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Nutritional strategies to optimize gut health and performance of weaned piglets

Part 1. Low crude protein diets, functional amino acids, and fiber

INTRODUCTION

Post-weaning diarrhea associated with enteric infections is a major cause of poor performance in weaned pigs. Multiple stressors, such as moving to a new environment, social fights, and change of diet, in combination with low feed intake during the first week after weaning promotes intestinal inflammation, which is often associated with imbalanced gut microbiota (dysbiosis) having increased proportion of pathogenic bacteria and reduction in beneficial bacteria (Gresse *et al.*, 2017).

Antimicrobial growth promoters (AGPs) and zinc oxide (ZnO) have been used in weaned pig diets to control the incidence of diarrhea; however, the use of in-feed AGPs has been banned in many countries due to human health concern associated with the increasing emergence of antimicrobial-resistant bacteria. Among various alternatives to AGPs, there are different nutritional strategies that need to be considered to minimize the risk of post-weaning diarrhea. Thus, the aim of this AMINONews review article is to briefly present in three parts the effects of different nutritional strategies. In the first part, low dietary crude protein (CP) level, levels of functional amino acids (AA), and different types of dietary fiber are addressed as nutritional strategies to improve gut health and performance of piglets. In the second chapter, supplementation of feed additives, such as probiotics and organic acids are covered, and the third chapter, the effects of combining some of these strategies on gut health, growth performance and nitrogen (N) utilization of weaned pigs are explored.

Gut health challenges of piglets at weaning

Weaning is a stressful process that consists of the separation of the piglets from their mothers. Under natural conditions this process occur at 17 weeks of age (Jensen and Recén, 1989), however, under commercial conditions, piglets are weaned around 3 or 4 weeks of age. This early weaning has disadvantages for the piglets, as for this early age, they still have an immature immune system, and an immature digestive capacity with a limited enzyme production in the gut (McCracken *et al.*, 1999; Lallès *et al.*, 2007).

After weaning, due to many stress factors, including the change from sow’s milk to solid feed, feed intake of piglets is usually reduced (Le Dividich and Sève, 2000), which strongly correlates with the risk of disease over the post-weaning period (Madec *et al.*,1998). This underfeeding causes intestinal inflammation and impairs gut morphology, increasing the amount of undigested feed in the large intestine, creating an ideal environment for the proliferation of pathogenic bacteria (Campbell *et al.*, 2013). During this period, there is a microbial dysbiosis, for example there is a proliferation of enterotoxigenic strains of Escherichia coli (ETEC; Konstantinov *et al.*, 2006), and a reduction of Lactobacillus sobrius, L. acidophilus, and L. reuteri (Konstantinov *et al.*, 2006; Lallès *et al.*, 2007). Thus, the dysbiosis coupled with the immature digestive system of weaned pigs can impair the barrier function of the small intestine and increase the incidence of diarrhea, reducing growth performance, increasing morbidity, or mortality of piglets (McCracken *et al.*, 1999; Lallès *et al.*, 2004; Konstantinov *et al.*, 2006).

The gut is an organ that plays an important role not only in digestion and absorption of nutrients but also as a protective barrier along and has immune mechanisms which can protect the animal from pathogens. It is important to keep in mind that inflammation of the gastrointestinal tract (GIT) results in immune activation, energy expenditures and compromised ability to digest and absorb nutrients (Willing *et al.*, 2012). Therefore, to maximize utilization of the feed, maintenance of gut health is important, which will lead to optimal growth performance.

Effects of low protein diets on gut health, immune status and diarrhea incidence

Diets fed to weaned pigs usually contain high CP levels because of a higher AA requirement (% of diet) and a lower capacity for feed intake compared with growing pigs. The disadvantage is that high CP diets have a high buffering capacity (Partanen and Mroz, 1999) which increases the gastric pH level. As a result, more hydrochloric acid (HCl) has to be produced in the stomach to lower the gastric pH and offset this high buffering capacity (Schutte, 2000). Compared with growing pigs, the digestive organs of weaned pigs are still immature and have an insufficient production of HCl to maintain a low pH level in the stomach (Prohaszka and Baron, 1980), resulting lower digestibility for protein and amino acids (Figure 1). Consequently, feeding high CP diets increases microbial fermentation of undigested dietary protein in the hindgut, promoting the growth of pathogenic bacteria, e.g. ETEC, which increases the incidence of post-weaning diarrhea (Ball and Aherne, 1987).

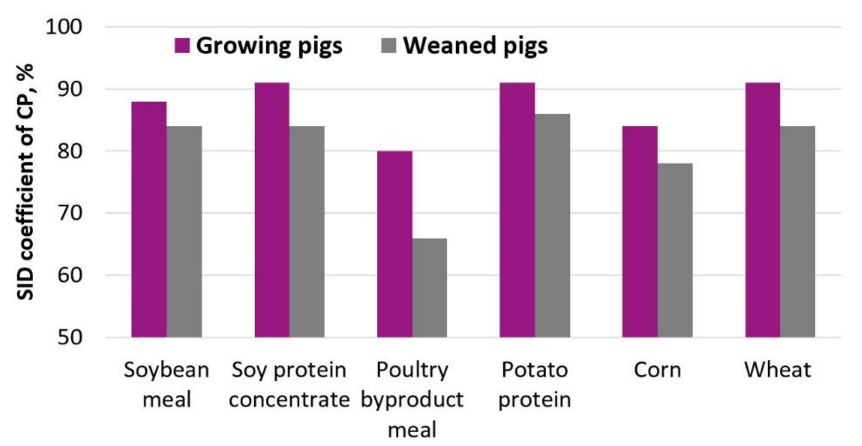


Figure 1: Standardized ileal digestibility of CP in selected ingredients for growing and weaned pigs (Swine SID Compendium 2018, Evonik Nutrition & Care GmbH)

The dietary CP level can affect the availability of substrate for fermentation and consequently, the composition and diversity of the gut microbiota. For example, Opapeju *et al.* (2009) reported a significantly lower population of *E. coli* K88$^+$ in the ileal digesta and a lesser prevalence of bacteria from the family *Clostridiaceae* and genus *Clostridium* but a greater prevalence of butyrate-producing bacteria *Lachnospiraceae* and genus *Roseburia* in the colon digesta of weaned pigs when fed with 17.6 % CP diet compared with 22.5 % CP diet. Similarly, Bhandari *et al.* (2010) observed a marked reduction in *E. coli* counts from ileal mucosa of weaned pigs subjected to an *E. coli* K88$^+$ challenge by reducing the dietary CP content from 22 to 17 %. Chen *et al.* (2018) evaluated the effect of dietary CP levels (12, 15 and 18 % CP) on intestinal health of growing pigs. Compared with 12 and 18 % CP, moderate CP reduction to 15 % while balancing for all AA optimized the microbial balance in the ileum of growing pigs by lowering the abundances of harmful bacteria *Streptococcaceae* and *Enterobacteriaceae* and increasing the proportion of beneficial *Lactobacillaceae* (Figure 2). Interestingly, a suboptimal supply of AA in 12 % CP diet, which was deficient in some essential AA, also had negative impact on intestinal microbial balance. These results suggest that low CP, AA-adequate diets can improve gut microbial balance which is essential for optimal gut health.

