

Alternatives to antibiotic growth promoters in prevention of diarrhoea in weaned piglets: a review

H. VONDRUSKOVA, R. SLAMOVA, M. TRCKOVA, Z. ZRALY, I. PAVLIK

Veterinary Research Institute, Brno, Czech Republic

ABSTRACT: The weaning time is a crucial period in the management of piglets. The risk of development of post-weaning diarrhoea (PWD) in piglets is high. PWD is the cause of serious economic losses in pig herds. Since 2006, the use of antibiotic growth promoters for prevention of diarrhoeal diseases in piglets has been banned. This measure also led to the investigation of alternative suitable feed supplements that would be reasonably efficient in protecting and sustaining animal health and performance. Various natural materials such as probiotics, prebiotics, organic acids, zinc and plant extracts have been tested as effective alternatives to antibiotics. Recently, owing to their high adsorption capacity, research efforts have been conducted on the application of natural clays and clay-based feed supplements. The purpose of this review is to summarize the effect of different alternative components as growth promoters on the health and performance of weaned and growing piglets.

Keywords: infection; swine; antibiotics; intestinal microflora; performance; probiotics; prebiotics, organic acids; zinc; phytobiotics; aluminosilicate

List of abbreviations

CFU = colony-forming unit; ETEC = enterotoxigenic *Escherichia coli*; MMT = montmorillonite; PWD = post weaning diarrhoea; SCFA = short chain fatty acids; VFA = volatile fatty acids

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1. Introduction

Postweaning diarrhoea (PWD) is one of the most frequent causes of heavy economic losses in pig herds. PWD can be caused by a number of causative

agents. The major bacteria which cause diarrhoea are *Escherichia coli* and members of the genera *Clostridium*, *Lawsonia* and *Brachyspira*. Regarding viral agents, rotaviruses (Bertschinger, 1999; Jung et al., 2006a,b; Thomsson et al., 2008), coronavi-

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ruses (Moller et al., 1998; Song et al., 2006), transmissible gastroenteritis virus (Hampson et al., 1987; Alexa et al., 1995, 2001; Chae et al., 2000; Madec et al., 2000; Melin et al., 2004; Song et al., 2006; Thomsson et al., 2008) and others have been most frequently diagnosed.

Early-weaned piglets are exposed to several stress factors, with nutrition, etiology and indoor environment of housing being particularly implicated (Madec et al., 2000; Laine et al., 2008). Non-infectious stress factors which are involved in the development of gastroenteric disorders are:

- age of piglets when they are weaned from their dam (Svensmark et al., 1989; Skirrow et al., 1997),
- sudden change of feed from sow milk that provides piglets with immunoglobulins (Bailey et al., 1992),
- irregular feed intake (Bark et al., 1986; Spencer and Howell, 1989; Svensmark et al., 1989; Madec et al., 1998; Laine et al., 2008),
- feed structure (Amezcuca et al., 2002),
- animal hygiene and housing conditions (Le Dividich, 1981; Le Dividich and Herpin, 1994; Madec et al., 1998),
- inadequate feeder space per piglet in the pen (Amezcuca et al., 2002).

Numerous changes in the early-weaned piglet body can initiate PWD, such as morphological (Hampson, 1986) and functional alterations of the small intestine (Kidder and Manners, 1980; Hampson and Kidder, 1986), changes in intestinal colonization with predominance of *E. coli* (Melin et al., 1997; Katouli et al., 1999) and weakening of the immune system (Blecha et al., 1983; Watrang et al., 1998).

2. Ban of antibiotic growth promoters

Regarding the fact that weaning greatly affects general health condition of piglets, it is necessary to stimulate the indigenous intestinal microflora and keep it well-balanced because it provides protection to animals against invasion by pathogenic microorganisms (Jensen, 1998; Katouli et al., 1999). Before 2006, health strategies widely used antibiotic growth promoters to reduce enteric infections and the occurrence of pathogens able to adhere to intestinal mucosa (Barton, 2000; Budino et al., 2005). These are added to feed for piglets from birth to weaning with the aim of improving the compo-

sition of intestinal microflora in piglets and thus ameliorate the potential consequences of PWD (Sorensen et al., 2009).

The increased use of antibiotics has given rise to a fear of the development of resistant pathogenic bacterial strains (Wegener et al., 1998; Kyriakis et al., 1999; Budino et al., 2005) and residual contamination of the food chain with antibiotics (Chen et al., 2005; Roselli et al., 2005). This has led to the adoption of safety measures and a gradual withdrawal of antibiotic promoters from pig diets. In 2006, the use of antibiotics as growth promoters was forbidden in the EU (Castro, 2005; Chen et al., 2005).

Due to the fact that the use of antibiotics as growth promoters has been banned and that the expansion of this policy to other countries can now be expected, intensive research has focused on the development of alternative strategies with the aim of maintenance of animal health and performance (He et al., 2002; Castro, 2005; Chen et al., 2005; Bomba et al., 2006; Castillo et al., 2008). Various natural materials, many of which are commercially available, have been investigated as efficient alternatives to antibiotic growth promoters. At present, probiotics, prebiotics, organic acids, enzymes, phytobiotics, clay adsorbents and others are under investigation. These materials can exert beneficial effects on the microflora composition and consequently affect animal health and growth performance.

3. Intestinal microflora in piglets

Intestinal microflora contains high numbers of various species of bacteria involved in the process of digestion. Microbial composition is determined by mutual interactions between the host and the microorganisms, and also among different microorganisms. These factors are designated as autogenic (Fuller et al., 1978; Jensen, 1998; Budino et al., 2005). On the other hand, pH in the stomach, digestive enzymes, intestinal peristalsis, nutrients and immunity of the host are termed allogenic factors (Jensen, 1998; Budino et al., 2005; Roselli et al., 2005). The predominance of beneficial species of microorganisms over pathogens is essential for stability of the immune system of the intestines and consequently of the entire body (Apgar et al., 1993; Makala et al., 2000; Mikkelsen et al., 2003).

Enteric bacteria constitute a wide range of mostly strictly anaerobic or facultatively anaerobic spe-

cies with counts giving an estimate of 10^{11} to 10^{14} CFU/g of digesta (Ghnassia, 1979; Makala et al., 2000). Ducluzeau (1983) reported that numbers of microorganisms can reach values of between 10^8 and 10^9 CFU/g of faeces already 10 to 12 h after the birth of piglets and that their numbers stabilize within 24 to 48 hours after birth. However, the composition of microflora is not definitive. It develops gradually and numerous changes occur during weaning (Rojas and Conway, 1996; Mikkelsen, 2003; Roselli et al., 2005).

