Growth performance and gut health of *Escherichia coli*-challenged weaned pigs fed diets supplemented with a *Bacillus subtilis* direct fed microbial

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ABSTRACT: Study was conducted to investigate the effects of a direct fed microbial (DFM) product (Bacillus subtilis strain DSM 32540) in weaned pigs challenged with K88 strain of Escherichia coli on growth performance and indicators of gut health. A total of 21 weaned pigs (initial body weight = 8.19 kg) were housed individually in pens and fed 3 diets (7 replicates/diet) for 21 d in a completely randomized design. The three diets were corn-soybean meal-based basal diet without feed additives, a basal diet with 0.25% antibiotics (neo-Oxy 10-10; neomycin + oxytetracycline), or a basal diet with 0.05% DFM. All pigs were orally challenged with sub-clinical dose ($6.7 \times 10^8$ CFU/mL) of K88 strain of E. coli on d 3 of the study (3 d after weaning). Feed intake and body weight data were collected on d 0, 3, 7, 14, and 21. Fecal scores were recorded daily. On d 21, pigs were sacrificed to determine various indicators of gut health. Supplementation of the basal diet with antibiotics or DFM did not affect the overall (d 0 to 21) growth performance of pigs. However, antibiotics or DFM supplementation increased ($P = 0.010$) G:F of pigs during the post E. coli challenge period (d 3 to 21) by 23 and 24%, respectively. The G:F for DFM-supplemented diet did not differ from that for antibiotics-supplemented diet. Frequency of diarrhea for pigs fed diet with antibiotics or DFM tended to be lower ($P = 0.071$) than that of pigs fed the basal diet. The jejunal villous height (VH) and the villous height to crypt depth ratio (VH:CD) were increased ($P < 0.001$) by 33 and 35%, respectively, due to inclusion of antibiotics in the basal diet, and by 43 and 41%, respectively due to inclusion of DFM in the basal diet. The VH and VH:CD for the DFM-supplemented diet was greater ($P < 0.05$) than that for antibiotics-supplemented diet. Ileal VH was increased ($P < 0.05$) by 46% due to inclusion of DFM in the basal diet. The empty weight of small intestine, cecum or colon relative to live body weight was unaffected by dietary antibiotics or DFM supplementation. In conclusion, addition of DFM to the basal diet improved feed efficiency of E. coli-challenged weaned pigs similar to that of the antibiotics-supplemented diet, and increased jejunal VH and VH:CD ratio to values greater than those for the antibiotics-supplemented diet. Thus, under E. coli challenge, the test DFM product may replace the use of antibiotics as growth promoter in diets for weaned pigs to improve feed efficiency and gut integrity.

Key words: direct fed microbial, growth performance, gut health, weaned pig
| Abbreviation | Definition                      |
|--------------|---------------------------------|
| CD           | crypt depth                     |
| DFM          | direct fed microbials           |
| ETEC         | enterotoxigenic E. coli         |
| GIT          | gastrointestinal tract          |
| VFA          | volatile fatty acids            |
| VH           | villous height                  |
| VH:CD        | villous height to crypt depth   |
INTRODUCTION

Postweaning diarrhea caused by Escherichia coli strains lead to tremendous economic losses in swine industry due to decreased growth rate, and increased mortality and morbidity of weaned pigs (Fairbrother et al., 2005; Pan et al., 2017). Enterotoxigenic E. coli (ETEC) K88+ is one of the major strains of E. coli that causes diarrhea in weaned pigs (Marquardt et al., 1999; Yang et al., 2014). Antibiotics have been widely used as a strategy for dealing with the postweaning diarrhea (Fairbrother et al., 2005; Wang et al., 2016). However, due to public concerns on the potential risks to human health coupled with the development of antibiotic resistance (Kemper, 2008; Li et al., 2015; Park et al., 2017), there is a need to adopt antibiotic-free feeding systems for pigs for pork production. The adoption of antibiotic-free feeding systems for pigs requires development of feed additives that can be used as alternatives to in-feed antibiotics (Pettigrew, 2006; Stein and Kil, 2006). One of the promising key members among these alternatives is direct-fed microbials (DFM), also known as probiotics (FAO/WHO, 2002). For a DFM to be beneficial, it should have at least one of the following functions in the gastrointestinal tract (GIT): (1) enhance growth of beneficial bacteria, (2) prevent colonization of GIT with pathogenic microorganisms, (3) increase digestive capacity and lower GIT pH, (4) improve mucosal immunity, or (5) enhance gut tissue maturation and integrity (de Lange et al., 2010). The DFM used in the swine industry are classified into 3 main categories including lactic acid-producing bacteria, Bacillus species, and yeast (Kenny et al., 2011; NRC, 2012). Of these, Bacillus species form spores, which enable them to be thermostable and survive at low pH. Bacillus species also produce antimicrobial peptides that kill pathogenic microorganisms, modify composition of GIT microorganisms that result in reduced competition for nutrients between host and microorganisms, and increase the production of mucin in GIT, which protect the GIT from invasion by pathogens and other toxins (Grant et al, 2018). Additionally, Bacillus species produce fiber-degrading enzymes that enhance nutrient digestibility of plant feedstuffs-based diets (Liu et al., 2018).

A DFM product (Bacillus subtilis strain DSM 32540) that can potentially inhibit growth of the main commercially relevant pathogens of swine, has a very high proliferation rate in presence of bile and can effectively digest cellulose, has been recently developed (protected in International Patent Application WO 2019/002471). However, information is lacking on the effect of including this newly developed DFM in diets for weaned pigs on growth performance and gut health. The objective of this study was to evaluate the effects of including Bacillus subtilis strain DSM 32540 in diets for ETEC K88-challenged weaned pigs on growth performance, and indicators of gut health.
MATERIALS AND METHODS

Experimental procedures were reviewed and approved by the Institutional Animal Care and Use Committee at South Dakota State University (# 17-051A).

Experimental Diets

In this study, three experimental diets were fed to the pigs (Table 1). The three diets were: basal diet without any feed additives, basal diet with antibiotics (neomycin and oxytetracycline) or the DFM product (Bacillus subtilis; DSM 32540; GutPlus®; Evonik Nutrition & Care GmbH, Hanau-Wolfgang, Germany). The diets were isoenergetic and similar in nutrient content, and formulated to meet or exceed the NRC (2012) recommended energy and nutrient requirements for nursery pigs. The diets were fed in mash form.