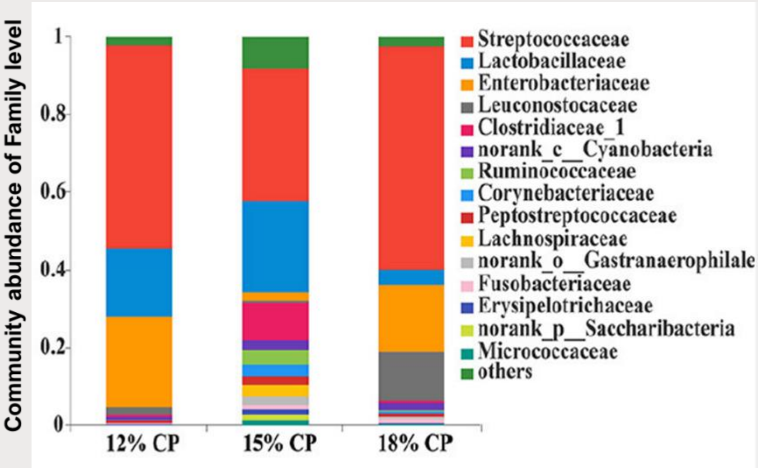


Figure 2: Effects of low-protein diets on the richness and composition of ileal microbiota in growing pigs (Chen *et al.*, 2018)

By regulating gut microbial composition, feeding low CP diets can reduce intestinal inflammation and maintain gut morphology and barrier function. Opapeju *et al.* (2008) reported that weaned pigs that were fed a low (17 %) CP diet had significantly reduced crypt depth in the small intestine than those fed a high (21 %) CP diet. In another study, weaned pigs fed a 17.6 % CP diet had a higher villus height and increased villus height:crypt depth ratio both before and after an ETEC K88 challenge compared with those fed a 22.5 % CP diet (Opapeju *et al.*, 2009; Figure 3). Similarly, lowering dietary CP from 23 to 17 % CP diets increased villus height and reduced crypt depth in the jejunum, which is an indication of improved gut integrity (Nyachoti *et al.*, 2006). When all AA were adequately balanced, feeding low CP diets did not decrease the activities of intestinal enzymes including sucrase, lactase, maltase, aminopeptidase (Bikker *et al.*, 2006; Opapeju *et al.*, 2009). However, the villus height of duodenum and jejunum, as well as the activities of lactase and sucrase in the jejunum were reduced when weaned pigs were fed an extremely low CP diet (6 %-units reduction) which was deficient in non-essential AA (Yue and Qiao, 2008; Peng *et al.*, 2016).

Feeding weaned pigs with a low (17.6 %) CP diet reduced inflammatory responses by lowering the serum concentrations of interleukin-1 beta and haptoglobin at 8 hours post-challenge with ETEC K88 compared with those fed a high (22.5 %) CP diet (Opapeju *et al.*, 2010). Houdijk *et al.* (2007) also reported that lowering dietary CP level from 22.8 to 13.7 % reduced plasma concentrations of haptoglobin and C-reactive protein in weaned pigs infected with ETEC. The results of Peng *et al.* (2016) showed that reducing dietary CP level from 20.0 to 15.3 % and balanced for all AA did not impair immunological parameters in weaned pigs.

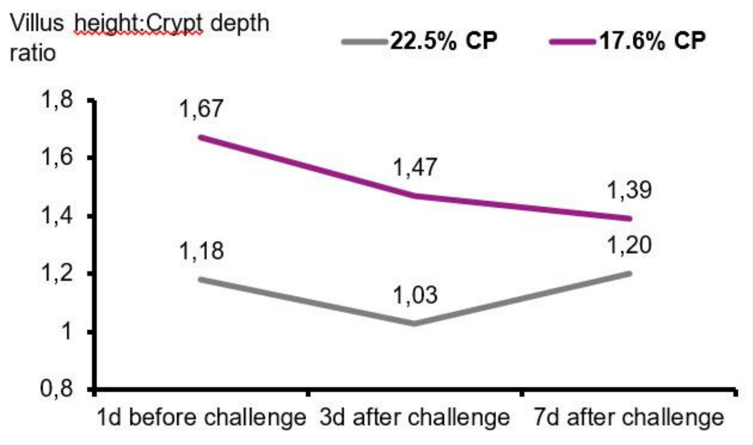


Figure 3: Lowering dietary CP increased villi height:crypt depth ratio of weaned pigs challenged with E. coli K88 (Opapeju *et al.*, 2009)

The main source of substrate for the proliferation of gut microbes comes from the feed. The advantage of feeding low CP diets is that it lowers the buffering capacity and directly reduces the amount of excess protein available for the proliferation of pathogenic bacteria, e.g. *E. coli*, and hence minimizes the fermentation and production of toxic substances, such as ammonia, amines and hydrogen sulfide (Ball and Aherne, 1987; Nyachoti *et al.*, 2006; Htoo *et al.*, 2007; Opapeju *et al.*, 2008), and consequently reduces the post-weaning diarrhea incidence in weaned pigs particularly when exposed to an ETEC or when fed AGP-free diets (Heo *et al.*, 2008, 2010; Kim *et al.*, 2011). A relatively short period of feeding a low CP (17.3 %) diet for 5 days after weaning was sufficient to decrease the incidence of post-weaning diarrhea (PWD) compared with those fed a high CP (24.3 %) diet (Heo *et al.*, 2008). The results of Heo (2010) clearly showed that the diarrhea incidence of weaned pigs can be reduced by feeding a low CP (19 %) diet compared with feeding a high CP (25 %) diet under both non-challenged and ETEC K88 challenged conditions (Figure 4). Post-weaning diarrhea becomes more challenging for the global swine industry after the ban of AGPs or ZnO as growth promoters. A trial conducted in China (Wu *et al.*, 2015) showed that feeding 21 to 35 day old weaned pigs with a low (17 %) CP diet resulted a higher performance and the lowest diarrhea incidence compared with those fed a high (19 or 23 %) CP diets when AGP was not used in all diets.

Overall, various studies have shown that feeding low CP diets regulates gut the microbiota by reducing the proliferation of pathogenic bacteria and toxic metabolites in the gut, maintaining gut morphology and consequently lowering post-weaning diarrhea in weaned pigs.