The highest number of microorganisms is found in the caudal part of the intestines (Table 1), where around 500 different species of microorganisms have been described and identified to date (Rojas and Conway, 1996; Budino et al., 2005). In a well-balanced microbial environment, members of the following genera prevail: *Streptococcus*, *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, *Eubacterium*, *Fusobacterium*, *Peptostreptococcus*, *Enterobacter*, *Bacteroides*, *Porphyromona*, while the numbers of coliform bacteria *E. coli* and *Clostridium* sp. are lower (Fuller et al., 1978; Maxwell et al., 2004; Stokes et al., 2004; Budino et al., 2005; Pasca et al., 2009). Due to a relatively high pH value in the stomach, members of the genus *Lactobacillus* are more commonly found in the non-secretory part of the stomach, from which they further spread to the small intestine (McAllister et al., 1979; Rojas and Conway, 1996).

Anaerobic conditions, favourable temperature, pH and slow passage of the digesta are the pre-conditions for the presence of large numbers of bacteria in the large intestine and caecum, up to 10^{10} CFU/g (Kidder and Manners, 1980; Ambroz, 1981; Mikkelsen et al., 2003). In the caecum Gram-negative bacteria predominate, whilst these are outnumbered by Gram-positive bacteria in the colon (Robinson et al., 1981; Rojas and Conway, 1996; Mikkelsen et al., 2003).

Intestinal microorganisms participate in various physiological functions, by which they influence their hosts (Jensen, 1998). Protection against pathogenic and conditionally pathogenic microorganisms in the form of colonization resistance is most important (Gedek, 1992a; Jin et al., 1997; Roselli et al., 2005). Natural intestinal microflora adhere to intestinal mucosa and inhibit colonization by pathogens. This inhibition effect is caused by competition for nutrients and binding sites, bacteriocin production, lactobacilli fermentations and short chain fatty acid production (Teitelbaum and Walker, 2002; Roselli et al., 2005). Subsequently, immunological memory is created and intestinal immunity develops (Jin et al., 1997; Makala et al., 2000; Stokes et al., 2004).

Even though avirulent strains of *E. coli* are a common constituent of intestinal microflora, pathogenic strains of the same bacteria are the most frequent causes of PWD in piglets (Madej et al., 1999; Madec et al., 2000; Melin et al., 2004). The acquiring of virulence factors happens by the enrichment of some *E. coli* strains through special mobile genes and with the joint influence of bacteriophages or plasmids. Mobile genes are localized in pathogenicity islands. Pathogenic strains are endowed with at least six virulence factors: shiga toxin, adhesion factor intimin, hemolysin, serin protease, thermostable enterotoxin and special katalase system (Alexa et al., 2001; Hayashi et al., 2001; Sousa, 2006).

4. Improvement of intestinal microflora

The health of organisms largely depends on the composition of the intestinal microflora. Its composition and function can be beneficially influenced by many factors. These factors can be significantly supported by probiotics, prebiotics, organic acids, zinc oxide and plant extracts.

Table 1. Comparison of microflora in the stomach, small and large intestines (CFU \log_{10} /g chyme; Fuller, 1989; Rojas and Conway, 1996; Stokes et al., 2004)

Microorganisms	Microflora in the stomach	Microflora in the small intestine		Microflora in the large intestine	
		proximal	caudal	caecum	colon
Total count	5.5–9.5	5.5–8.5	5.5–9.5	8.5–9.5	8.0–10.0
<i>Lactobacillus</i>	5.0–9.0	5.5–8.5	6.0–9.5	8.0–9.5	7.5–9.5
<i>Streptococcus</i>	4.0–7.0	4.0–6.5	5.0–7.5	7.5	6.0–8.0
<i>Bifidobacterium</i>	4.5–6.5	4.0–5.5	5.5–7.5	5.0–8.0	5.5–8.5

4.1. Probiotics

Probiotics are live microbial feed supplements which beneficially affect the host by improving its intestinal microbiocenosis. Probable mechanisms of action of probiotics are based on the following:

- competition between them and pathogenic microorganisms for binding sites in the intestinal mucosa (Fuller, 1989; Sissons, 1989; Bomba et al., 2002),
- nutrient availability (Guerra et al., 1997; Bomba et al., 2002)
- total inhibition of pathogen growth by production of organic acids and antibiotic-like compounds (MantereAlhonen, 1995; Guerra et al., 1997; Zimmermann et al., 2001; Bomba et al., 2002; Marinho et al., 2007).

Probiotics are mainly active in the caudal segments of the ileum, in the caecum and the ascending colon. Probiotics influence the digestive process in the body by increasing the activity of microbial probiotic enzymes and the digestibility of food (Roselli et al., 2005). They stimulate the immune system and the regeneration of intestinal mucosa. They can elicit an increase in immunoglobulin a production (Perdigon et al., 1995) and stimulate macrophages and NK cells (natural killers cells; Chiang et al., 2000; Matsuzaki and Chin, 2000). They can also regulate anti- and pro-inflammatory cytokine production (Lessard and Brisson, 1987; Shu et al., 2001; Roselli et al., 2005).

The effect of probiotics depends on the combination of selected bacterial genera (Table 2), their doses, and on the interactions of probiotics with some pharmaceuticals, feed composition, storage conditions and feed technology (Kyriakis et al., 1999; Park et al., 2001; Chen et al., 2005). Probiotic application to piglets is important especially in the post-weaning period for the prophylaxis of PWD which is usually caused by enterotoxigenic *E. coli* strains (MantereAlhonen, 1995; Roberfroid, 1998; Bomba et al., 2002; Roselli et al., 2005; Marinho et al., 2007).

Multiple studies have confirmed the stimulating effects of probiotics on the intestinal environment (Barrow et al., 1977; Roth et al., 1992b; Depta et al., 1998; Mathew et al., 1998; Jadamus et al., 2001; Scharek et al., 2005, 2007; Reiter et al., 2006; Lodemann et al., 2008). By lowering the pH value in the small intestine and producing organic acids and antibacterial substances probiotic supplements

Table 2. Microorganisms used as probiotics (Kumprecht et al., 1994; Fooks and Gibson, 2002; Ouwehand et al., 2002; Lodemann et al., 2006)

Genus	Bacterial species
<i>Lactobacillus</i>	<i>L. acidophilus</i>
	<i>L. casei</i>
	<i>L. rhamnosus</i>
	<i>L. reuteri</i>
	<i>L. plantarum</i>
	<i>L. fermentum</i>
	<i>L. brevis</i>
<i>Lactococcus</i>	<i>L. lactis</i>
	<i>E. faecium</i>
	<i>S. thermophilus</i>
<i>Streptococcus</i>	<i>P. pentosaceus</i>
<i>Bacillus</i>	<i>B. subtilis</i>
	<i>B. cereus</i>
	<i>B. toyoi</i>
	<i>B. natto</i>
	<i>B. mesentericus</i>
	<i>B. licheniformis</i>
<i>Bifidobacterium</i>	<i>B. bifidum</i>
	<i>B. pseudolongum</i>
	<i>B. breve</i>
<i>Saccharomyces</i>	<i>B. thermophilum</i>
	<i>S. cerevisiae</i>
Avirulent <i>Escherichia coli</i>	<i>E. coli</i>

inhibit pathogenic microorganisms, improve the intestinal microflora and stimulate immune function (Kumprecht et al., 1994; MantereAlhonen, 1995; Marinho, 2007).

