



Original Research Article

Dietary supplementation of xylanase and protease on growth performance, digesta viscosity, nutrient digestibility, immune and oxidative stress status, and gut health of newly weaned pigs

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ABSTRACT

This study was to investigate the effect of dietary supplementation with xylanase and protease on growth performance, digesta viscosity, apparent ileal digestibility (AID) of nutrients, and gut health in nursery pigs. Forty-eight pigs (24 barrows and 24 gilts at 21 d of age with 7.2 ± 0.4 kg BW) were randomly allotted to 4 dietary treatments (2×2 factorial arrangement) in a randomized complete block design and fed in 2 phases (phase 1 for 10 d and phase 2 for 14 d). Factors were xylanase (0 or 45,000 XU/kg) and protease (0 or 300,000 U/kg). Feed intake and BW gain were measured on d 10 and 24. Titanium dioxide (0.25%) was added to all diets as an indigestible external marker from d 20 to 24. On d 24, all pigs were euthanized to obtain jejunal and ileal digesta to measure viscosity and apparent ileal digestibility. The jejunal mucosa was collected to measure immune and oxidative stress status. Jejunal tissues were used to measure morphology and crypt cells proliferation. In phase 2, xylanase increased ($P < 0.05$) the average daily gain (ADG) which was further increased ($P < 0.05$) when combined with protease. Overall, combinational use of xylanase and protease increased ($P < 0.05$) ADG compared with the use of xylanase or protease alone, whereas protease improved ($P < 0.05$) feed efficiency. In jejunum, xylanase reduced ($P < 0.05$) viscosity of digesta, mucosal malondialdehyde (MDA), crypt depth and crypt cells proliferation, and protease increased ($P < 0.05$) villus height, and decreased ($P < 0.05$) crypt depth and crypt cells proliferation. Collectively, xylanase improved growth performance, digesta viscosity, and oxidative stress, whereas protease improved feed efficiency and gut morphology. The combinational use of xylanase and protease enhanced growth performance of newly weaned pigs.

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1. Introduction

The early weaning is a delicate proceeding for pigs since pigs are suddenly exposed to nutritional, immunologic, and psychologic changes. Among these changes, the diet based on vegetables, dryer,

less digestible and containing antinutritional factors, replaces the sow milk which is rich in protein, fat and lactose, nutrients highly digestible. This promotes physiologic alteration and consequently affects the performance of newly weaned pigs.

It is well known that corn and soybean meal is the most used feedstuffs in the diet of non-ruminants in the world. However, these ingredients have a significant quantity of antinutritional factors that can interfere in the growth performance of the animals (Berrococo et al., 2015; Gutierrez et al., 2014; Kim et al., 2010; Taliércio and Kim, 2013). In young pigs, these effects are even more pronounced due to their low digestive capacity to vegetable-based diets (Lindberg, 2014).

The content of non-starch polysaccharides (NSP) in the plant cell wall limits the use of vegetable feedstuffs in the diet of pigs (Kerr and Shurson, 2013). The major NSP in the swine corn-soybean

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diets are arabinoxylan, present in corn (Jaworski et al., 2015), and xyloglucan and xylan in soybean (Karr-Lilienthal et al., 2005). Non-ruminant animals do not produce endogenous enzymes capable to digesting NSP. Once ingested, NSP can increase the digesta viscosity, alter the epithelial morphology of the intestine and reduce the digestibility of nutrients (Lindberg, 2014; Passos et al., 2015).

As well as, glycinin and β -conglycinin, the main storage globulins in soybean (Krishnan et al., 2007) have an allergenic effect that can also reduce the growth performance, affect the immune system and change the morphology of the intestinal epithelium (Krishnan et al., 2009; Wang et al., 2010; Zhao et al., 2010; Taliercio and Kim, 2013). Besides that, these proteins show resistance to hydrolysis by endogenous enzymes due the presence of disulfide bond, especially in young animals (Wang et al., 2011). Due to the immaturity of the digestive system of young animals, the immunoreactivity of these proteins and their partially digested segments are even more pronounced when compared to adult animals (Wang et al., 2010, 2009; Zhao et al., 2008).

Thus, the dietary supplementation with exogenous enzymes, such as xylanase, reduces the NSP content in the digesta and, consequently, enhances the use of nutrients (Kim et al., 2003; Lærke et al., 2015; Pedersen et al., 2012), whereas the protease complements the proteolytic activity, mainly hydrolyzing those proteins that are resistant to digestion by endogenous enzymes (Wang et al., 2011). These enhancements can also reduce the nutrient excretion in the environment (Ferket et al., 2002).