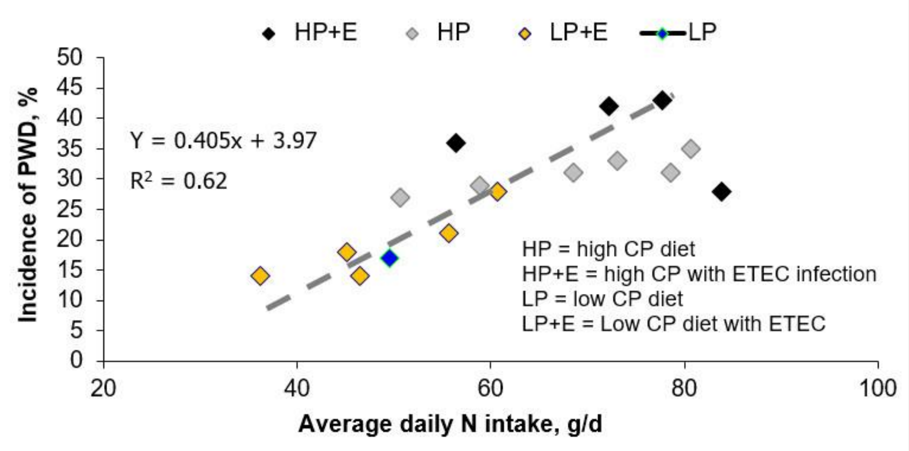


Figure 4: Effect of N intake (g/d) on the incidence of postweaning diarrhea (PWD) in weaned pigs (Adapted from Heo, 2010)

Effects of low CP diets on growth performance and N excretion

Numerous studies showed that lowering dietary CP level roughly by 4 %-units and adequately balancing all AA greatly increases N utilization efficiency without affecting performance of pigs of different body weight ranges (Htoo, 2017). In weaned pigs, Toledo *et al.* (2014) found that average daily gain (ADG) or feed conversion ratio (FCR) of 6 to 14 kg pigs was not affected by lowering the dietary CP level by 6 %-points when all essential amino acids (EAA) are well balanced. Similar positive results of low CP diets for 7 to 13 kg pigs were also reported (Heo *et al.*, 2010; Nemechek *et al.*, 2014). By balancing similar levels of EAA on standardized ileal digestible (SID) basis and net energy (NE) relative to the high CP diets, 4-6 %-points CP reduction was possible without affecting the performance of 8 to 17 kg pigs (Htoo *et al.*, 2007) and 12 to 27 kg pigs (Le Bellego and Noblet, 2002).

Table 1: Effect of dietary CP level on performance, nitrogen excretion, water intake and urine production of 12 to 27 kg nursery pigs (Le Bellego and Noblet, 2002)

	Dietary CP, %				Reduction
	22.4	20.4	18.4	16.9	22.4 vs. 16.9
Feed intake (g/d)	959a	1039b	1061b	1048b	
ADG (g/d)	642	661	690	663	
FCR	1.50	1.58	1.54	1.58	
N retention (g/d)	17.8	17.7	18.5	15.6	
Total N excretion (g/d)	10.7a	9.4a	6.8b	5.1c	- 52 %
Water consumption (g/d)	1941	1887	1867	1645	- 15 %
Urine excretion (g/d)	757	643	625	481	- 36 %

Diets were formulated to contain about 10.4 MJ NE/kg and 1.01 g SID Lys/MJ NE. Ratios of SID Thr, Met + Cys, Trp, Ile and Val were at least at 65, 60, 19, 60 and 70 % of SID Lys, respectively.
^{a,b,c} Different superscripts indicate significantly different means ($P < 0.05$).

Research has consistently showed that lowering the dietary CP levels, and balancing the AA profiles by supplementing the diet with crystalline AA, is a simple but effective way to reduce N excretion. Pigs fed low CP diets consumed less water, and excreted less urine and manure compared to animals fed high CP diets (Le Bellego and Noblet, 2002; Leek *et al.*, 2005). In 11 to 15 kg weaned pigs, the dietary CP level was reduced by 6 %-units without affecting N retained when the diets were balanced to meet optimal SID AA and NE (Toledo *et al.*, 2014; Le Bellego and Noblet, 2002). In a study by Le Bellego and Noblet (2002), feed intake of nursery pigs was lowest in pigs fed the diet with the highest CP compared to those fed the other diets (Table 1). This indicates that providing excess amount of protein bound AA could lead to imbalanced AA that may reduce feed intake in young animals (Henry, 1985). While growth performance and N retention were not affected, lowering the dietary the CP level from 22.4 to 16.9 % resulted a marked reduction of total N excretion (52 %), water consumption (15 %) and urine excretion (36 %), respectively, which is an effective solution to minimize the environmental impact. On average, a 1 %-unit CP reduction in pig diets contributes a roughly 9 % reduction in total N excretion, a 12 % reduction in ammonia emissions and a 2 % reduced need for drinking water (Canh *et al.*, 1998; Htoo, 2017), which all contribute towards sustainable pork production.

Effects of dietary amino acids levels on gut immune function

Under commercial conditions, pigs are usually exposed to a sub-clinical level of infection, which has an adverse effect on the immune system. Some AA are involved in metabolic pathways that have functions beyond growth that can help to improve immune and gut health status in pigs (Wu, 2010).

Threonine (Thr): is usually the second-limiting AA in typical swine diets and it is needed for synthesis of mucins, which are secreted along the epithelium of the GIT to help maintain intestinal integrity (Li *et al.*, 2007). Moreover, Thr also plays a key role in modulating the immune function through its incorporation into immunoglobulins. The need of Thr for synthesis of mucin proteins is increased when pigs are exposed to an immune challenge or fed high fiber diets. Recently, Wellington *et al.* (2019) reported that supplementing dietary Thr at 20 % above the NRC (2012) recommendation in growing pigs exposed to enteric challenge with *Salmonella typhimurium* and fed with low or high fiber diets resulted in an increased ADG by 14 %. Feeding Thr-deficient diets to piglets reduced intestinal mass, goblet cell numbers, mucin secretion, impaired gut intestinal morphology and increased the incidence of diarrhea (Hamard *et al.*, 2007; Law *et al.*, 2007), indicating a key role of Thr for gut health.