Experimental Animals and Procedure

A total of 21 pigs (Large White-Landrace female × Duroc male from Pig Improvement Company) weaned around 21 d of age and with initial body weight (BW) of 8.19 ± 0.77 kg were obtained from a commercial farm and housed individually in 21 pens in rooms of the Animal Resource Wing, South Dakota State University. The pigs were fed 3 experimental diets for 21 d in completely randomized design (7 pens per diet).

All pigs were orally challenged with freshly grown K88 strain of E. coli on d 3 of the study as described by Lin et al. (2013). Diets and fresh water were offered to pigs ad libitum during the entire period. Pigs were observed 4 times per day during the experimental period for signs of illness, including diarrhea, lethargy, and dehydration. Animal BW and feed intake were determined on d 0, 3, 7, 14 and 21 of the study to calculate ADG, ADFI, and G:F. The occurrence and severity of post-weaning diarrhea were assessed daily throughout the study on a pen basis by using the following fecal scoring system: 1 = firm feces, 2 = soft feces, 3 = mild pasty diarrhea, 4 = pasty diarrhea, 5 = watery diarrhea and dehydration, and 6 = most severe condition.

At the end of the feeding trial, all pigs were euthanized, and the following procedures took place. The gastrointestinal tract was divided into stomach, small intestine, cecum, and colon by using clamps to minimize digesta movement. The small intestine was stripped free of its mesentery and further divided into 3 sections: (1) duodenum (from pylorus to 80 cm distal to the pylorus), (2) ileum (from the ileal-cecal junction to 80 cm cranial to this junction), and (3) jejunum (the rest of small intestine). A segment of 2 cm was collected from the middle of jejunum, and from ileum at 15 cm proximal to the ileo-cecal junction. The collected segments were prepared as described by Woyengo et al. (2011) for determination of gut histomorphology. Samples of digesta from the distal ileum, and the cecum were collected from each pig aseptically into sterile plastic containers. The ileal and cecal digesta samples were used to determine ileal and cecal pH; cecal digesta sample were then stored frozen at −20°C for later determination volatile fatty acids (VFA) concentration. The stomach, all sections of small intestine, cecum and colon were emptied of their digesta and weighed. Also, spleen and liver were obtained, blotted dry with paper towels, and weighed.
Sample Analyses

Crude protein (method 990.0; AOAC Int., 2007) and total amino acid analyses of diets were determined by ion-exchange chromatography with post-column derivatization with ninhydrin. Amino acids were oxidized with performic acid, which was neutralized with Na metabisulfite (Llames and Fontaine, 1994; Commission Directive, 1998). Amino acids were liberated from the protein by hydrolysis with 6 N HCl for 24 h at 110°C and quantified with the internal standard by measuring the absorption of reaction products with ninhydrin at 570 nm. Tryptophan was determined by HPLC with fluorescence detection (extinction 280 nm, emission 356 nm), after alkaline hydrolysis with barium hydroxide octahydrate for 20 h at 110°C (Commission Directive, 2000). Spore count in diets was determined VDLUFA method 28.2.2 (VDLUFA, 1976).

Samples for histomorphology were analyzed for villous height (VH) and crypt depth (CD) as described by Woyengo et al. (2011). Villous height to crypt depth (VH:CD) ratio was calculated. Cecal digesta samples for VFA analysis were thawed and centrifuged, the resulting digesta fluid was prepared and analyzed for VFA (acetate, propionate, butyrate and branched chain VFA) as described by Woyengo et al. (2016). The pH in the ileum and cecum digesta were determined using a pH meter (AB 15; Fisher Scientific, Pittsburgh, PA).

Statistical Analysis

All data obtained from this study were subjected to analysis of variance using the GLM procedure of SAS® (SAS Inst. Inc., Cary, NC). The initial BW was treated as covariate. Means were separated by tukey test. The residual versus the predicted plot procedure in SAS was used to identify outliers. Frequency of diarrhea was analyzed using the FREQ procedure of SAS, treatments were separated using the X² statistic. Significance and tendencies were set at $P \leq 0.05$ and $0.05 < P \leq 0.10$, respectively, for all statistical tests.

RESULTS

The analyzed crude protein values for the diets in Table 2 are close to the calculated values in Table 1. Growth performance data is presented in Table 3. There was no effect of dietary treatment on final BW of pigs. The ADG, ADFI, and G:F for pigs fed basal diet with antibiotics or DFM did not differ from those of pigs fed the unsupplemented basal diet during the entire study period (d 0 to 21). However, supplementation of the basal diet with antibiotics or DFM increased ($P < 0.05$) the G:F of pigs during the post-challenge period (from d 3 to 21), but did not affect ADG and ADFI of pigs during this post-challenge period. The G:F for DFM-supplemented diet did not differ from that for the antibiotic-supplemented diet. Diarrhea data is presented in Figures 1 and 2. Supplementation of the basal diet with antibiotics or DFM tended to decrease ($P = 0.071$) frequency of diarrhea (fecal score of 3 to 6) from d 0 to 21. The frequency of diarrhea was 22% for basal diet, 12% for basal diet with antibiotics, and 15% for basal diet with DFM. In addition, the survival rate of the pigs fed the basal diet was 75% whereas 100% survival was observed for the pigs fed the antibiotic or DFM supplemented diet. In the basal diet, 2 out of 7 pigs died on 1 and 2 d post-challenge, and results from necropsy confirmed that this was due to the *E. coli* challenge.

Data on the effects of diets on small intestinal histomorphology is shown in Table 4. The VH and VH:CD ratio of jejunum were increased ($P < 0.001$) by antibiotics or DFM.
supplementation. However, the CD was not affected by supplementation with antibiotics or DFM. The jejunal VH and VH:CD ratio for DFM-supplemented were greater \( (P < 0.05) \) than those fed antibiotic-supplemented diet. Ileal VH was increased \( (P < 0.05) \) by DFM supplementation. However, CD and VH:CD ratio of ileum were unaffected by any of the two supplementation. Effects of diets on visceral organ weights and gastrointestinal pH of pigs at 21 day of age are presented in Table 5. The weights of liver, stomach, small intestine, cecum, and colon were not affected by antibiotics or DFM supplementation. Spleen weight was increased \( (P < 0.05) \) by antibiotics supplementation. Moreover, addition of antibiotics to the basal diet reduced \( (P < 0.05) \) the ileal digesta pH value. Cecal digesta pH was unaffected by antibiotics or DFM supplementation.