Intestinal microflora can be modulated by the supplementation of feeds with probiotic bacterial species of the genera *Lactobacillus*, *Bifidobacterium* (Bomba et al., 1998), *Bacillus* (Roth et al., 1992b; Alexopoulos et al., 2001; Scharek et al., 2005, 2007), *Enterococcus* and *Streptococcus* (Scharek et al., 2005, 2007) and their combinations (Mathew et al., 1998; Bomba et al., 2002). The bacteria *Enterococcus faecium* were found to be able to prevent the K88

positive ETEC strain from adhering to the intestinal mucous membrane of piglets (Jin and Zhao, 2000; Scharek et al., 2005). Regulating intestinal microbial balance by increasing the activity of microbial digestive enzymes, it improves digestion, feed digestibility and nutrient utilization (Bomba et al., 2002). In consequence, the morbidity and mortality of farm animals decrease and performance increase (Mathew et al., 1998; Taras et al., 2005; Lodemann et al., 2006).

Members of the genus *Bacillus* support natural intestinal microflora in the digestive tract, compete with undesirable microorganisms, and reduce the numbers of *Enterococci*, *Bacteroides* and coliforms (Ozawa et al., 1981; Adami and Cavazzoni, 1999; Kyriakis et al., 1999; Alexopoulos et al., 2001; Link et al., 2005; Link and Kovac, 2006) whilst *Saccharomyces cerevisiae* do not markedly alter the composition of host microflora (Mathew et al., 1998). These results are in contradiction to information provided by Mathew et al. (1993, 1996) who observed changes in the microbial environment due to *S. cerevisiae* activity. This can be explained by the ability of various strains of *S. cerevisiae* to alter cellulotic microflora (Newbold et al., 1995).

Inconsistent data have also been reported for other probiotic genera (Table 3). While some authors have observed beneficial effects of several members of the genera *Lactobacillus* and *Bacillus* (Depta et al., 1998; Bomba et al., 1999, 2002; Kyriakis et al., 1999; Reiter et al., 2006; Scharek et al., 2007), others have failed to confirm any stimulating effect on the composition of the pig intestinal microflora

(Spriet et al., 1987; De Cupere et al., 1992; Newbold et al., 1995). These contradictory results can be explained by the low doses of the used species of probiotic bacteria, their stability, interactions with other medications, and the health condition, age and genetic predisposition of animals (Kyriakis, 1999; Reiter et al., 2006).

Improvement in the health condition and growth performance (Tables 4 and 5) was observed in newborn and weaned piglets after feeding with probiotics of the genera *Lactobacillus*, *Streptococcus* and *Bacillus* (Roth et al., 1992b; Mathew et al., 1998; Alexopoulos et al., 2001; La Ragione et al., 2001; Chen et al., 2005; Reiter et al., 2006).

E. faecium (Ushe and Nagy, 1985; Roth and Kirchgessner, 1986; Rekiel and Wiecek, 1996; Jadamus et al., 2001; Lodemann et al., 2008) and *Bifidobacterium lactis* (Alexopoulos et al., 2001; Shu et al., 2001) has been shown to be effective in reducing the occurrence and intensity of diarrhoea and increasing the performance of piglets. On the other hand, Kirchheim and Schone (1995) failed to find any positive effect of these bacteria in reducing diarrhoea incidence.

Whilst nonpathogenic *E. coli* strains lacking virulence genes have been used for the prophylaxis of *E. coli* infection (Davidson and Hirsch, 1976; Setia et al., 2009), Smith and Huggins (1983) used phages that specifically bind with K-antigens. The effects in both experiments were strictly specific and no direct protective function was observed. On the other hand, Melin and Wallgren (2002) applied non-virulent *E. coli* in combination with zinc oxide

Table 3. The effect of probiotics on the intestinal microflora of pigs

Genus/species	Beneficial effects	Nonsignificant beneficial effects
<i>Lactobacillus</i>	Bomba et al. (1998); Depta et al. (1998); Mathew et al. (1998); Alexopoulos et al. (2001); Scharek et al. (2005, 2007); Reiter et al. (2006)	De Cupere et al. (1992); Newbold et al. (1995)
<i>Bifidobacterium</i>	Bomba et al. (1998, 2002); Depta et al. (1998); Alexopoulos et al. (2001); Reiter et al. (2006)	none
<i>Bacillus</i>	Ozawa et al. (1981); Mathew et al. (1998); Adami and Cavazzoni (1999); Kyriakis et al. (1999), Link et al. (2005); Scharek et al. (2007)	Spriet et al. (1987); De Cupere et al. (1992)
<i>Streptococcus</i>	Bomba et al. (1998); Mathew et al. (1998); Alexopoulos et al. (2001)	none
<i>Enterococcus/E. faecium</i>	Jin and Zhao (2000); Scharek et al. (2005, 2007)	none
<i>Saccharomyces/S. cerevisiae</i>	Mathew et al. (1993, 1996)	Newbold et al. (1995); Mathew et al. (1998)

Table 4. The effect of probiotics on the occurrence of diarrhoeal diseases in pigs

Genus/species	Beneficial effects	Nonsignificant beneficial effects
<i>Lactobacillus/L. casei</i>	Danek et al. (1990); Mathew et al. (1998); Chen et al. (2005)	
<i>Bifidobacterium/B. lactis</i>	Alexopoulos et al. (2001); Shu et al. (2001)	
<i>Bacillus/B. subtilis, B. licheniformis</i>	Adami and Cavazzoni (1999); Kyriakis et al. (1999); La Ragione et al. (2001); Link et al. (2005)	Martelli (1992)
<i>Streptococcus/Sp.</i>	Mathew et al. (1998); Alexopoulos et al. (2001); Chen et al. (2005); Reiter et al. (2006)	
<i>Enterococcus/E. faecium</i>	Ushe and Nagy (1985); Roth and Kirchgessner (1986); Rekiel and Wiecek (1996); Jadamus et al. (2001); Lodemann et al. (2006)	Kirchheim and Schone (1995)
<i>Escherichis/Avirulent E. coli</i>	Melin and Wallgren (2002)	Davidson and Hirsch (1976); Duval-Iflah et al. (1983); Setia et al. (2009)

and a mixture of lactulose and fibre and observed a markedly reduced incidence of PWD in comparison with the control group.