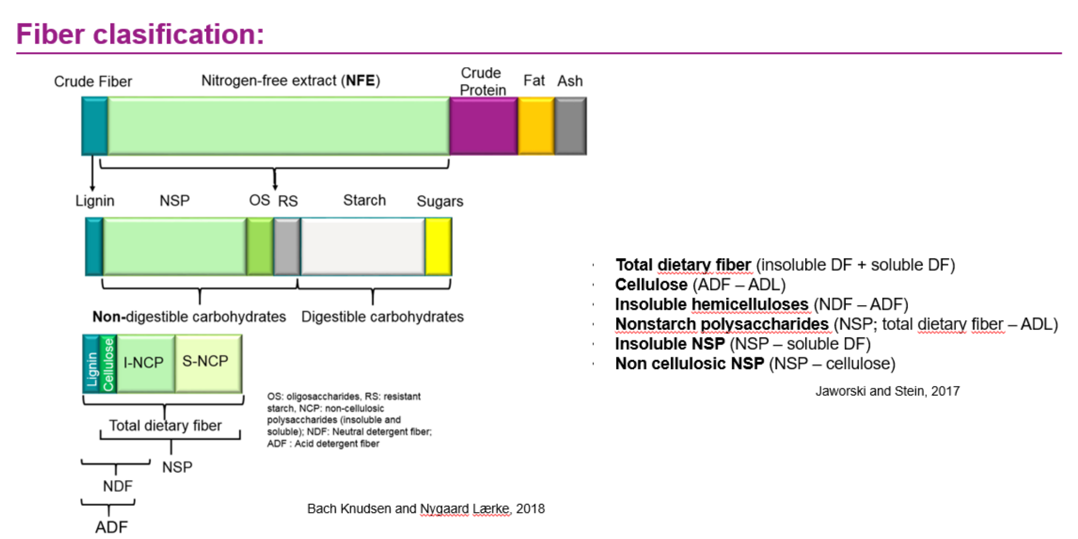
Methionine (Met): a sulfur-containing is usually the third limiting AA in typical swine diets. Met serves as a methyl donor for DNA methylation, is involved in the synthesis of glutathione (GSH), a major intracellular antioxidant, is involved in the activation of T-lymphocytes, cytokine production, and in scavenging free radicals and reactive oxygen species (Wu *et al.*, 2004; Lu, 2009). Zong *et al.* (2018) reported that dietary supplementation with DL-Met for a SID (Met + Cys):Lys ratio of 62 to 71 % improved growth performance and intestinal absorptive functions of

weaning piglets.
Research showed that an increased dietary supply of Met counteracts the detrimental effects of *E. coli* infection. For example, Capozzalo *et al.* (2017a) showed that increasing dietary SID (Met + Cys):Lys ratio from 55 % (NRC, 2012 recommendation) to 71 % increased ADG (365 to 428 g), G:F (0.71 to 0.77) and feed intake (503 to 554 g) of weaned pigs infected with ETEC K88 and fed AGP-free diets. Similarly, growth performance of *E. coli* challenged weaned pigs were optimized when the AGP-free diet contained 60 % SID Met+Cys:Lys and 24 % SID Trp:Lys ratio (Capozzalo *et al.*, 2017b).

Tryptophan (Trp): is typically the fourth limiting AA in swine diets and is needed for synthesis of serotonin, a neurotransmitter involved in regulation of feed intake and stress response behaviors. Furthermore, Trp is important for immune function modulation through the kynurenine pathway (Botting, 1995). Jayaraman *et al.* (2017) reported that increasing SID Trp:Lys ratio linearly decreased the mRNA expression of the pro-inflammatory cytokine TNF-α in the ileum of weaned pigs challenged with ETEC K88, and pig performance was optimized at SID Trp:Lys of 22.6 %. This was in line with Capozzalo *et al.* (2015), who reported that increasing the dietary SID Trp:Lys ratio to 24 % improved feed efficiency in *E. coli* challenged weaned pigs fed AGP-free diets. Recently, Rodrigues *et al.* (2021) evaluated the effect of dietary supply of Thr, Met and Trp at or 20 % above NRC requirement, at 2 CP levels (20 or 16 %) and in healthy weaned pigs or challenged with *Salmonella typhimurium.* Compared with healthy pigs, ADG of *Salmonella*-challenged pigs was reduced by 48 %, regardless of dietary CP level, when they were fed a diet containing Thr, Met and Trp at 100 % NRC requirement; however, the ADG of *Salmonella*-challenged pigs was reduced to a lesser extent only by 20 % when fed a diet containing Thr, Met and Trp at 120 % NRC requirement.These functional AA have positive effects on intestinal health and antioxidant defense systems, attenuating the impact of immune challenges. Overall, these results suggest that increased supply of key functional AA (Thr, Met, Trp) supports gut health and performance when pigs are under enteric challenges such as infection with *E. coli* or *Salmonella*.

Dietary fiber to optimize gut health

During recent years the interest in understanding the role of fiber in pigs has increased, not only because fibrous by-products are being included in diets but also because the advantage of fiber on gut functionality and microbiota balance has been reported. For a long time, fiber has been analytically referred to as crude fiber or as acid detergent fiber (ADF) and neutral detergent fiber (NDF), however, these fractions are not enough to understand the role fiber has on the digestive physiology and gut health of pigs (Wenk *et al.*, 2001; Chen *et al.*, 2013; 2014). During the few last years, progress has been made towards the differentiation and effects of soluble and insoluble dietary fiber in the pig.
Dietary fiber is defined as the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the small intestine with complete or partial fermentation in the large intestine (adapted from AACC, 2000). In figure 5, fiber classification is illustrated. Total dietary fiber (TDF) is part of the non-digestible carbohydrates, removing resistant starch and oligosaccharides, and it is basically the non-starch polysaccharides (NSP) plus the lignin fraction. The TDF can be divided into soluble (SDF) and insoluble dietary fiber (IDF). Some of the main characteristics of SDF are hydration properties (i.e. Water holding capacity), increased viscosity, transit time, and satiety; this type of fiber is mostly fermented before the colon, promoting growth of beneficial bacteria (Bach Knudsen, 2001; de Godoy *et al.*, 2013; Jaworski and Stein, 2017). Comparatively, IDF reduces transit time, increases fecal output, and is less fermentable than SDF, but most of the fermentation occurs in the colon (Bach Knudsen, 2001; Jaworski and Stein, 2017).