The effects of dietary treatment on cecal digesta VFA concentration on d 21 of the experiment are presented in Table 6. The concentration of acetic acid, propionic acid, butyric acid, isobutyric acid, and isovaleric acid were not affected by antibiotics or DFM supplementation. Supplementation of the NC diet with antibiotics or DFM lowered \( (P < 0.05) \) valeric acid concentration in cecal digesta.

**DISCUSSION**

In the current study, supplementation of the basal diet with antibiotics or DFM resulted in improved feed efficiency of pigs during the post-challenge period, which could partly be explained by the reduced frequency of diarrhea and increased jejunal VH by the supplementation. Diarrhea is positively correlated with increased water and nutrient secretion in GIT, or is negatively correlated with nutrient digestion and absorption, or both (O’Loughlin et al., 1991; Fairbrother et al., 2005); all these lead to reduced feed efficiency. Also, diarrhea due to ETEC is positively correlated with immune response, which in turn, is associated with an increase in proportion of dietary energy and nutrients that are utilized for maintenance (immune response) and a decrease in proportion of dietary energy and nutrients that are utilized for growth (skeletal tissue deposition; Kiarie et al., 2011) and hence reduced feed efficiency. Small intestinal VH is positively correlated with surface area for nutrient absorption and hence efficiency of dietary nutrient utilization (Wu et al. 1996; Pluske et al., 1996a). In addition to reducing diarrhea and increasing the VH, the DFM can improve G:F by enhancing nutrient digestibility through production of enzymes that digest carbohydrates such as non-starch polysaccharides (Tang et al., 2019). The improvement in G:F of pigs due to inclusion of antibiotics in diets fed in the current study was expected because antibiotics have been added in diets for weaned pigs to improve gut health and feed efficiency (Heo et al., 2013). Dietary antibiotics may improve feed efficiency partly by suppressing growth of certain intestinal microorganisms that are pathogenic or compete with host for nutrients (Dibner and Richards, 2005; Li, 2017). The improvement in G:F of pigs due to supplemental DFM in the current study is in agreement with previous studies using diets supplemented with DFM that contained *B. subtilis* (Guo et al., 2006; Wang et al., 2011; and Lee et al., 2014). However, the results of the current study are contrary to those reported from the study of Walsh et al. (2007), who did not observe an increase in feed efficiency of weaned pigs due to supplementation of DFM that contained *B. licheniformis* and *B. subtilis* to diets at 0.05%. Bontempo et al. (2006) suggested that the efficacy of DFM with regard to improving growth
performance of weaned pigs may partly depend on dosage and composition of DFM. The DFM product fed in the current study contained B. subtilis and was added in diets at 0.05%, whereas the DFM product fed in the study of Walsh et al. (2007) contained B. licheniformis and B. subtilis. Thus, the differences among the studies with regard to the effects of DFM on feed efficiency could be explained by differences in composition of DFM products. The G:F for DFM-supplemented diet did not differ from that of antibiotics-supplemented diet during the post challenge period, implying the dietary DFM product in the current study can improve the feed efficiency of E. coli infected weaned pigs to that of antibiotic-containing diet.

Infection of weaned pigs with pathogenic strains of E. coli including K88+ strain causes diarrhea as the toxins produced by pathogenic E. coli lead to increased secretion of fluids into the small intestine and reduced (re)absorption of fluids (O’Loughlin et al., 1991; Fairbrother et al., 2005). The post-weaning diarrhea is more severe during the first 2 weeks postweaning (Fairbrother et al., 2005). In the current study, the frequency of diarrhea by E. coli challenged weaned pigs was reduced by dietary inclusion of antibiotics or DFM. In the small intestine, most cells in villous have absorptive function, whereas most cells in the crypt have secretory function, implying that an increase in VH:CD ratio results in an increase in net absorption of nutrients and fluids (De Jonge, 1975; Woyengo et al., 2011; Park et al., 2020). Thus, the increase in the jejunal VH:CD ratio observed in the current study due to antibiotics or DFM supplementation could partly explain the reduction in frequency of E. coli derived diarrhea. The results from the current study are in agreement with those from previous studies that reported reduction in diarrhea (or frequency) in weaned pigs fed DFM (Bhandari et al., 2008; Yang et al., 2014; Pan et al., 2017).

Cell proliferation occurs in the crypt, and hence a decrease in VH:CD ratio indicate a net decrease in mitotic activity in mucosa and hence weight of small intestine (King et al., 2008). In the current study, however, the weight of small intestine relative to live weight of weaned pigs was unaffected by antibiotic or DFM supplementation despite the fact that VH:CD ratio was increased by the antibiotic or DFM supplementation. Kiarie et al. (2011) also did not observe a change in the weight of the small intestine relative to live weight of weaned pigs due to supplementation of diets with antimicrobial agents or DFM. Thus, it appears that small intestinal VH:CD ratio can change without a change in total weight of small intestinal relative to live body weight. The weight of large intestine (cecum and colon) relative to that of live body weight was also unaffected by DFM supplementation, which could be attributed to the lack of effect of DFM on VFA production. The VFA, especially butyric acid, stimulates cell proliferation in large intestine (Sakata, 1987; Kien et al., 2007). Similarly, Awad et al. (2009) did not observe change in the weight of the large intestine relative to live weight of weaned pigs due to supplementation of diets with DFM.

One of the functions of the spleen in animals is to induce immune in response to infection (Lewis et al., 2019). Thus, the size of spleen in animals can potentially be increased due to infection, implying that the size of spleen of E. coli-challenged pigs is expected to reduce due to supplementation of diets with feed additives that alleviate the E. coli infection (Kiarie et al., 2011). In the current study, supplementation of the NC diet with antibiotics increased the size of the spleen relative to the live body weight, and reason for this is not clear. The size of the spleen relative to live weight was not affected by supplementation of
the NC diet with DFM. It should be noted that DFM can alleviate GIT infections partly by stimulating immune response (Grant et al., 2018), which may explain the lack of effect of DFM of spleen. White blood cell production was not measured in the current study.

