF	288	404	1.80
	Fully FLF	291	363	1.96
Hurst et al. (2008)	Dry pellets	16	962[a]	2.09[a]
47.2-86 kg BW	Soaked pellets 1:1.5	16	1041[ab]	1.94[b]
restrictedly fed	Soaked pellets 1:3	16	1051[b]	1.87[bc]
	Soaked pellets 1:3 (acidified with lactic acid pH 4)	16	1091[b]	1.79[c]
Han et al. (2006)	DF for 40 days	24	459[a]	1.55[a]
Initial BW 5.7 kg	LF for 10 days + DF for 30 days	24	482[b]	1.56[ab]
Fed *ad libitum*	LF for 20 days + DF for 20 days	24	475[ab]	1.60[b]

Notes: *From weaning at 14 d of age until about day 157 (first 14 d after weaning fed in conventional nursery).

**From weaning at 14 d of age until about day 157 (first 14 d after weaning fed in special nursery).

[$] BW: Body weight

[a,b]: means within the same column and study with different superscripts are significantly different at $p<0.05$



989
990 Figure 1. Schematic representation of the microbial population and pH during the
991 different phases in the fermentation of FLF according to Brooks (2008; phases 1, 2
992 and 3) and according to Canibe and Jensen (2003; initial and steady state)
993

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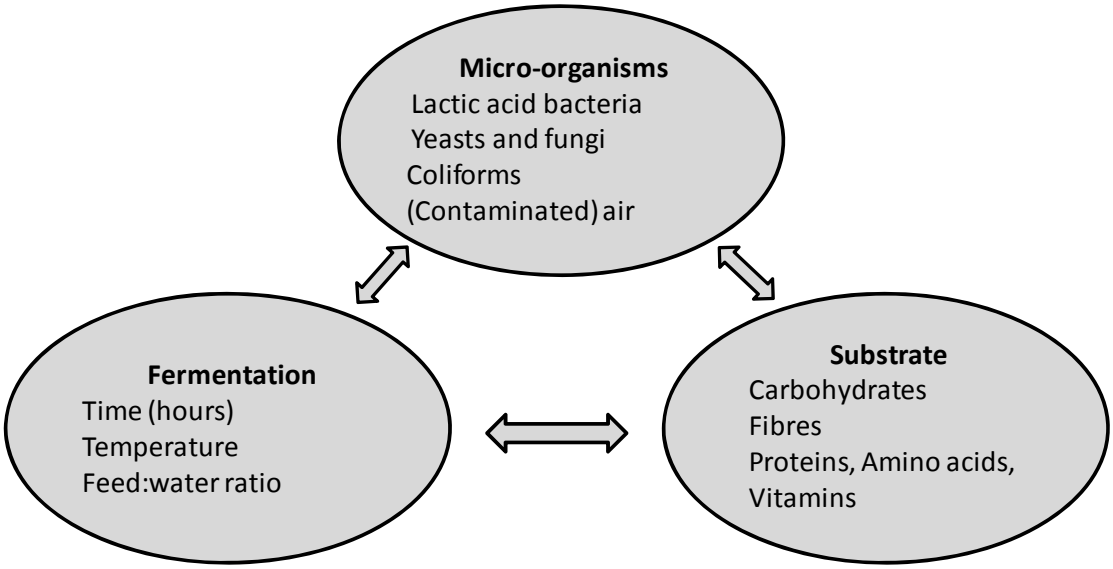

995

996 Figure 2. Interactions in the fermented liquid feed between the present micro-
997 organisms, fermentation parameters and substrate quantity and quality affects the final
998 end product, adapted from Niba et al. (2009)

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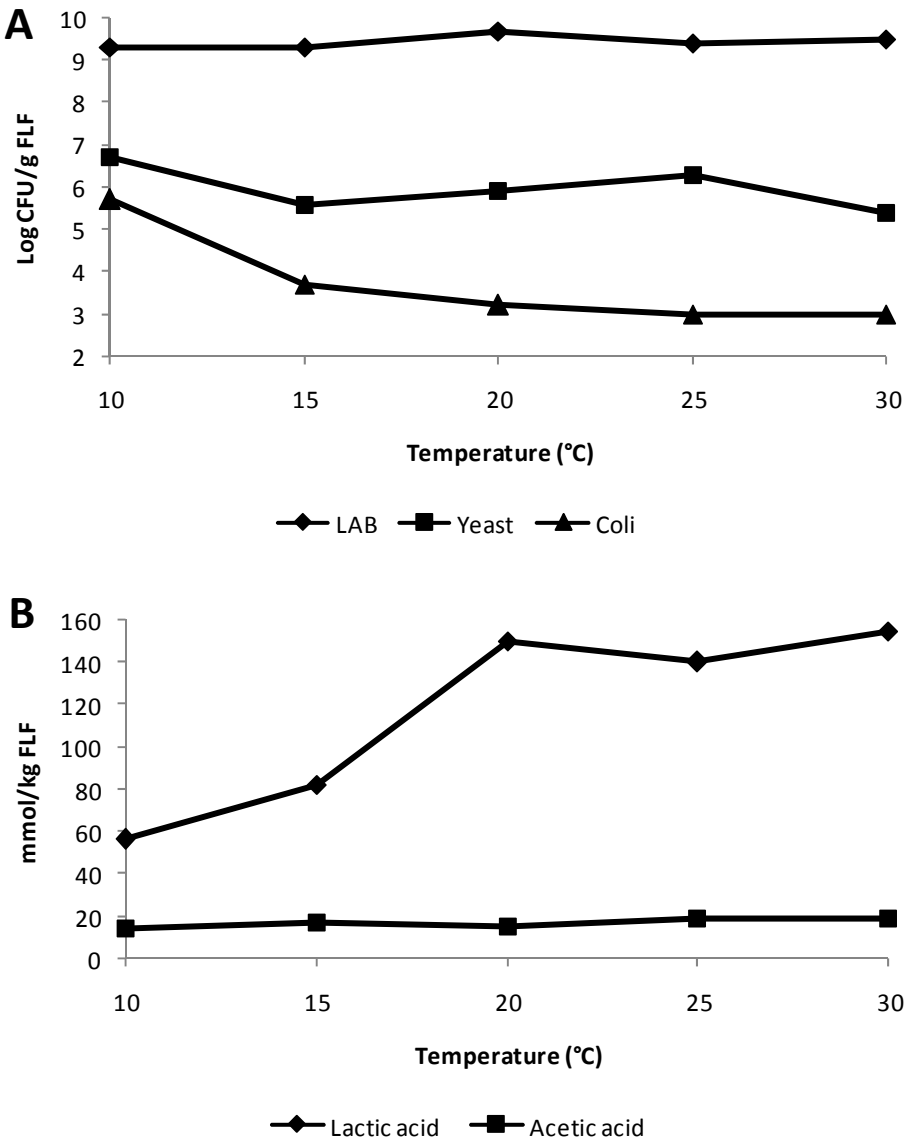

1001
1002 Figure 3. The effect of fermentation temperature on various bacterial populations
1003 [$\log_{10}$ CFU/g FLF] (A) and concentration of organic acids [mmol/kg FLF] (B) in FLF
1004 in steady state (n = 3). Redrafted after Jensen and Mikkelsen (1998)
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