Fiber clasification:

OS: oligosaccharides, RS: resistant starch, NCP: non-cellulosic polysaccharides (insoluble and soluble); NDF: Neutral detergent fiber; ADF : Acid detergent fiber

Bach Knudsen and Nygaard Lærke, 2018

- **Total dietary fiber** (insoluble DF + soluble DF)
- **Cellulose** (ADF – ADL)
- **Insoluble hemicelluloses** (NDF – ADF)
- **Nonstarch polysaccharides** (NSP; total dietary fiber – ADL)
- **Insoluble NSP** (NSP – soluble DF)
- **Non cellulosic NSP** (NSP – cellulose)

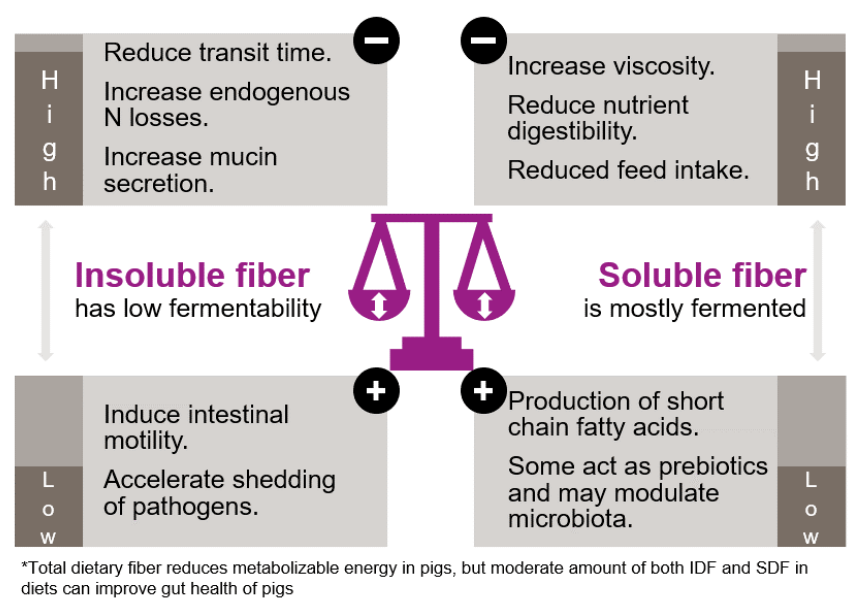
Jaworski and Stein, 2017

Figure 5: Fiber classification (adapted from Bach Knudsen and Nygaard Lærke, 2018)

There is a general understanding of the roles that dietary fiber play in the animal. For example, fiber increases large intestine weight (Hermes *et al.*, 2009; Jaworski *et al.*, 2016), increases pancreatic juice and enzyme production (Low, 1989), as well as increases N and AA endogenous losses from mucus production and sloughed off epithelial cells (Mosenthin *et al.*, 1994; Mariscal-Landin *et al.*, 1995; Leterme *et al.*, 1996; 1998), leading to an increase in some nutrient requirements, such as threonine (Mathai *et al.*, 2016). For a better understanding on the roles of fiber, however, it is more adequate to separate by the roles that insoluble and soluble fiber play in the animal, which are presented in Figure 6. Some studies have used the purified fiber sources such as cellulose and inulin, as a source of insoluble and soluble fiber, respectively, to elucidate the roles specifically on gut health. A recent study added 1 % cellulose, 1 % inulin, or a combination of both 0.5 % cellulose and 0.5 % inulin. It was reported that IDF increases the abundance of *Bacteroidetes* and *Euryarchaeota* compared to SDF, whereas SDF increases the abundance of *Proteobacteria* compared to IDF (Chen *et al.*, 2019). Changes in microbiota may explained by the increase in total short chain fatty acid (SCFA), propionate, and butyrate production with SDF compared to IDF (Chen *et al.*, 2019). In addition, an increase in the gene expression of intestinal tight junction proteins with SDF was observed compared to basal diet (Chen *et al.*, 2019).

This evolved into nutritional strategies that suggest including higher proportions of IDF during the first phase after weaning to reduce the risk of post-weaning diarrhea by accelerating the shedding of pathogenic bacteria, and adding more soluble fiber in the second phase to promote microbial fermentation and enhance gut integrity, with suggested ratios of 75:25 of IDF:SDF and 25:75 of IDF:SDF, respectively. Thus, in a separate study, it was compared IDF and SDF supplementation alone or in combinations of 75:25 (2 weeks) and 25:75 (2 weeks) or 50:50 (4 weeks) of IDF and SDF, respectively. (Chen *et al.*, 2020). An increase in feed efficiency and butyrate production was observed when SDF and IDF were included in combination rather than alone. Furthermore, the 50:50 (IDF: SDF) combination increased the gene expression of tight junction proteins and significantly reduced the incidence of diarrhea (Chen *et al.*, 2020).
Other studies use natural fiber sources rather than purified fiber sources, for example sugar beet pulp (44.6 % IDF and 4.0 % SDF) or wheat bran (48 % IDF and 2.9 % SDF), which results in the inclusion of different amounts of SDF and IDF at the same time. Adding sugar beet pulp up to 12 % or wheat bran up to 10 % improved gut morphology and gene expression of tight junctions, as well as modulated microbiota by increasing *Bifidobacterium* counts and reducing *E. coli* counts (Gebbink *et al.*, 1999; Schiavon *et al.*, 2004; Schedle *et al.*, 2008; Chen *et al.*, 2013; 2014). The response of wheat fiber was more favorable than feeding other sources of fiber such as soybean, pea, or corn fiber. In addition, a proper combination of SDF and IDF, feeding both 4 %

wheat bran and 3 % sugar beet pulp to weaned pigs, lead to a high production of butyrate with a further reduction of *Enterobacteria* counts (Molist *et al.*, 2009).



*Total dietary fiber reduces metabolizable energy in pigs, but moderate amount of both IDF and SDF in diets can improve gut health of pigs

Figure 6: Effects of insoluble and soluble dietary fiber in the animal at different inclusion levels

The site of production of SCFA in the GIT varies with type of fiber. Ingredients such as wheat middlings (38.1 % IDF and 1.6 % SDF) have a high fermentation in the ileum and cecum, and low fermentation in the colon, thus the SCFA production is higher in the upper than in the lower intestinal tract (Abelilla, 2018). Comparatively, ingredients rich in IDF such as soybean hulls (63.9 % IDF and 5 % SDF) are mostly fermented in the colon, which results in higher SCFA production in this region compared to the upper intestinal tract (Jaworski and Stein, 2017; Abelilla, 2018). This dynamic in fermentation of fiber has led to the development of further concepts such as fast or slow fermentable fiber and resistant to fermentation (Jaworski *et al.*, 2020). Fast-fermentable fiber stimulates the growth of beneficial bacteria, SCFA production, and reduces pH whereas slow fermentable fiber ferments in the large intestine, helping to reduce pH and reducing the negative effects of undigested N in the large intestine. Resistant fiber, which cannot be fermented, helps to promote intestinal motility, gut maturation, and fecal consistency.