The VH in small intestine of weaned pigs is positively correlated with small intestinal luminal energy and nutrients availability (Pluske et al., 1996b) and negatively correlated with small intestinal proliferation of pathogenic microorganisms (O’Loughlin et al., 1991). Thus, in the current study, the increase in jejunal VH:CD by DFM supplementation could have been due to an increase in luminal availability of energy and other nutrients or reduced proliferation of the pathogenic microorganisms such as ETEC, or both by the supplementation. The DFM supplementation could have increased luminal availability of energy and other nutrients by increasing their digestibility (not measured in the current study) because feed intake was not affected by the DFM supplementation. As previously mentioned, the B. subtilis in the DFM product fed in the current study produces various fiber degrading enzymes including xylanase and cellulase. These fiber-degrading enzyme can hydrolyze fiber in the upper part of the small intestine, thereby releasing fiber-encapsulated nutrients for digestion and absorption (Woyengo and Nyachoti, 2011).

The jejunal VH:CD for pigs fed the DFM-supplemented diet was greater than that of pigs fed the antibiotic-supplemented diet, implying that the DFM product fed in the current study was more effective than the antibiotics with regard to improving jejunal histomorphology of ETEC-challenged weaned pigs. The ileal VH:CD was unaffected by the antibiotic or DFM supplementation. Weaning stress and availability of nutrients in lumen of small intestine have significant effect on integrity of upper part, but not lower part, of the small intestine of weaned pigs (Wijtten et al., 2011), which could partly explain the limited effect of DFM supplementation. The ileal VH:CD was unaffected by the antibiotic or DFM supplementation. Weaning stress and availability of nutrients in lumen of small intestine have significant effect on integrity of upper part, but not lower part, of the small intestine of weaned pigs (Wijtten et al., 2011), which could partly explain the limited effect of DFM supplementation. Weaning stress and availability of nutrients in lumen of small intestine have significant effect on integrity of upper part, but not lower part, of the small intestine of weaned pigs (Wijtten et al., 2011), which could partly explain the limited effect of DFM supplementation. Weaning stress and availability of nutrients in lumen of small intestine have significant effect on integrity of upper part, but not lower part, of the small intestine of weaned pigs (Wijtten et al., 2011), which could partly explain the limited effect of DFM on ileal VH:CD. Also, it could be possible that the upper part of small intestine of weaned pigs is more colonized by food-borne pathogenic E. coli compared to the lower part leading to limited effect of the E. coli infection on integrity of the lower part of the small intestine.

The DFM supplementation did not affect acetic acid, propionic acid and butyric acid production and hence pH in the cecal digesta. It had been assumed that the DFM would increase VFA and hence reduce pH in GIT because the B. subtilis in DFM product fed in the current study can promote fiber fermentation because it has xylanase activity (International Patent Application WO 2019/002471), and xylanase targets arabinoxylans that are the major nonstarch polysaccharides in corn (Knudsen, 2014). Diets fed in the current study were based on corn. However, the DFM may have increased the nutrients digestibility in the upper part of the small intestine (as evidenced by increased VH:CD without increased feed intake), leading to reduced availability of substrate for fermentation in the lower part of the small intestine and in the large intestine. Results from previous studies have shown reduced hindgut digestibility or fermentation as a result of an increase in digestibility of nutrients in small intestine by fiber-degrading enzyme supplementation (Woyengo et al., 2016; Lee et al., 2018). In deed, DFM supplementation numerically reduced the cecal digesta concentration of the fore-mentioned VFA (acetic acid, propionic acid and butyric acid); and significantly reduced the cecal digesta valeric acid concentration, which could support this afore-mentioned hypothesis. Valeric acid is by-product of protein fermentation (van Straalen and Tas, 2010).
Thus, its reduced concentration in cecal digesta implies that the DFM increased protein digestion in small intestine or inhibited growth of protein-fermenting microorganisms in the cecum. Fermentation of protein in hindgut is negatively associated with gut health because the end products of protein fermentation such as ammonia, indoles and skatoles are toxic to animals (Heo et al., 2013). Thus, the DFM product fed in the current study may improve health of pigs partly by reducing protein fermentation in hindgut.

In conclusion, supplementation of the basal diet with the DFM improved feed efficiency, increased jejunal VH and VH:CD, and decreased frequency of diarrhea of weaned pigs that were challenged with K88 strain of E. coli. The feed efficiency of pigs fed diet supplemented with DFM (Bacillus subtilis DSM 32540 strain) did not differ from that of pigs fed antibiotic-supplemented diet, whereas the jejunal VH and VH:CD for pigs fed DFM-supplemented diet was greater than that of pigs fed antibiotic-supplemented diet. Thus, the use of Bacillus subtilis DSM 32540 strain containing DFM product in diets for weaned pigs under E. coli challenge may replace the use of antibiotics in diets to improve growth performance and gut histomorphology.
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Conflict of interest statement
Drs. González-Vega and John K. Htoo, Evonik Operations GmbH, 63457 Hanau-Wolfgang, Germany.
LITERATURE CITED

AOAC Int. 2007. Official methods of analysis of AOAC international. 18th ed. AOAC international, Gaithersburg, MD.

Awad, W. A., K. Ghareeb, S. Abdel-Raheem, and J. Böhm. 2009. Effects of dietary inclusion of probiotic and synbiotic on growth performance, organ weights, and intestinal histomorphology of broiler chickens. Poult. Sci. 88:49–55. doi:10.3382/ps.2008-00244.

Bhandari, S. K., B. Xu, C. M. Nyachoti, D. W. Giesting, and D. O. Krause. 2008. Evaluation of alternatives to antibiotics using an Escherichia coli K88+ model of piglet diarrhea: Effects on gut microbial ecology. J. Anim. Sci. 86:836–847. doi:10.2527/jas.2008-00244.

Bontempo, V., A. Di Giancamillo, G. Savoini, V. Dell’Orto, and C. Domeneghini. 2006. Live yeast dietary supplementation acts upon intestinal morpho-functional aspects and growth in weanling piglets. Anim. Feed Sci. Technol. 129:224–236. doi.org/10.1016/j.anifeedsci.2005.12.015.

Commission Directive. 1998. Establishing community methods for the determination of amino acids, crude oils and fats, and olaquindox in feeding stuff and amending Directive 71/393/EEC, annex part A. Determination of Amino Acids. Offic. J. L257:14–23.

Commission Directive. 2000. Establishing community methods for the determination of vitamin A, vitamin E and tryptophan, annex part C. Determination of Tryptophan. Offic. J. L174:45-50.