Therefore, it was hypothesized that by eliminating or reducing the effects of antinutritional factors, these enzymes enhance the growth performance of newly weaned pigs through the benefits in the gastrointestinal tract and the improvement in the nutrient digestibility. Thus, this study was conducted to evaluate the effect of the supplementation with xylanase and protease on growth performance, digesta viscosity, oxidative stress, immune status, digestibility of nutrients and gut health of pigs from 21 to 45 d of age.

2. Materials and methods

The protocol used in this study was approved by the Institutional Animal Care and Use Committee of North Carolina State University.

2.1. Animals, experimental design, and diets

A total of 48 newly weaned pigs (24 barrows and 24 gilts), with an initial body weight (BW) of 7.2 ± 0.4 kg, were allotted in a randomized complete block design with sex and body weight at weaning as blocking criteria. Four dietary treatments were arranged based on a 2×2 factors. First factor was supplementation of xylanase (0 or 45,000 XU/kg, Xylamax, BRI, Durham, NC) and the second factor was supplementation of protease (0 or 300,000 U/kg, Versazyme, BRI).

The experimental diets were formulated meeting the requirement for nursery pigs suggested by NRC (2012) in 2 phases: phase 1 (10 d) and phase 2 (14 d). The composition of basal diets is shown in Table 1.

Pigs had free access to the feed and water. Titanium dioxide (0.25%) was added to all diets from d 20 to 24 as an indigestible marker to determine the digestibility. The weight of the pigs and feed disappearance were recorded individually on d 10 and 24 to determine BW, average daily gain (ADG), average daily feed intake (ADFI), and gain to feed ratio (G:F).

2.2. Samples collection, and processing

Blood samples were collected from the jugular vein of all pigs at d 21 of the experiment. The blood samples (7 mL) were drawn into

Table 1
Composition of basal diets.

Item	Phase 1	Phase 2
Ingredient, %		
Corn	32.04	43.72
Soybean meal	23.00	27.00
Blood plasma	3.30	0.00
Corn DDGS	20.00	20.00
Whey permeate ¹	12.00	2.00
Poultry meal	5.00	3.00
L-Lys·HCl	0.35	0.35
DL-Met	0.08	0.05
L-Thr	0.03	0.03
Limestone	1.30	1.10
Vitamin premix ²	0.03	0.03
Mineral premix ³	0.15	0.15
Salt	0.22	0.22
Zinc oxide	0.25	0.25
Dicalcium phosphate	0.15	0.50
Poultry fat	2.00	1.50
Supplement (corn or enzyme)	0.10	0.10
Calculated composition		
DM, %	90.80	89.70
ME, MJ/kg	14.27	14.10
SID Lys, %	1.35	1.24
SID Met + Cys, %	0.74	0.68
SID Trp, %	0.25	0.22
SID Thr, %	0.79	0.73
Ca, %	0.80	0.71
STTD P, %	0.41	0.34
Total P, %	0.63	0.59

DDGS = distillers dried grains with solubles; SID = standardized ileal digestible; STTD = standardized total tract digestible.

¹ DairyLac80 (International Ingredient Corporation) was used as a source of whey permeate containing $(79.3 \pm 0.8)\%$ lactose.

² The vitamin premix provided the following per kilogram of complete diet: 6,613.8 IU of vitamin A as vitamin A acetate, 992.0 IU of vitamin D₃, 19.8 IU of vitamin E, 2.64 mg of vitamin K as menadiene sodium bisulfate, 0.03 mg of vitamin B₁₂, 4.63 mg of riboflavin, 18.52 mg of D-pantothenic acid as calcium pantothenate, 24.96 mg of niacin, and 0.07 mg of biotin.

³ The trace mineral premix provided the following per kilogram of complete diet: 4.0 mg of Mn as manganous oxide, 165 mg of Fe as ferrous sulfate, 165 mg of Zn as zinc sulfate, 16.5 mg of Cu as copper sulfate, 0.30 mg of I as ethylenediamine dihydroiodide, and 0.30 mg of Se as sodium selenite.

vacutainers without anticoagulant (BD, Franklin Lakes, NJ). Sera were obtained after centrifugation ($3,000 \times g$, 15 min) at room temperature, and then stored at -80°C in Eppendorf tubes until the analysis determining the concentration of tumor necrosis factor α (TNF- α), as an indicator of local inflammatory response, protein carbonyl and malondialdehyde (MDA), as an indicator of local oxidative stress status, and immunoglobulin G (IgG), as an indicator of local humoral immune status.