Because quantitative amounts of IDF and SDF do not always reflect the degree of viscosity and/or the degree of fermentability, some studies address these characteristics specifically and classify them into low or high fermentability and low or high viscosity sources of fiber. Using purified fiber fractions to reach 5 % NSP in the diet, four diets with the four possible combinations were formulated to include: 5.20 % of cellulose (low-fermentability, low-viscosity), 6.25 % of carboxymethylcellulose (low-fermentability, high-viscosity), 8.95 % oat -glucan (OatVantage; high-fermentability, low-viscosity); or 9.25 % of oat -glucan (Viscofiber; high-fermentability, high-viscosity). The total SCFA, acetate, propionate, and butyrate production were increased with all sources of fiber, except with low fermentable and high viscous source of fiber (carboxymethylcellulose; Metzler-Zebeli *et al.*, 2010). In addition, fecal samples of pigs fed low fermentable and high viscous fiber diet had the highest levels of *Streptococcus* spp. and Enteroaggregative *E. coli* heat-stable enterotoxin 1 (EAST1; Metzler-Zebeli *et al.*, 2010). Thus, the degree of viscosity should be more considerate when formulating diets.

Resistant starch (RS) is a non-digestible carbohydrate, and although it is not part of TDF, it can be used as a strategy to promote gut health in pigs as well (Regassa *et al.*, 2018). Resistant starch influences microbial composition of pigs by promoting starch fermentation and increasing production of SCFA (Bhandari *et al.*, 2009; Haenen *et al.*, 2013; Fang *et al.*, 2014). Inclusion of 7 % RS as raw potato starch in piglet diets reduced fecal score, whereas including 14 % RS increased diarrhea and reduced microbiota diversity (Bhandari *et al.*, 2009). However, in growing-finishing diets, higher inclusion levels of RS up to 28 % from raw potato starch increased production of total SCFA, acetate, propionate, butyrate, isobutyrate, and isovalerate in colon, and increased mucosa thickness (Fang *et al.*, 2014). This better utilization of RS in older pigs may be due to a higher capacity for fermentation due to a more mature GIT.

In summary, the effects of SDF and IDF on the microbiota, SCFA production, and intestinal barrier function were easier to correlate and explain, indicating that these fractions may be more suitable to understand the effects of fiber in gut health of pigs (Chen *et al.*, 2019; 2020) than with crude fiber or ADF and NDF fractions (Chen *et al.*, 2013; 2014). A key component is the role that the microbiota has, as it has also been correlated to nutrient digestibility (Le Sciellour *et al.*, 2018). However, considering fermentability and viscosity of fiber improves the degree of understanding about the roles of fiber in the gut health of pigs. Finally, more research is needed towards the functions and modulation of microbiota and their importance not only in gut health but also in feed efficiency.

Conclusions

Weaning is a stressful period for piglets that causes negative effects in gut health and performance. Due to restriction of the use of antibiotics, new strategies need to be implemented to promote a good gut health status, which is important for optimal growth of weaned pigs. Implementation of low protein diets with an adequate balancing of functional AA, not only for growth but also for functional roles, mitigates the negative effects on gut health and growth performance under stress conditions. Fiber should not be ignored when formulating diets as it plays an important role in digestion of nutrients, microbiota balance, and gut development and integrity. However, a better understanding is needed due to interactions, as SDF and IDF are not present in pure form in common feed ingredients.

Reference

Abelilla, J. J. 2018. Fermentation and energetic value of fiber in feed ingredients and diet fed to pigs. PhD dissertation University of Illinois at Urbana-Champaign, USA.

Anonymous (American Association of Cereal Chemist- AACC). 2000. AACC holds midyear meeting. Cereal Foods World 45: 327.

Bach Knudsen, K. E. 2001. The nutritional significance of “dietary fibre” analysis. Anim Feed Sci Technol. 90:3–20.

Ball, R. O., and F. X. Aherne. 1987. Influence of dietary nutrient density, level of feed intake and weaning age on young pigs. 2. Apparent nutrient digestibility and incidence and severity of diarrhea. Can. J. Anim. Sci. 67: 1105-1115.

Bhandari, S. K., F. O. Opapeju, D. O. Krause, and C. M. Nyachoti. 2010. Dietary protein level and probiotic supplementation effects on piglet response to *Escherichia coli* K88 challenge: Performanc and gut microbial population. Livest. Sci. 133:185-188.

Bhandari, S. K., C. M. Nyachoti, D. O. Krause. 2009. Raw potato starch in weaned pig diets and its influence on postweaning scours and the molecular microbial ecology of the digestive tract, Journal of Animal Science, Volume 87, Issue 3, Pages 984–993, https://doi.org/10.2527/jas.2007-0747

Bikker, P., A. Dirkzwager, J. Fledderus, P. Trevisi, I. le Huerou-Luron, J. P. Lalles, and A. Awati. 2006. The effect of dietary protein and fermentable carbohydrates levels on growth performance and intestinal characteristics in newly weaned piglets. J. Anim. Sci. 84:3337–3345.

Botting, N. P. 1995. Chemistry and neurochemistry of the kynurenine pathway of tryptophan metabolism. Chemical Society Reviews 24:401-412.

Campbell JM, Crenshaw JD, Polo J. 2013. The biological stress of early weaned piglets. J Anim Sci Biotechnol. 4:19.

Canh, T. T, A. J. A Aarnink, J. B Schutte, A. Sutton, D. J Langhout, and M. W. A Verstegen. 1998. Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing–finishing pigs, Livest. Prod. Sci., 56(3): 181-191, ISSN 0301-6226, https://doi.org/10.1016/S0301-6226(98)00156-0.

Capozzalo M. M., J. C. Kim, J. K. Htoo, C. F. M. de Lange, B. P. Mullan, C. F. Hansen, J. W. Resink, P. A. Stumbles, D. J. Hampson, J. R. Pluske. 2015. Effect of increasing the dietary tryptophan to lysine ratio on plasma levels of tryptophan, kynurenine and urea and on production traits in weaner pigs experimentally infected with an enterotoxigenic strain of *Escherichia coli*. Arch. Anim. Nutr. 69(1):17-29.

Capozzalo, M., J. Pluske, J-W. Resink, J. C. Kim, J. Htoo, C. de Lange, C. F. Hansen, B. Mullan. 2017a. Determination of the optimum standardised ileal digestible sulphur amino acids to lysine ratio in weaned pigs challenged with enterotoxigenic Escherichia coli. Anim. Feed Sci. Technol. 227:118-130.

Capozzalo, M. M., J. C. Kim, J. K. Htoo, C. F. M. de Lange, B. P. Mullan, C. F. Hansen, J. W. Resink, and J. R. Pluske. 2017b. Pigs experimentally infected with an enterotoxigenic strain of *Escherichia coli* have improved feed efficiency and indicators of inflammation with dietary supplementation of tryptophan and methionine in the immediate post-weaning period. Animal Production Science. 57:935-947.