De Jonge, H. R. 1975. The response of small intestinal villous and crypt epithelium to choleratoxin in rat and guinea pig: evidence against a specific role of the crypt cells in choleraigen-induced secretion. Biochim. Biophys. Acta (BBA)-General Subj. 381:128–143. doi:10.1016/0304-4165(75)90195-6.

de Lange, C. F. M., J. Pluske, J. Gong, and C. M. Nyachoti. 2010. Strategic use of feed ingredients and feed additives to stimulate gut health and development in young pigs. Livest. Sci. 134:124–134. doi:10.1016/j.livsci.2010.06.117.

Dibner, J. J., and J. D. Richards. 2005. Antibiotic growth promoters in agriculture: History and mode of action. Poult. Sci. 84:634–643. doi: 10.1093/ps/84.4.634.

Fairbrother, J. M., E. Nadeau, and C. L. Gyles. 2005. Escherichia coli in postweaning diarrhea in pigs: an update on bacterial types, pathogenesis, and prevention strategies. Anim. Heal. Res. Rev. 6:17–39. doi:10.1079/AHR2005105.

FAO/WHO (Food and Agriculture Organization/World Health Organization). 2002. Guidelines for the evaluation of probiotics in food. Food and Agriculture Organization of the United Nations and World Health Organization Working Group Report. http://www.fao.org/es/ESN/food/ foodandfood_probio_en.stm.
Grant, A., C. G. Gay, and H. S. Lillehoj. 2018. Bacillus spp. as direct-fed microbial antibiotic alternatives to enhance growth, immunity, and gut health in poultry. Avian Pathol. 47:339–351. doi: 10.1080/03079457.2018.1464417.

Guo, X., D. Li, W. Lu., X. Piao, and X. Chen. 2006. Screening of Bacillus strains as potential probiotics and subsequent confirmation of the in vivo effectiveness of Bacillus subtilis MA139 in pigs. Antonie van Leeuwenhoek. 90:139–146. doi:10.1007/s10482-006-9067-9.

Heo, J. M., F. O. Opapeju, J. R. Pluske, J. C. Kim, D. J. Hampson, and C. M. Nyachoti. 2013. Gastrointestinal health and function in weaned pigs: a review of feeding strategies to control post-weaning diarrhoea without using in-feed antimicrobial compounds. J. Anim. Physiol. Anim. Nutr. 97:207–237. doi: 10.1111/j.1439-0396.2012.01284.x.

Kemper, N. 2008. Veterinary antibiotics in the aquatic and terrestrial environment. Ecol. Indic. 8:1–13. doi:10.1016/j.ecolind.2007.06.002.

Kenny, M., H. Smidt, E. Mengheri, and B. Miller. 2011. Probiotics – do they have a role in the pig industry? Animal. 5:462–470. doi:10.1017/s175173111000193x.

Kiarie, E., S. Bhandari, M. Scott, D. O. Krause, and C. M. Nyachoti. 2011. Growth performance and gastrointestinal microbial ecology responses of piglets receiving Saccharomyces cerevisiae fermentation products after an oral challenge with Escherichia coli (K88). J. Anim. Sci. 89:1062–1078. doi:10.2527/jas.2010-3424.

Kien, C. L., R. Blauwikel, J. Y. Bunn, T. L. Jetton, W. L. Frankel, and J. J. Holst. 2007. Cecal infusion of butyrate increases intestinal cell proliferation in piglets. J. Nutr. 137:916–922. doi:10.1093/jn/137.4.916.

King, M. R., P. C. H. Morel, D. K. Revell, J. R. Pluske, and M. J. Birtles. 2008. Dietary bovine colostrum increases villus height and decreases small intestine weight in early-weaned pigs. Asian–Aust. J. Anim. Sci. 21:567–573. doi.org/10.5713/ajas.2008.70491.

Knudsen, K. E. B. 2014. Fiber and nonstarch polysaccharide content and variation in common crops used in broiler diets. Poult. Sci. 93:2380–2393. doi:10.3382/ps.2014-03902.

Lee, S. H., S. L. Ingale, J. S. Kim, K. H. Kim, A. Lokhande, E. K. Kim, I. K. Kwon, Y. H. Kim, and B. J. Chae. 2014. Effects of dietary supplementation with Bacillus subtilis LS 1-2 fermentation biomass on growth performance, nutrient digestibility, cecal microbiota and intestinal morphology of weanling pig. Anim. Feed Sci. Technol. 188:102–110. doi:10.1016/j.anifeedsci.2013.12.001.

Lee, J. W., R. Patterson, and T. A. Woyengo. 2018. Porcine in vitro degradation and fermentation characteristics of canola co-products without or with fiber-degrading enzymes. Anim. Feed Sci. Technol. 241:133–140. doi.org/10.1016/j.anifeedsci.2018.04.019.

Lewis, S. M., A. Williams, and S. C. Eisenbarth. 2019. Structure-function of the immune system in the spleen. Sci. Immunol. 4(33): . doi:10.1126/sciimmunol.aau6085.

Li, H., P. Zhao, Y. Lei, T. Li, and I. Kim. 2015. Response to an Escherichia coli K88 oral challenge and productivity of weanling pigs receiving a dietary nucleotides supplement. J. Anim. Sci. Biotechnol. 6:1–9. doi:10.1186/s40104-015-0049-5.
Li, J. 2017. Current status and prospects for in-feed antibiotics in the different stages of pork production — A review. Asian-Australas J. Anim. Sci. 30:1667-1673. doi.org/10.5713/ajas.17.0418.

Lin, J., K. S. Mateo, M. Zhao, A. K. Erickson, N. Garcia, D. He, R. A. Moxley, and D. H. Francis. 2013. Protection of piglets against enteric colibacillosis by intranasal immunization with K88ac (F4ac) fimbriae and heat labile enterotoxin of Escherichia coli. Vet. Microbiol. 162:731–739. doi:10.1016/j.vetmic.2012.09.025.

Liu, Y., C. D. Espinosa, J. J. Abellilla, G. A. Casas, L. V. Lagos, S. A. Lee, W. B. Kwon, J. K. Mathai, D. M. D. L. Navarro, N. W. Jaworski, and H. H. Stein. 2018. Non-antibiotic feed additives in diets for pigs: A review. Anim. Nutr. 4:113–125. doi:10.1016/j.aninu.2018.01.007.

Llames, C. R., and J. Fontaine. 1994. Determination of amino acids in feeds: collaborative study. J. Assoc. Off. Anal. Chem. 77:1362-1402. doi:10.1093/jaoac/77.6.1362

Marquardt, R. R., L. Z. Jin, J.-W. Kim, L. Fang, A. A. Frohlich, and S. K. Baidoo. 1999. Passive protective effect of egg-yolk antibodies against enterotoxigenic Escherichia coli K88+ infection in neonatal and early-weaned piglets. FEMS Immunol. Med. Microbiol. 23:283–288. doi:10.1111/j.1574-695x.1999.tb01249.x.