The genus *Bacillus*, especially its members *B. subtilis* and *B. licheniformis* have been described to markedly reduce the severity of diarrhoea caused by *E. coli* (Adami and Cavazzoni, 1999; Kyriakis et al., 1999; La Ragione et al., 2001; Link et al., 2005) and at the same time improve growth parameters in weaned piglets (Roth et al., 1992b; Alexopoulos et al., 2001), whilst no improvement in health was observed after application of *B. toyoi* to sows and their piglets in a previous study (Martelli, 1992). However, Link and Kovac (2006) noted improvement in nutrient digestibility after feed supplementation with the same bacterium.

Improved nutrient digestibility resulting from increased enzymatic activity was also observed after feeding other probiotic bacteria such as *Lactobacillus plantarum*, *L. acidophilus*, *L. casei* and *E. faecium* (Collington et al., 1990; Scheuermann, 1993; Bhatt et al., 1995; Kumprecht and Zobac, 1998) and a significantly higher activity of carbohydrates was detected in mucosal tissues of pigs (Collington et al., 1990) in response to such treatment. However, the effects of probiotic bacteria of the genus *Lactobacillus* on growth parameters were limited to the first stage of fattening in some cases, and thus no positive effect on growth and feed conversion was detected in growing-finishing pigs (Pollman et al., 1980; Park et al., 2001).

Table 5. The effect of probiotics on the growth performance of piglets

Genus/species	Beneficial effects	Nonsignificant beneficial effects
<i>Lactobacillus/L. plantarum, L. acidophilus, L. casei</i>	Collington et al. (1990); Scheuermann (1993); Bhatt et al. (1995); Kumprecht and Zobac (1998)	Pollman et al. (1980); Harper et al. (1983); Lessard and Brissom (1987); Park et al. (2001)
<i>Bifidobacterium/B. lactis</i>	Mathew et al. (1998); Shu et al. (2001)	none
<i>Bacillus/B. subtilis, B. licheniformis, B. toyoi</i>	Alexopoulos et al. (2001)	none
<i>Streptococcus/Sp.</i>	Mathew et al. (1998); Alexopoulos et al. (2001); Chen et al. (2005); Scharek et al. (2005, 2007); Reiter et al. (2006)	none
<i>Enterococcus/E. faecium</i>	Roth and Kirchgessner (1986); Collington et al. (1990); Rekiel and Wiecek (1996); Jadamus et al. (2001); Lodemann et al. (2008)	none
<i>Saccharomyces/S. cerevisiae</i>	Mathew et al. (1998)	Burnett and Neil (1977); Dusel et al. (1994)

S. cerevisiae has been reported to have a varying influence on pig efficiency. Mathew et al. (1998) observed increased feed intake and body weight gain of piglets after feed supplementation, but Burnett and Neil (1977) and Dusel et al. (1994) did not see any positive effect.

To obtain the highest effect of probiotic preparations, supplementation of piglets shortly after birth is recommended. Martin et al. (2009) reported a beneficial effect of probiotic stimulation of the immune responses in pregnant sows before parturition. Feeding of probiotics to sows before farrowing and during lactation and to neonatal piglets caused a fall in numbers of pathogenic microorganisms present in sow and piglet faeces, and resulted in the reduced occurrence of digestive disturbances and mortality (Danek et al., 1991; Martin et al., 2009).

4.2. Prebiotics

Prebiotics are dietary short-chain carbohydrates (oligosaccharides), which cannot be digested by pigs, but are specifically utilizable by intestinal microflora. They have been referred to as the bifidus factor, because they support the growth and/or activities of probiotic microorganisms in the gastrointestinal tract (Gibson and Roberfroid, 1995; Gibson, 2004; Marinho et al., 2007; Rayes et al., 2009).

Prebiotic supplementation of the diet influences volatile fatty acid content (VFA), branched-chain proportion, lactic acid concentrations and ammonia concentrations in the gut (Pie et al., 2007). Increased concentrations of short-chain fatty acids (SCFA) stimulate natural bacterial activity and pro-

liferation of bifidobacteria and lactic acid bacteria. The production of butyrate which is a dominant energy source for enterocytes also increases (Houdijk et al., 2002).

Table 6 lists the non-digestible oligosaccharides, which are used as prebiotics. The mannanoligosaccharides are important because they modify the microbial gut ecosystem by binding to the receptors present in the intestinal epithelium, thereby preventing the colonization of bacterial pathogens (Zimmermann et al., 2001; Shim et al., 2005). Mannanoligosaccharides isolated from the *S. cerevisiae* cell wall also have a beneficial effect on the intestinal microflora (Lyons and Bourne, 1995) and animal growth (Kumprecht et al., 1994; Kumprecht and Zobac, 1998; Shim et al., 2005). It was found that they suppress the growth of *E. coli*, *Salmonella typhimurium*, *Clostridium botulinum* and *C. sporogenes*, and conversely stimulate the growth of *B. longum*, *L. casei*, *L. acidophilus* and *L. delbrückei*. Lyons and Bourne (1995) reported that mannanoligosaccharides from the yeast cell wall stimulate the local immune system by increasing the activities of macrophages and T-lymphocytes.

Bifidogenic effects of galactooligosaccharides, fructooligosaccharides and soybeanoligosaccharides have been repeatedly confirmed by many *in vitro* and *in vivo* experiments, where they selectively interacted with the intestinal bacterial ecosystem (Roberfroid, 1998; Smiricky-Tjardes et al., 2003; Tuohy et al., 2005). Smiricky-Tjardes et al. (2003) observed an increase in *Bifidobacterium* and *Lactobacillus* genera numbers in the intestine, a concomitant increase in SCFA concentration and improved small intestine morphology (Rayes et al., 2009). Fructooligosaccharides and galactooligosac-

Table 6. Non-digestible oligosaccharides (NDO) used as prebiotics (Grizard and Barhomeuf, 1999; Zimmermann et al., 2001; Tuohy et al., 2005)

NDO	Mode of production
Mannanoligosaccharides	enzymatic synthesis from mannose
Galactooligosaccharides	trans-galactosylation of lactose with <i>Aspergillus oryzae</i> β -galactosidase
Fructooligosaccharides	partial enzymatic hydrolysis of inulin/transfructosylation from saccharose
Soybeanoligosaccharides	extraction from soyabean whey
Isomaltooligosaccharides	enzymatic hydrolysis of starch/transglucosylation of maltose
Xylooligosaccharides	enzymatic hydrolysis of xylan
Lactulose	alkali isomeration
Inulin	isolation from chicory root

charides stimulate acetate and lactate production, thereby reducing faecal *Bacteroides*, *Clostridia* and *Fusobacteria* shedding in pigs (Gibson et al., 1995; Zimmermann et al., 2001).