Chen, H., Mao, X., He, J., Yu, B., Huang, Z., Yu, J., Zheng, P., and D. Chen. 2013. Dietary fibre affects intestinal mucosal barrier function and regulates intestinal bacteria in weaning piglets. The British journal of nutrition, 110(10), 1837–1848. https://doi.org/10.1017/S0007114513001293

Chen, H., X. B. Mao, L. Q. Che, B. Yu, J. He, J. Yu, G. Q. Han, Z. Q. Huang, P. Zheng, and D.W. Chen. 2014.Impact of fiber types on gut microbiota, gut environment and gut function in fattening pigs, Animal Feed Science and Technology, Volume 195. Pages 101-111, ISSN 0377-8401, https://doi.org/10.1016/j.anifeedsci.2014.06.002.

Chen X, Song P, Fan P, He T, Jacobs D, Levesque CL, Johnston LJ, Ji L, Ma N, Chen Y, Zhang J, Zhao J, and X. Ma. 2018. Moderate dietary protein restriction optimized gut microbiota and mucosal barrier in growing pig model. Front Cell Infect Microbiol. 18 (8):246.

Chen, T., D. Chen, G. Tian, P. Zheng, X. Mao, J. Yu, J. He, Z. Huang, Y. Luo, J. Luo, and B. Yu. 2019. Soluble Fiber and Insoluble Fiber Regulate Colonic Microbiota and Barrier Function in a Piglet Model. BioMed Research International Volume 2019, Article ID 7809171, 12 pages https://doi.org/10.1155/2019/7809171

Chen, T., D. Chen, G. Tian, P. Zheng, X. Mao, J. Yu, J. He, Z. Huang, Y. Luo, J. Luo, B. Yu. 2020. Effects of soluble and insoluble dietary fiber supplementation on growth performance, nutrient digestibility, intestinal microbe and barrier function in weaning piglet. Animal Feed Science and Technology, 260:114335, ISSN 0377-8401, https://doi.org/10.1016/j.anifeedsci.2019.114335.

de Godoy, M. R. C., K. R. Kerr, and G. C. Fahey, Jr. 2013. Alternative dietary fiber sources in companion animal nutrition. Nutrients 5:3099-3117.

Fang L, Jiang X, Su Y, Zhu W. 2014. Long-term intake of raw potato starch decreases back fat thickness and dressing percentage but has no effect on the longissimus muscle quality of growingefinishing pigs. Livest Sci.170:116e23.

Gebbink, G., A. Sutton, B. Richert, J. Patterson, J. Nielsen, D. Kelly, M. Verstegen, B. Williams, M. Bosch, M. Cobb, D. Kendall, and S. DeCamp. 1999. Effects of Addition of Fructooligosaccharide (FOS) and Sugar Beet Pulp to Weanling Pig Diets on Performance, Microflora and Intestinal Health. Acess.. 12.

Gresse, R., F. Chaucheyras-Durand, M. A. Fleury, T. Van de Wiele, E. Forano and S. Blanquet-Diot. 2017. Gut Microbiota Dysbiosis in Postweaning Piglets: Understanding the Keys to Health.Trends in Microbiology, 25:10:851-873.

Haenen D, Zhang J, da Silva CS, Bosch G, van der Meer Ingrid M, *et al.* A diet high in resistant starch modulates microbiota composition, SCFA concentrations, and gene expression in pig intestine. J Nutr 2013;143:274e83.

Hamard, A., B. Sève and N. Le Floch. 2007. Intestinal development and growth performance of early-weaned piglets fed a low-threonine diet. Animal 1: 1134-1142.

Henry, Y. 1985. Dietary factors involved in feed intake regulation in growing pigs: A review. Livest. Prod. Sci. 12: 339-354.

Heo, J-M. J-C. Kim, C. Fink Hansen, B. P. Mullan, . J. Hampson and J. R. Pluske. 2008. Effects of feeding low protein diets to piglets on plasma urea nitrogen, faecal ammonia nitrogen, the incidence of diarrhoea and performance after weaning. Archives of Animal Nutrition 62 (5): 343–358.

Heo, J. M., J. C. Kim, C. F. Hansen, B. P. Mullan, D. J. Hampson, J. R. Pluske. 2010. Feeding a diet with a decreased protein content reduces both nitrogen content in the gastrointestinal tract and post-weaning diarrhoea, but does not affect apparent nitrogen digestibility in weaner pigs challenged with an enterotoxigenic strain of Escherichia coli. Animal Feed Science and Technology 160: 148-159.

Heo, J. M. 2010. Reducing the protein content in diets for weaner pigs to control post-weaning diarrhea: Physiological and metabolic responses of the gastrointestinal tract. PhD thesis. Murdoch University, Australia.

Hermes, R. G., F.Molist, M. Ywazaki, M. Nofrarías, A. Gomez de Segura, J. Gasa, and J. F. Pérez. 2009. Effect of dietary level of protein and fiber on the productive performance and health status of piglets. J Anim Sci. 87(11):3569-77. doi: 10.2527/jas.2008-1241.

Houdijk, J. G. M., F. M. Campbell, P. D. Fortomaris, P. D. Eckersall, and I. Kyriazakis. 2007. Effects of subclinical post-weaning colibacillosis and dietary protein on acute phase proteins in weaner pigs. Livest. Sci. 108:182-185.

Htoo, J. K., B. A. Araiza, W. C. Sauer, M. Rademacher, Y. Zhang, M. Cervantes and R. T. Zijlstra. 2007. Effect of dietary protein content on ileal amino acid digestibility, growth performance, and formation of microbial metabolites in ileal and cecal digesta of early-weaned pigs. J. Anim. Sci. 85: 3303-3312.

Htoo, J. 2017. The potential for feeding low crude protein-amino acid supplemented diets to starter and growing-finishing pigs. AMINONews No. 1, Vol. 21. Evonik Nutrition & Care GmbH.

Jayaraman, B., J. K. Htoo and C. M. Nyachoti. 2015. Effects of dietary threonine:lysine ratio and sanitary conditions on performance, plasma urea nitrogen, plasma-free threonine and lysine of weaned pigs. Animal Nutrition 1:283-288.

Jayaraman, B., A. Regassa., J. K. Htoo and C. M. Nyachoti. 2017. Effects of dietary

standardized ileal digestible tryptophan:lysine ratio on performance, plasma urea

nitrogen, ileal histomorphology and immune responses in weaned pigs challenged with Escherichia coli K88. Livest. Sci. 203:114-119.

Jaworski, N. W. 2016. Utilization of energy in high-fiber diets fed to pigs. PhD dissertation. University of Illinois at Urbana-Champaign, USA.

Jaworski, N. W., T. Faber, and F. Madsen. 2020. Deciphering the dietary fiber message. Trouw nutrition press release.