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

O’Loughlin, E. V., R. B. Scott, and D. G. Gall. 1991. Pathophysiology of infectious diarrhea: Changes in Intestinal structure and function. J. Pediatr. Gastroenterol. Nutr. 12:5-20. doi:10.1097/00005176-199101000-00004.

Pan, L., P. F. Zhao, X. K. Ma, Q. H. Shang, Y. T. Xu, S. F. Long, Y. Wu, F. M. Yuan, and X. S. Piao. 2017. Probiotic supplementation protects weaned pigs against enterotoxigenic Escherichia coli K88 challenge and improves performance similar to antibiotics. J. Anim. Sci. 95:2627–2639. doi:10.2527/jas2016.1243.

Park, S., B. Kim, Younghoon Kim, S. Kim, K. Jang, Youngwha Kim, J. Park, M. Song, and S. Oh. 2016. Nutrition and feed approach according to pig physiology. Korean J. Agric. Sci. 43:750–760. doi:10.7744/kjoas.20160078.

Park, S., J. J. Lee, B. M. Yang, J. H. Cho, S. Kim, J. Kang, S. Oh, D. Park, R. Perez-maldonado, J.-Y. Cho, I.-H. Park, H. B. Kim, and M. Song. 2020. Dietary protease improves growth performance, nutrient digestibility, and intestinal morphology of weaned pigs. J. Anim. Sci. Technol. 62:21–30. doi:10.5187/jast.2020.62.1.21.

Pettigrew, J. E. 2006. Reduced use of antibiotic growth promoters in diets fed to weanling pigs: dietary tools, part 1. Anim. Biotechnol. 17:207–215. doi:10.1080/10495390600956946.

Pluske, J. R., M. J. Thompson, C. S. Atwood, P. H. Bird, I. H. Williams, and P. E. Hartmann. 1996a. Maintenance of villus height and crypt depth, and enhancement of disaccharide digestion and monosaccharide absorption, in piglets fed on cows’ whole milk after weaning. Br. J. Nutr. 76:409–422. doi: 10.1079/bjn19960046.

Pluske, J. R., I. H. Williams, and F. X. Aherne. 1996b. Villous height and crypt depth in piglets in response to increases in the intake of cows’ milk after weaning. Anim. Sci. 62: 145-158. doi.org/10.1017/S1357729800014429.
Sakata, T. 1987. Stimulatory effect of short-chain fatty acids on epithelial cell proliferation in the rat intestine: a possible explanation for trophic effects of fermentable fibre, gut microbes and luminal trophic factors. Br. J. Nutr. 58:95-103. doi: 10.1079/bjn19870073.

Stein, H. H., and D. Y. Kil. 2006. Reduced use of antibiotic growth promoters in diets fed to weanling pigs: dietary tools, part 2. Anim. Biotechnol. 17:217–231. doi:10.1080/10495390600956946.

Tang, W., Y. Qian, B. Yu, T. Zhang, J. Gao, J. He, Z. Huang, P. Zheng, X. Mao, J. Luo, J. Yu, and D. Chen. 2019. Effects of Bacillus subtilis DSM32315 supplementation and dietary crude protein level on performance, gut barrier function and microbiota profile in weaned piglets. J. Anim. Sci. 97:2125–2138. doi: 10.1093/jas/skz090.

van Straalen, W. M., and B. M. Tas. 2010. Principles and applications of glucogenic nutrient feed evaluation for ruminants. Pages 147-162 in Dynamics in Animal Nutrition. J. Doppenberg and P. Van der Aar ed. Wageningen Academic Publishers, Wageningen, The Netherlands.

VDLUFA (Association of German Agricultural Investigators and Research Institutes). 1976. Agricultural Handbook Test and Investigation methodology (Method Book Vol. III): The chemical Analysis of Feed (1st – 8th Supplement Delivery, 3rd ed. VDLUFA Publishing House, Darmstadt, Germany.

Walsh, M. C., K. L. Saddoris, D. M. Sholly, R. B. Hinson, A. L. Sutton, T. J. Applegate, B. T. Richert, and J. S. Radcliffe. 2007. The effects of direct fed microbials delivered through the feed and / or in a bolus at weaning on growth performance and gut health. Livest. Sci. 108:254–257. doi:10.1016/j.livsci.2007.01.051.

Wang, S.P., Y. Lingyuan, S. T. Xiang, C. C. Li, L. Gang, F. K. Xiang, B. Francois, L. Y. Yu. 2011. Dietary supplementation with high-dose Bacillus subtilis or Lactobacillus reuteri modulates cellular and humoral immunities and improves performance in weaned piglets. J. Food Agric. Environ. 9:181–187. doi: https://doi.org/10.1234/4.2011.2083.

Wang, Z., L. Wang, Z. Chen, X. Ma, X. Yang, J. Zhang, and Z. Jiang. 2016. in vitro evaluation of swine-derived lactobacillus reuteri: Probiotic properties and effects on intestinal porcine epithelial cells challenged with enterotoxigenic Escherichia coli K88. J. Microbiol. Biotechnol. 26:1018–1025. doi:10.4014/jmb.1510.10089.

Wijtten P. J. A., J. van der Meulen, and M. W. A. Verstegen. 2011. Intestinal barrier function and absorption in pigs after weaning: a review. Br. J. Nutr. 105:967-981. doi: 10.1017/S0007114510005660.

Woyengo, T. A., and C. M. Nyachoti. 2011. Supplementation of phytase and carbohydrases to diets for poultry: A review. Can. J. Anim. Sci. 91:177-192. doi.org/10.4141/cjas10081.

Woyengo, T. A., J. C. Rodriguez-Lecompte, O. Adeola, and C. M. Nyachoti. 2011. Histomorphology and small intestinal sodium-dependent glucose transporter 1 gene expression in piglets fed phytic acid and phytase-supplemented diets. J. Anim. Sci. 89:2485–2490. doi:10.2527/jas.2010-3204.
Woyengo, T. A., R. Jha, E. Beltranena, and R. T. Zijlstra. 2016. In vitro degradation and fermentation characteristics of canola meals and cakes simulating the pig intestine. Animal. 10:911–918. doi: 10.1017/S1751731115002566.