In contrast, Mikkelsen et al. (2003) and Visentini et al. (2008), while observing significantly increased numbers of *S. cerevisiae*, failed to find a stimulating effect of galactooligosaccharides and fructooligosaccharides on *Bifidobacterium* sp. growth in weaned piglets and on the improvement of pig efficiency.

Lactulose, which is formed by lactose isomerisation, is due to its high prebiotic activity widely used in the prevention and treatment of enteric disorders in animals and humans. Lactulose cannot be hydrolyzed by the β -galactosidase of the digestive tract and hence, it cannot be absorbed from the small intestine. It passes down to the large intestine where resident microflora consume it and produce lactic and/or acetic acid (Gibson, 2004; Bohacenko et al., 2007). Consequently, it stimulates the growth and/or activity of indigenous intestinal microflora, especially of the genera *Bifidobacterium* and *Lactobacillus*, and reduces the activity of proteolytic bacteria. Immobilization of proteolytic bacteria results in the reduction of ammonia release into the outer environment. Pig diets are usually supplemented with one per cent lactulose (Gibson, 2004; Marinho et al., 2007).

Inulin is present in a number of raw materials of vegetable origin such as onion, garlic, asparagus, banana and chicory root, which is one of the richest sources of dietary inulin. Chicory inulin-type fructans for animal nutrition typically contain more than 70 per cent of inulin, some flower sugars, organic acids, protein fragments and minerals. Dietary supplementation with inulin has a positive effect on SCFA production, sufficient height of intestinal villi, stimulation of natural microflora and improvement of efficiency parameters (Crittenden and Playne, 1996).

4.3. Synbiotics

A list of the possibilities of how to influence the intestinal microflora and thus improve the health condition and growth of pigs would not be complete if we did not mention the combination of probiotics and prebiotics – synbiotics. Preparations containing probiotics and prebiotics increase the passage of probiotic bacteria through the upper part of the intestine and help the colonization of

local receptors in the intestine (Robefroid, 1998; Bomba et al., 2002; Maxwell et al., 2004).

Some studies have confirmed a significant synergistic growth-stimulating effect (Kumprecht and Zobac, 1998; Shim et al., 2005), reducing mortality and increasing the counts of species that are components of natural microfloras (Nemcova et al., 1999; Frece et al., 2009). Furthermore, it was found that synbiotic preparations increase SCFA production (Shim et al., 2007; Bird et al., 2009) and reduce faecal noxious gas emission (Lee et al., 2009).

Protective effects have been attributed to different combinations. The positive contribution of maltodextrins and *L. paracasei* (Bomba et al., 2002, 2006) or *E. faecium* (Kumprecht and Zobac, 1998) on increasing the efficiency of piglets, reducing pathogenic *E. coli* growth in the digestive tract and their adhesion to intestinal mucosa have often been observed. Improved efficiency was also observed after the feeding of animals with biological preparations containing *L. fermentum*, *L. brevis*, *L. salivarius* or *E. faecium* with lactulose or lactitol (Bomba et al., 2002; Piva et al., 2005).

Feeding a mixture of fructooligosaccharides and *L. paracasei* has been demonstrated to have a stimulating effect on the growth of natural intestinal microorganisms, to decrease the numbers of undesirable microflora including coliforms, *Clostridium* and Enterobacteriaceae and to improve the morphology of intestinal villi (Spencer et al., 1997; Nemcova et al., 1999; Bomba et al., 2002; Shim et al., 2005). Moreover, a higher effectiveness of synbiotics was shown when they were given to animals during the preweaning period (Shim et al., 2005). In the experiments performed by Bird et al. (2009), proliferation of *Bifidobacteria* in the intestinal tract occurred as a consequence of diet supplementation with *B. animalis* subsp. *lactis* and/or *B. choerinum* with fructooligosaccharides.

The incorporation of prebiotics with unsaturated fatty acids also yielded a superior synbiotic effect (Ringo et al., 1998; Bomba et al., 2002; Bontempo et al., 2004).

4.4. Organic acids

Besides antimicrobial function, organic acids and their salts have a beneficial effect on digestibility, nutrient resorption (Roth and Kirchgessner, 1998; De Freitas et al., 2006) and performance of weaned and growing piglets (Kirchgessner et al.,

1995; Roth and Kirchgessner, 1998; Partanen and Mroz, 1999; De Freitas et al., 2006). Antimicrobial effects can be explained by two mechanisms: First, by a pH fall below 6 in the stomach, which inhibits the growth of pathogenic microorganisms and, second, the ability of organic acids to penetrate in their non-dissociated form through the bacterial wall and destroy some specific microorganisms (Eidelsburger et al., 1992; Roth et al., 1992a; Hansen et al., 2007). Bactericidal or bacteriostatic effects of organic acids consist above all in a direct effect of the organic acid anions on bacterial cell walls. This ability is primarily characteristic of acids with low numbers of carbon atoms in their molecules, such as formic, acetic, propionic and lactic acids (Kirchgessner et al., 1992; Roth et al., 1998; Partanen et al., 2001).

According to their effects, organic acids can be categorized into two groups. The first group comprises lactic, fumaric and citric acids and is characterized by an indirect effect in reducing bacterial populations by decreasing pH in the stomach. The second group comprises formic, acetic, propionic and sorbic acids, and are characterized by a direct effect of lower pH in the digestive tract on the cell wall of gram-negative bacteria thereby preventing their deoxyribonucleic acid replication (Roth et al., 1992a; Hansen et al., 1997; Castro, 2005).

Furthermore, organic acids contribute to the stabilization of intestinal microflora due to their effective biocidal qualities and their ability to improve enzymatic digestion (Kirchgessner et al., 1995; Roth and Kirchgessner, 1998; Marinho et al., 2007). The digestion of proteins by pepsin in the stomach begins when pH is low, while high pH values reduce enzyme activity. This is associated with the utilizability of feed minerals because solubility of minerals increases with a decrease in pH (Kirchgessner et al., 1995; Hansen et al., 2007). For these reasons, the use of organic acids in piglets is important because in the first days they suffer from a post-weaning syndrome associated with a typical starvation period which is followed by ingestion of excessive amounts of feed, resulting in mild acidification of the stomach chyme. Consequently, higher pH values cause weakening of the protective barrier function of the stomach against ingested bacteria and leads to intensive bacterial propagation in the small and large intestine (Castro 2005; De Freitas et al., 2006; Marinho et al., 2007).