Jaworski, N. W., and H. H. Stein. 2017. Disappearance of nutrients and energy in the stomach and small intestine, cecum, and colon of pigs fed corn-soybean meal diets containing distillers dried grains with solubles, wheat middlings, or soybean hulls. J. Anim. Sci. 95:727-739. doi:10.2527/jas.2016.0752

Jensen P and B. Recén.. 1989. When to wean – observations from free-ranging domestic pigs. Applied Animal Behaviour Science 23, 49–60.

Kim, J. C., J.M. Heo, B.P. Mullan and J.R. Pluske. 2011. Efficacy of a reduced protein diet on clinical expression of post-weaning diarrhoea and life-time performance after experimental challenge with an enterotoxigenic strain of Escherichia coli. Animal Feed Science and Technology 170:222– 230.

Konstantinov, S. R., E. Poznanski, S. Fuentes, A. D. Akkermans, H. Smidt H, and W. M. de Vos. 2006. Lactobacillus sobrius sp. nov., abundant in the intestine of weaning piglets. Int J Syst Evol Microbiol. 56(Pt 1):29-32. doi: 10.1099/ijs.0.63508-0. PMID: 16403862.

Lallès, J-P., P. Bosi, H. Smidt, and C. R. Stokes. 2007. Weaning – A challenge to gut physiologists. Livest. Sci. 108, 82-93.

Law, G. K., R. F. Bertolo, A. Adjiri-Awere, P. B. Pencharz and R. O. Ball. 2007. Adequate oral threonine is critical for mucin production and gut function in neonatal piglets. American Journal of Physiology-Gastrointestinal and Liver Physiology 292: G1293-G1301.

Le Bellego, L. and J. Noblet. 2002. Performance and utilization of dietary energy and amino acids in piglets fed low protein diets. Livest. Prod. Sci. 76: 45-58.

Le Dividich J, and B. Sève. 2000. Effects of underfeeding during the weaning period on growth, metabolism, and hormonal adjustments in the piglet. Domest Anim Endocrinol. 19:63–74.

Le Sciellour, M., Labussière, E., Zemb, O., and D. Renaudeau. 2018. Effect of dietary fiber content on nutrient digestibility and fecal microbiota composition in growing-finishing pigs. PloS one, 13(10), e0206159. https://doi.org/10.1371/journal.pone.0206159

Leterme, P., van Leeuwen, P., Théwis, A., J. Huisman. 1996. Chemical composition of pea inner fibre isolates and their effect on the endogenous digestive secretions in pigs. J. Sci. Food Agric. 72 ,127-134.

Leterme, P., Froidmont, E., Rossi, F., A., Théwis. 1998. The high water-holding capacity of pea inner fibres affects the ileal flow of endogenous amino acids in pigs. J. Agric. Food Chem. 46 ,1927-1934.

Li, P., Y-L. Yin, D. Li, S. W. Kim, and G. Wu. 2007. Amino acids and immune function. British Journal of Nutrition 98:237-252.

Low., A. G. 1989. Secretory response of the pig gut to non-starch polysaccharides. Anim. Feed Sci. Technol. 23:55-65.

Lu, S. C. 2009. Regulation of glutathione synthesis. Molecular Aspects of Medicine 30:42-59.

Madec F, Bridoux N, Bounaix S, and A. Jestin. 1998. Measurement of digestive disorders in the piglet at weaning and related risk factors. Prev Vet Med. 35:53–72.

Mariscal-Landín, G., B. Sève, Y. Colléaux, and Y. Lebreton. 1995. Endogenous amino nitrogen collected from pigs with end-to-end ileorectal anastomosis is affected by the method of estimation and altered by dietary fiber. J. Nutr. 125:136-146.

Mathai, J. K., J. K. Htoo, J. E. Thomson, K. J. Touchette, and H. H. Stein. 2016. Effects of dietary fiber on the ideal standardized ileal digestible threonine:lysine ratio for twenty-five to fifty kilogram growing gilts. J Anim Sci. 94(10):4217-4230. doi: 10.2527/jas.2016-0680.

McCracken, B. A., M. E. Spurlock, M. A. Roos, F. A. Zuckermann, and H. R. Gaskins. 1999. Weaning anorexia may contribute to local inflammation in the piglet small intestine. J. Nutr. 129, 613-619.

Metzler-Zebeli, B. U., Hooda, S., Pieper, R., Zijlstra, R. T., van Kessel, A. G., Mosenthin, R., and M. G. Gänzle., 2010. Nonstarch polysaccharides modulate bacterial microbiota, pathways for butyrate production, and abundance of pathogenic Escherichia coli in the pig gastrointestinal tract. Applied and environmental microbiology, 76(11), 3692–3701. https://doi.org/10.1128/AEM.00257-10

Molist, F., A. Gomez de Seguraa, J. Gasaa, R. G. Hermesa, E. G. Manzanillab, M. Anguitaa, and J. F. Perez. 2009. Effects of the insoluble and soluble dietary fibre on the physicochemical properties of digesta and the microbial activity in early weaned piglets. Animal Feed Science and Technology 149: 346–353.

Mosenthin R, Sauer WC, and F. Ahrens. 1994. Dietary pectin's effect on ileal and fecal amino acid digestibility and exocrine pancreatic secretions in growing pigs. J Nutr. 124(8):1222-9. doi: 10.1093/jn/124.8.1222.

Nemechek, J. E., M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. M. DeRouchey. 2014. Evaluation of standardized ileal digestible valine:lysine, total lysine:crude protein, and replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline amino acids on growth performance of nursery pigs from seven to twelve kilograms. Journal of Animal Science 92:1548-1561.

NRC. 2012. Nutrient Requirements of Swine. 11th ed., Washington D.C. USA.

Nyachoti, C. M., F. O. Omogbenigun, M. Rademacher, and G. Blank. 2006. Performance responses and indicators of gastrointestinal health in early-weaned pigs fed low-protein amino acid-supplemented diets. J. Anim. Sci. 84:125-134.

Opapeju, F. O., M. Rademacher, G. Blank, and C. M. Nyachoti. 2008. Effect of low protein amino acid-supplemented diets on growth performance, gut morphology, organ weights, and digesta characteristics of weaned pigs. Animal 2:1457–1464.

Opapeju, F. O., D. O. Krause, R. L. Payne, M. Rademacher, and C. M. Nyachoti. 2009. Effect of dietary protein level on growth performance, indicators of enteric health, and gastrointestinal microbial ecology of weaned pigs induced with postweaning colibacillosis. J. Anim. Sci. 2009. 87:2635-2643.

Opapeju, F. O., M. Rademacher, R. L. Payne, D. O. Krause, and C. M. Nyachoti. 2010. Inflammation associated responses in piglets induced with postweaning colibacillosis are influenced by dietary protein level. Livest. Sci. 131:58-64.

Partanen, K. H., and Z. Mroz. 1999. Organic acids for performance enhancement in pig diets. Nutrition Research Reviews. 12: 117-145.

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