Wu, G., S. A. Meier, and D. A. Knabe. 1996. Dietary glutamine supplementation prevents jejunal atrophy in weaned pigs. J. Nutr. 126:2578–2584. doi: 10.1093/jn/126.10.2578.

Yang, K. M., Z. Y. Jiang, C. T. Zheng, L. Wang, and X. F. Yang. 2014. Effect of Lactobacillus plantarum on diarrhea and intestinal barrier function of young piglets challenged with enterotoxigenic Escherichia coli K88. J. Anim. Sci. 92:1496–1503. doi:10.2527/jas.2013-6619.
**Figure 1.** Proportion of fecal scores of pigs fed diets without or with antibiotics or DFM

Fecal score: 1 = firm feces, 2 = soft feces, 3 = mild pasty diarrhea, 4 = pasty diarrhea, 5 = watery diarrhea and dehydration, 6 = most severe condition. NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).

**Figure 2.** Frequency of diarrhea of pigs fed diets without or with antibiotics or DFM

Fecal score: 1 = firm feces, 2 = soft feces, 3 = mild pasty diarrhea, 4 = pasty diarrhea, 5 = watery diarrhea and dehydration, 6 = most severe condition. NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).
Table 1. Composition of the experimental diets (as-fed basis)

| Item                                    | NC    | PC    | DFM   |
|-----------------------------------------|-------|-------|-------|
| **Ingredient, %**                       |       |       |       |
| Corn                                    | 48.70 | 48.70 | 48.70 |
| Soybean meal, 46% CP                    | 32.05 | 32.05 | 32.05 |
| Whey powder                             | 10.00 | 10.00 | 10.00 |
| Soybean oil                             | 2.84  | 2.84  | 2.84  |
| Wheat bran                              | 3.00  | 3.00  | 3.00  |
| Limestone                               | 0.41  | 0.41  | 0.41  |
| Dicalcium phosphate                     | 1.41  | 1.41  | 1.41  |
| Salt                                    | 0.19  | 0.19  | 0.19  |
| Vitamin premix<sup>2</sup>              | 0.05  | 0.05  | 0.05  |
| Mineral premix<sup>3</sup>              | 0.15  | 0.15  | 0.15  |
| L-Lysine·HCl                            | 0.50  | 0.50  | 0.50  |
| L-Threonine                             | 0.20  | 0.20  | 0.20  |
| DL-Methionine                           | 0.30  | 0.30  | 0.30  |
| L-Tryptophan                            | 0.09  | 0.09  | 0.09  |
| L-Valine                                | 0.11  | 0.11  | 0.11  |
| Neomycin + oxytetracycline              | -     | 0.25  | -     |
| Direct fed microbial                    | -     | -     | 0.05  |
| **Calculated nutrient composition**     |       |       |       |
| Crude protein, %                        | 20.49 | 20.49 | 20.49 |
| Ether extract, %                        | 5.35  | 5.35  | 5.35  |
| Acid detergent fiber, %                 | 3.39  | 3.39  | 3.39  |
| Neutral detergent fiber, %              | 8.69  | 8.69  | 8.69  |
| Electrolyte balance, mEq/kg             | 200   | 200   | 200   |
| Net energy, kcal/kg                     | 2,462 | 2,462 | 2,462 |
| **SID<sup>4</sup> amino acid, %**       |       |       |       |
| Lys                                     | 1.35  | 1.35  | 1.35  |
| Met                                     | 0.55  | 0.55  | 0.55  |
| Met+Cys                                 | 0.81  | 0.81  | 0.81  |
| Thr                                     | 0.85  | 0.85  | 0.85  |
|     |       |       |       |
|-----|-------|-------|-------|
| Trp | 0.30  | 0.30  | 0.30  |
| Ile | 0.75  | 0.75  | 0.75  |
| Val | 0.92  | 0.92  | 0.92  |
| Leu | 1.48  | 1.48  | 1.48  |
| His | 0.45  | 0.45  | 0.45  |
| Phe | 0.84  | 0.84  | 0.84  |
| Total Ca, % | 0.75 | 0.75 | 0.75 |
| Total P, %   | 0.68 | 0.68 | 0.68 |
| Digestible P, % | 0.35 | 0.35 | 0.35 |

1NC = negative control diet, PC = NC supplemented with 0.25% antibiotics, DFM = NC supplemented with 0.05% direct fed microbials product (Bacillus subtilis; DSM 32540). Antibiotics and DFM were added on top of basal diet.

2Provided the following per kilogram of diet: 11,011 IU vitamin A, 1,652 IU vitamin D₃, 55 IU vitamin E, 0.04 mg vitamin B₁₂, 4.4 mg menadione, 9.9 mg riboflavin, 61 mg pantothenic acid, 55 mg niacin, 1.1 mg folic acid, 3.3 mg pyridoxine, 3.3 mg thiamine, and 0.2 mg biotin.

3Provided the following per kilogram of diet: 165 mg Zn as ZnSO₄, 23 mg Fe as FeSO₄; 17 mg Cu as CuSO₄, and 44 mg Mn as MnSO₄.

4SID = standardized ileal digestible.
Table 2. Analyzed composition of the experimental diets (as-fed basis)

| Item                        | Diet¹ | NC    | PC    | DFM   |
|-----------------------------|-------|-------|-------|-------|
| Dry matter, %               |       | 89.96 | 89.74 | 89.92 |
| Crude protein, %            |       | 21.29 | 21.61 | 21.51 |
| Amino acid, %               |       |       |       |       |
| Lys                         |       | 1.54  | 1.58  | 1.59  |
| Met                         |       | 0.60  | 0.59  | 0.60  |
| Met+Cys                     |       | 0.94  | 0.93  | 0.95  |
| Thr                         |       | 1.00  | 0.97  | 0.99  |
| Trp                         |       | 0.35  | 0.36  | 0.35  |
| Arg                         |       | 1.34  | 1.37  | 1.35  |
| Ile                         |       | 0.89  | 0.90  | 0.89  |
| Leu                         |       | 1.68  | 1.70  | 1.70  |
| Val                         |       | 1.09  | 1.08  | 1.09  |
| His                         |       | 0.56  | 0.57  | 0.53  |
| Phe                         |       | 0.98  | 0.99  | 0.99  |
| Spore count Bacillus subtilis, CFU/g |   | 0.00  | 0.00  | 1.3E+06 |
| Background Bacilli, CFU/g    |       | 5.7E+03 | 1.7E+03 | <1E+03 |