Organic acids cause a decline in the number of pathogenic microorganisms such as *E. coli*

in the stomach and small intestine (Kluge et al., 2006; Hansen et al., 2007). After application of organic acids in previous studies, a significant decrease in the number of microorganisms (*E. coli*, Bacteroidaceae, *Eubacterium*, *Lactobacillus* sp. and *Bifidobacterium* sp.) occurred in the duodenum, jejunum and ileum (Gedek et al., 1992b; Kirchgessner et al., 1992), whilst in the caecum and colon, the microflora was not greatly affected by the ingested organic acids (Gedek et al., 1992b). *In vitro* studies have shown that formic acid can inhibit the growth of pathogenic bacteria. Lactic acid was most effective in this regard, whereas the effect of acetic acid and propionic acid was low (Gedek et al., 1992b; Kirchgessner et al., 1992).

The effect of organic acids is initiated by their addition to the feed. Antibacterial and antifungal effects are elicited by a decrease in the feed pH (Eidelsburger et al., 1992; Castro 2005), which contributes to feed preservation. Acids in powder form are most suitable for preservation of feeds (Overland et al., 2008).

Feed acidifiers commonly used in animal nutrition, usually based on formic acid, are effective even when their proportion in a diet is low (less than 10 grams per kilogram; Eidelsburger et al., 1992; Gedek et al., 1992a; Partanen et al., 2002, 2007). Even though formic acid alone is an efficient acidifier; it is often combined with other organic acids such as sorbic acid (Kirchgessner et al., 1995), fumaric acid (Gedek et al., 1992b), citric, propionic and benzoic acids (Partanen and Mroz, 1999) so as to increase its effect. The antimicrobial effects of different organic acids vary greatly and depend on their concentration and pH. Specific effects of different organic acids towards different bacteria have been observed. It is necessary to note that an increased intake of organic acids can cause a reduction in feed intake, body weight gain and general efficiency of young pigs (Roth and Kirchgessner, 1998; Partanen et al., 2007).

Partanen et al. (2001) documented that formic acid tended to decrease bacterial nitrogen in different parts of the small intestine in pigs and improved apparent ileal digestibility of protein sources, certain essential amino-acids, lipids, calcium and phosphorus. The results showed a similar or higher effect in comparison with that of antibiotic growth promoters. The growth efficiency of market pigs was significantly increased by the addition of formic acid and this effect was further enhanced by combination of formic acid with potassium sorbate

(Partanen et al., 2002). Piva et al. (2002) supplemented piglet diet with a combination of citric, fumaric and malic acids. A beneficial effect of organic acids on the growth performance, feed intake and general health condition was observed. Biagi et al. (2006) described a favourable effect of gluconic acid on intestinal microflora, morphology of intestinal villi and general condition of piglets.

Positive combinatory effects can be achieved with lactic, formic, fumaric, benzoic and sorbic acids by suppressing *E. coli*, *Salmonella* and *Enterococcus* in the intestinal content. Several studies documented an improvement in growth efficiency have been reported in the literature (Knarreborg et al., 2002; Franco et al., 2005; Overland et al., 2008; Missotten et al., 2009).

A combination of organic acids with highly concentrated extracts, i.e., essential oils, shows synergistic activity. The bacterial cell wall damaging effect of essential oils permits the organic acids to enter. This effect is ascribed to thymol and carvacrol from plant extracts (Varley, 2002; Namkung et al., 2004; Kommera et al., 2006).

The significance of organic acids can also be assessed from the standpoint of sensory attributes. The addition of organic acids to diets can reduce the concentration of skatole present in the faeces and thereby reduce the boar taint problem of the meat (Claus et al., 1994; Babol and Squires, 1995; Bonneau et al., 2000).

4.5. Zinc oxide

Zinc is a component of several enzymes, is involved in their activation and is thus central to biochemical processes occurring in the body. It is a significant dietetic factor that regulates amino-acid and protein metabolism (Ou et al., 2007; Wang et al., 2009). Furthermore, it contributes to stabilisation of sensitive intestinal mucosa, diversity and functions of bacterial microflora, inhibits the growth of some pathogens and enhances the immune responses of the body against infections (Hahn and Baker, 1993; Srivastava et al., 1995; Case and Carlson, 2002; Hojberg et al., 2005; Han and Thacker, 2009). Some zinc compounds such as zinc sulphate, zinc lysine and zinc methionine stimulate the activity of macrophages (Van Heugten et al., 2003).

Zinc oxide has been included in piglet weaning diets for many years. High doses of zinc oxide (2500 to 3000 mg Zn/kg of feed) added to feed

have been used as a preventative measure against PWD. Feeding zinc to weaned piglets has been demonstrated to reduce diarrhoea incidence and to improve growth rates (Hahn and Baker, 1993; Scott and Koski, 2000; Ou et al., 2007; Wang et al., 2009).

However, the mechanisms of zinc action on growth promotion and against diarrhoea are still not exactly known. Several hypotheses have been advanced to explain the effect of zinc oxide on weaned piglets. According to Srivastava et al. (1995) zinc is important for maintaining the integrity of the cell membrane, probably via translocation of redox-active metal ions, which can be responsible for inducing peroxidative damage at the target site. Higher cell-mediated immunity in rats fed with zinc has been observed as far back as in the study of Chandra and Au (1980). Liao et al. (2008) and Rhoads and Wu (2009) ascribed the decrease in the incidence of diarrhoea and the increase in average body weight gain in piglets to the regulation of cellular signalling pathways. Another hypothesis regarding zinc oxide activity was formulated by Wang et al. (2009) who assumed that the beneficial effect of zinc oxide may be related to its involvement in protein expression associated with glutathione metabolism and oxidative stress in the gut.

Dietary supplementation with zinc oxide has a beneficial effect on the stability of the intestinal microflora of weaned piglets (Jensen Waern et al., 1998; Huang et al., 1999; Katouli et al., 1999; Owusu-Asiedu et al., 2003) and morphology of their small intestine – increased height of villi in comparison with the depths of crypts (Katouli et al., 1999; Castillo et al., 2008; Hedemann et al., 2009). Zinc deficiency can contribute to intestinal villus ulceration and to the damage of the immune barrier function (Hennig et al., 1992; Wapnir, 2000; Roselli et al., 2005).

Furthermore, zinc can decrease the virulence of some microorganisms such as *Staphylococcus aureus* (Walsh et al., 1994), *Salmonella typhi* and *Aeromonas hydrophylia* (Fiteau and Tomkins, 1994). A comparable zinc content, which positively affected microbial environment of the intestine, also reduced the intensity of ETEC-elicited diarrhoea (Mores et al., 1998; Bosi et al., 2003; Li et al., 2006). Roselli et al. (2005) also observed a beneficial effect of glutamate zinc on the course of infection.

The beneficial effect of Zn²⁺ on the activity of some enzymes present in the pancreatic and intestinal juices, mucin production, digestion, nu-

trient absorption (Hedemann and Jensen, 2004; Hedemann et al., 2009) and intestinal growth of weanling piglets is exerted through increasing IGF-1 (insulin like growth factor) and IGF-IR (IGF receptor) expression in the small-intestinal mucosa (Li et al., 2006).

The stimulating effect of zinc oxide is best harnessed during the first two weeks after weaning when the assumed protective effect occurs (Katouli et al., 1999). An adverse effect of a long-term elevation in Zn²⁺ content in piglet faeces can constitute a potential environmental hazard (Carter et al., 2002; Bosi et al., 2003).

4.6. Plant extracts

Plants and their extracts had been used in traditional medicine for centuries. After the ban on antibiotic growth promoters, natural feed additives (plants and spices) started to be used as alternatives in broiler and pig diets (Borovan, 2004; Hernandez et al., 2004). Plant extracts and essential oils have been exploited in animal nutrition, particularly for their antimicrobial (Namkung et al., 2004; Brambilla and De Filippis, 2005; Costa et al., 2007), anti-inflammatory, anti-oxidative (Liu et al., 2008), and anti-parasite properties (Magi et al., 2006). It was found for some natural materials that due to their immunological and pharmacological qualities, these can have prophylactic ef-

fects against a series of enteric disorders (Laine et al., 2008).

The antibacterial activity of essential oils depends on their chemical composition and concentration (Russo et al., 1998). The existing data shows that their effect depends on the type of plant extract, correct combination and appropriate dosage (Oetting et al., 2006; Utiyama et al., 2006). A synergistic effect of plant extracts and organic acids has been also demonstrated (Namkung et al., 2004; Kommera et al., 2006).

Garlic extract is generally considered as the most effective antimicrobial agent of plant origin (Arnault et al., 2003) and *in vitro* studies have shown the antibacterial effects of thyme (Azaz et al., 2004), oregano, cloves, cinnamon (Carson et al., 2006) and juniper (Pepeljnjak et al., 2005).

Regarding the prevention of diarrhoeal diseases, it is important to focus on the extracts and essential oils that inhibit the proliferation of *E. coli* which is a common cause of intestinal diseases in piglets (Laine et al., 2008). Khan et al. (2009) reported that pathogenic strains of *E. coli* are sensitive to the following plant extracts: *Acacia nilotica*, *Syzygium aromaticum* and *Cinnamum zeylanicum*. However, a major disadvantage of plant extracts lies in the fact that their compositions are unstable (Bomba et al., 2006). This is due to the influence of many factors such as climate, season, harvesting method and others (Borovan, 2004). Probably for this reason there is a multiplicity of controversial results

Table 7. Plant extracts in pig nutrition

Plant	The effect observed	Reference
Oregano, cinnamon and Mexican pepper	decreased ileum total microbial mass, increased the lactobacilli : enterobacteria ratio	Manzanilla et al. (2004)
Sangrovit (alkaloids of <i>Macleaya cordata</i>)	increased body weight gain and feed conversion by growing pigs	Borovan (2004)
Cinnamon, thyme, oregano	inhibited pathogenic <i>E. coli</i> in piglet intestine	Namkung et al. (2004)
Thyme, clove, oregano, eugenol and carvacrol	improved pig performance	Oetting et al. (2006)
Clove, oregano	growth performance of pigs close to pigs fed antimicrobials	Costa et al. (2007)
Specific blend of herbal extract	increase ADG, decrease feed conversion ratio in finishing pigs	Liu et al. (2008)
Aged garlic extract, allicin	improved body weight, morphological properties of intestine villi and non-specific defense mechanisms of piglets	Tatara et al. (2008)
<i>Camellia sinensis</i>	decrease of clostridia and enterococci counts in the faeces of piglets	Zanchi et al. (2008)

obtained in different scientific studies examining the effect of these substances in animal nutrition. Accordingly, it is necessary to select effective plant extracts, standardize them and investigate a potential synergistic benefit deriving from their combination (Budzinski et al., 2000; Oetting et al., 2006).

5. Clay minerals

Another possibility for PWD prevention is the use of natural and modified clay minerals. Clay minerals, designated as silicates in systemic mineralogy, are stratified clay minerals formed by a net of tetrahedral and octahedral layers. They contain molecules of silicon, aluminium and oxygen. The layers can be interconnected by a system of hydrogen bonds or a group of cations, and this space is termed an interlayer. Phyllosilicates are classified into the main groups according to the type of the layers, interlayer content, charge of the layers and chemical formulas. The natural extracted clays (bentonite, zeolite, kaolin etc.) are a mixture of various clay minerals differing in chemical composition (Velebil, 2009). The best-known are montmorillonite (MMT), smectite, illite, kaolinite, biotite and clinoptilolite.

5.1. Adsorption capacity and effects of clay minerals

A common feature of clay minerals is a high sorption capacity determined by their stratified structure. Within the layers of these clays, substitution of other metal ions for silicon or aluminium can occur resulting in a net negative charge on the surface of the clay platelet. This charge imbalance is offset by hydrated cations, the predominant ones being Na^+ and Ca^{2+} . These interlaminar cations can be exchanged with other metal cations. In aqueous solutions, water is intercalated into the interlaminar space of clay, leading to an expansion of the minerals (Ma and Guo, 2008).

Due to their sorption capacity and absence of primary toxicity, clay minerals are regarded as a simple and effective tool for chemical prevention of a series of toxic materials, not only in the environment, but also in the living bodies. Clays added to a diet can bind and immobilize toxic materials in the gastro-intestinal tract of animals and largely

reduce their biological availability and toxicity for the body (Phillips, 1999; Lemke et al., 2001; Phillips et al., 2002; Trckova et al., 2004). Multiple studies have confirmed the decontaminating properties of clay minerals. They can bind:

- aflatoxins (Phillips et al., 1987, 1988; Lindemann et al., 1993; Schell et al., 1993a,b; Phillips et al., 2002; Abdel-Wahhab et al., 2002; Huebner and Phillips, 2003; Rizzi et al., 2003; Shi et al., 2005, 2007; Maciel et al., 2007; Magnoli et al., 2008; Nguyen et al., 2008),
- plant metabolites (Dominy et al., 2004),
- heavy metals (Hassen et al., 2003; Katsumata et al., 2003; Lin et al., 2004; Xu et al., 2004; Yu et al., 2005, 2008; Abbes et al., 2007),
- toxins (Knezevich and Tadic, 1994).