¹NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (Bacillus subtilis; DSM 32540).
Table 3. Effect of different dietary treatments on growth performance of *Escherichia coli* challenged weaned pigs

| Item                        | Diet¹ | SEM  | P-value |
|-----------------------------|-------|------|---------|
|                             | NC    | PC   | DFM     |
| Body weight, kg             |       |      |         |
| Day 0                       | 8.02  | 8.00 | 8.62    | 0.299 | 0.28 |
| Day 3                       | 8.48  | 8.23 | 8.48    | 0.141 | 0.38 |
| Day 7                       | 8.54  | 8.55 | 8.68    | 0.294 | 0.97 |
| Day 14                      | 10.46 | 10.55| 10.44   | 0.627 | 0.67 |
| Day 21                      | 14.30 | 14.38| 14.95   | 0.960 | 0.63 |
| ADG, kg                     |       |      |         |
| Days 0 to 21                | 0.283 | 0.288| 0.310   | 0.050 | 0.91 |
| Days 3 to 21                | 0.308 | 0.333| 0.347   | 0.048 | 0.86 |
| ADFI, kg                    |       |      |         |
| Days 0 to 21                | 0.429 | 0.378| 0.403   | 0.050 | 0.73 |
| Days 3 to 21                | 0.483 | 0.421| 0.448   | 0.053 | 0.72 |
| G:F, kg/kg                  |       |      |         |
| Days 0 to 21                | 0.653 | 0.740| 0.766   | 0.037 | 0.14 |
| Days 3 to 21                | 0.633ᵇ| 0.778ᵃ|0.785ᵃ  | 0.033 | 0.01 |

ᵃᵇWithin a row, means without a common superscript differ (*P* < 0.05).

¹NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).
Table 4. Effect of different dietary treatments on gut histomorphology of *Escherichia coli* challenged weaned pigs

| Item                        | Diet | SEM | P-value |
|-----------------------------|------|-----|---------|
|                             | NC   | PC  | DFM     |        |
| Jejunum                     |      |     |         |        |
| Villus height, µm           | 305<sup>c</sup> | 406<sup>b</sup> | 435<sup>a</sup> | 2.131 | <0.001 |
| Crypt depth, µm             | 177  | 177 | 182     | 2.862 | 0.470 |
| Villus height: crypt depth, µm/µm | 1.72<sup>c</sup> | 2.29<sup>b</sup> | 2.40<sup>a</sup> | 0.037 | <0.001 |
| Ileum                       |      |     |         |        |
| Villus height, µm           | 298<sup>b</sup> | 389<sup>ab</sup> | 437<sup>a</sup> | 42.78 | 0.095 |
| Crypt depth, µm             | 170  | 164 | 171     | 16.18 | 0.95  |
| Villus height: crypt depth, µm/µm | 1.98 | 2.64 | 2.53    | 0.261 | 0.18  |

<sup>abc</sup> Within a row, means without a common superscript differ (*P* < 0.05).

<sup>1</sup>NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).
Table 5. Effect of different dietary treatments on visceral organ weights and gastrointestinal digesta pH of *Escherichia coli* challenged weaned pigs

| Item          | Organ weight, g/kg of BW | Digesta pH | SEM | P-value |
|---------------|--------------------------|------------|-----|---------|
|               | NC | PC | DFM | SEM | P-value |
| Spleen        | 1.76<sup>b</sup> | 2.53<sup>a</sup> | 2.03<sup>ab</sup> | 0.231 | 0.09 |
| Liver         | 26.9 | 28.7 | 26.3 | 1.125 | 0.33 |
| Stomach       | 7.31 | 8.88 | 8.00 | 0.575 | 0.18 |
| Small intestine | 35.4 | 41.2 | 41.2 | 2.918 | 0.29 |
| Cecum         | 2.08 | 2.39 | 2.08 | 0.181 | 0.40 |
| Colon         | 14.1 | 15.7 | 14.4 | 1.098 | 0.54 |
| Ileal         | 6.63 | 6.02 | 6.26 | 0.176 | 0.08 |
| Cecum         | 5.58 | 5.65 | 5.51 | 0.086 | 0.38 |

<sup>a</sup>b: Within a row, means without a common superscript differ (*P* < 0.05).

<sup>1</sup>NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).
Table 6. Effect of different dietary treatments on volatile fatty acids (VFA) in cecal digesta of *Escherichia coli* challenged weaned pigs

| Item                          | Diet¹  | SEM  | P-value |
|-------------------------------|--------|------|---------|
|                               | NC     | PC   | DFM     |        |
| VFA concentration, mM/ of DM  |        |      |         |        |
| Acetic acid                   | 2.49   | 2.58 | 1.87    | 0.525  | 0.531 |
| Propionic acid                | 1.59   | 1.33 | 0.94    | 0.302  | 0.266 |
| Butyric acid                  | 0.63   | 0.60 | 0.57    | 0.119  | 0.930 |
| Branched chain VFA            |        |      |         |        |
| Isobutyric acid               | 0.03   | 0.04 | 0.02    | 0.008  | 0.173 |
| Valeric acid                  | 0.23ᵃ  | 0.09ᵇ | 0.10ᵇ  | 0.040  | 0.051 |
| Isovaleric acid               | 0.03   | 0.03 | 0.02    | 0.007  | 0.288 |
| Molar ratios of VFA, %        |        |      |         |        |
| Acetic acid                   | 50.7   | 54.9 | 52.4    | 2.022  | 0.426 |
| Propionic acid                | 31.0   | 27.5 | 27.0    | 2.470  | 0.450 |
| Butyric acid                  | 12.9   | 14.3 | 16.8    | 1.856  | 0.268 |
| Branched chain VFA            |        |      |         |        |
| Isobutyric acid               | 0.47   | 0.97 | 0.41    | 0.189  | 0.141 |
| Valeric acid                  | 4.32ᵃ  | 1.47ᵇ | 2.85ᵃᵇ  | 0.613  | 0.037 |
| Isovaleric acid               | 0.61   | 0.84 | 0.53    | 0.165  | 0.420 |

ᵃᵇWithin a row, means without a common superscript differ ($P < 0.05$).

¹NC = negative control diet, PC = NC supplemented with 0.25% of antibiotics, and DFM = NC supplemented with 0.05% direct fed microbials product (*Bacillus subtilis*; DSM 32540).
Figure 2

X2 test: $P = 0.071$