Kaolin-based medication is used for the therapy of diarrhoea and digestive disorders in human medicine (Heimann, 1984; Madkour et al., 1993; Kasi et al., 1995; Knezevich, 1998; Gebesh et al., 1999; Narkeviciute et al., 2002; Gonzalez et al., 2004). The ability of clay minerals to allow adsorption of pathogens and enterotoxins to the surface layer by means of hydrogen bonds or if needed, into the interlayer sheets and to reduce their numbers in the intestinal tract has been demonstrated *in vivo* (Trckova et al. 2009) and *in vitro* (Novakova, 1968; Brouillard and Rateau, 1989; Ramu et al., 1997; Hu et al., 2002; Hu and Xia, 2006). The question of how much clay minerals reduce the occurrence and severity of PWD in piglets due to their adsorption qualities is still under discussion.

The extent of adsorption is determined by the chemistry of the clay minerals, exchangeable ions, the surface properties (Williams et al., 2008) and the fine structure of clay particles (Hassen et al., 2003). An important role is also played by pH, dosage and exposure time (Brouillard and Rateau, 1989). Hence, the resulting effect of clay mineral treatment is preconditioned by these factors. There is an abundance of published data which indicate that the dietary use of clay minerals reduces the incidence and decreases the severity and the duration of diarrhoea in pigs (Castro and Elias, 1978; Said et al., 1980; Vrzgula et al., 1982; Bartko et al., 1983; Brouillard and Rateau, 1989; Ramu et al., 1997; Narkeviciute et al., 2002; Dominy et al., 2004; Gonzalez et al., 2004; Martinez et al., 2004; Papaioannou et al., 2004; Castro, 2005).

The improvement of clinical manifestations of diarrhoeal diseases can also be explained by the elimination of various factors that are associated

with the occurrence of these diseases in piglets, primarily at the period of weaning. These factors include intestinal hypersensitivity to feed antigens or weaning-induced changes leading to the manifestation of malabsorption syndrome caused by a reduction in digestive enzyme activity, which can both result in a predisposition to infectious enteritis (Wilson et al., 1989; Papaioannou, et al., 2004, 2005). The use of clay minerals retards the rate of digestive passage through the intestines and their ability to absorb water results in more compact and better shaped faeces.

The capacity of clay minerals to immobilize anti-nutritional components in feeds (Albengres et al., 1985; Ma and Guo, 2008), reduce the number of pathogenic microorganisms and depress the activity of bacterial enzymes in the small intestinal digesta (Gonzalez et al., 2004; Xia et al. 2004, 2005; Trckova et al., 2009), prevents irritation and damage and improves the morphological characteristics of mucosa (Albengres et al., 1985; Xia et al. 2004, 2005; Trckova et al., 2009).

The supplementation of a diet with one to three per cent of clay-based adsorbents is generally recommended. Nevertheless, diets supplemented with a higher proportion of such adsorbents are also voluntarily ingested by animals (Castro and Elias, 1978; Vrzgula et al., 1982; Bartko et al., 1983; Castro and Iglesias, 1989), and do not exert any adverse effect on their growth and performance (Castro and Elias, 1978; Castro and Iglesias, 1989). Many studies have documented significant improvements in body weight gain and feed conversion after supplementation of a diet with clay minerals (Pond et al., 1981; Vrzgula et al., 1982; Bartko et al., 1983; Pond and Yen, 1987; Pond et al., 1988; Castro and Iglesias, 1989; Cabezas et al., 1991; Papaioannou et al., 2004, 2005; Chen et al., 2005; Kolacz et al., 2005; Alexopoulos et al., 2007; Prvulovic et al., 2007; Trckova et al., 2009).

5.2. Modified forms of clay minerals

Modification of clay minerals by the addition of Cu^{2+} can improve their antibacterial activity (Ye et al., 2003; Zhou et al., 2004; Xia et al. 2004; 2005; Hu and Xia, 2006), which is then a result of two mechanisms: one is electrostatic attraction which promotes the adherence of *E. coli* to the surface of clay minerals and the other is the slow release of Cu^{2+} , which can kill bacteria (Xia et al., 2004). For example, Hu and Xia (2006) reported that whilst

calcium MMT, sodium MMT and acid activated MMT showed some ability to reduce bacterial plate counts by 13 to 37 per cent, their modified cupric containing forms reduced this number by 96 to 99 per cent (Hu and Xia, 2006).

Xia et al. (2004) reported that Cu^{2+} -enriched MMT significantly decreased the frequency of diarrhoea by up to 72 per cent and significantly increased the villus height and the villus height to crypt depth ratio in the jejunal mucosa by 19 and 37 per cent, respectively. Specific physical and chemical modifications – nanocomposites (Lin et al., 2004; Xu et al., 2004; Shi et al., 2005, 2007; Yu et al., 2008), and complexes with organic materials (Xu et al., 1997; Herrera et al., 2000, 2004; Koh and Dixon, 2001), are characterized by much higher adsorptive abilities than other regular clay minerals. The effect of clay minerals can also be reinforced by the addition of other components such as charcoal or antioxidants (Bonna et al., 1991).

6. CONCLUSIONS

The body of literature on the characteristics of different alternative components intended as antibiotic growth promoters strongly argues that these can be used as effective means of preventing diarrhoea in weaned piglets. The modification of intestinal microflora composition via probiotic and prebiotic preparations and providing the body with species of microorganisms which have a beneficial effect on the intestinal tract stimulates the immune system and decreases the risk of diarrhoea. Altering the acidity of the intestinal content, stabilization of the intestinal mucosa and supporting the digestive process contribute to the maintenance of good intestinal health. Due to their adsorption and detoxifying capabilities, non-conventional feed supplements in the form of clay minerals appear to be effective agents for protection against infection. Provided the recommended dosage is observed, the above mentioned raw materials can be used as suitable alternatives to antibiotics for the prevention of diarrhoeal diseases and the enhancement of piglet growth in the crucial period of weaning.

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Corresponding Author:

Prof. MVDr. Ivo Pavlik, CSc., Veterinary Research Institute, Hudcova 70, 621 00 Brno, Czech Republic
Tel. +420 533 331 601, Fax +420 541 211 229, E-mail: pavlik@vri.cz, <http://www.vri.czi>