At the end of the d 24 of feeding, all the pigs were euthanized followed by removal of the gastrointestinal tract to samples collection. Digesta from ileum was collected in containers (50 mL), weighted and stored at -20°C . Before analysis, all samples were lyophilized, finely ground and stored until analyses to measure nutrient content to determine the apparent ileal digestibility (AID). Digesta from proximal jejunum was collected into falcon tubes (50 mL), placed on ice and immediately carried to the lab to measure its viscosity. As well as, approximately 10 mL of digesta from mid-colon (second third of colon) was collected into falcon tubes (15 mL) and placed on ice to measure pH.

Segments mid-jejunum (3 m after the duodenojejunal junction) were collected, rinsed with a 0.9% saline solution and then fixed in 10% buffered formaldehyde to be used for Ki-67 staining, and histological evaluation measuring the ratio of Ki-67 positive cells to total cells in the crypt (%), as an indicator of crypt cells proliferation, villus height, crypt depth, villus width, and villus height to crypt depth ratio.

Mucosal samples from mid-jejunum were scraped, placed in Eppendorf tubes (2 mL) and stored at -80°C (after snap-freezing in liquid nitrogen, immediately after collection). To measure the concentration of total protein, TNF- α , protein carbonyl, MDA, and immunoglobulin A and G (IgA and IgG), each sample was weighed (500 mg), suspended in 1 mL of phosphate-buffered saline (PBS) and homogenized on ice using a tissue homogenizer (Tissuemiser; Thermo Fisher Scientific Inc. Waltham, MA USA). After homogenization, samples were centrifuged ($14,000 \times g$ for 3 min) and the supernatant was divided in 5 aliquots and stored at -80°C until analyses.

2.3. Viscosity and pH

Samples of jejunum digesta from 50 mL tubes were divided into 2 falcon tubes (15 mL) and centrifuged at $1,000 \times g$ at 4°C for 10 min to obtain the liquid phase. Then, the liquid phase was removed to an Eppendorf tube (2 mL) to centrifuge at $10,000 \times g$ at 4°C for 10 min. The supernatant obtained was transferred to another Eppendorf tube (1.5 mL) for further measurement. 0.5 mL of digesta supernatant was placed in the viscometer (Brookfield Digital Viscometer, Model DV-II Version 2.0, Brookfield Engineering Laboratories Inc., Stoughton, MA), set at 25°C . The viscosity measurement was the average between 45.0/s and 22.5/s shear rates, and the viscosity values were recorded as apparent viscosity in millipascal-seconds (mPa s).

The pH was measured immediately after collecting using a pH meter (AB15 Basic, Thermo Fisher Scientific Inc., Waltham, MA), placed directly in the digesta.

2.4. Measurement of apparent ileal digestibility

The concentration of titanium dioxide of all samples (feed and digesta) was measured according to Myers et al. (2004), to determine the AID of nutrients. Gross energy (GE) content was measured in calorimeter bomb (Parr 6200 – Parr instrument company, Moline, Illinois). The nitrogen content was measured using a TruSpec N Nitrogen Determinator (LECO Corp., St. Joseph, MI) to calculate crude protein (CP, $6.25 \times \text{N}$). The AID of the nutrients was calculated using the equation:

$$\text{AID} = \left\{ 1 - \left[\left(\frac{\text{TiO}_{2\text{diet}}}{\text{TiO}_{2\text{digesta}}} \right) \times \left(\frac{\text{Nutrient}_{\text{digesta}}}{\text{Nutrient}_{\text{diet}}} \right) \right] \right\} \times 100,$$

in which $\text{TiO}_{2\text{diet}}$ and $\text{TiO}_{2\text{digesta}}$ were the concentrations of titanium dioxide in the diet and in the digesta; $\text{Nutrient}_{\text{digesta}}$ and $\text{Nutrient}_{\text{diet}}$ were the concentrations of nutrient in the digesta and in the diet.

2.5. Measurement of oxidative stress and immune status

The concentrations of MDA, protein carbonyl, IgG, IgA, and TNF- α were measured by ELISA methods using commercially available ELISA kits according to instructions of the manufacturers. The absorbance was read using an ELISA plate reader (Synergy HT, BioTek Instruments, Winooski, VT) and software (Gen5 Data Analysis Software, BioTek Instruments). The concentration was calculated based on the standard curve created from concentration and absorbance of the respective standard.

The concentration of mucosal total protein was determined using the kit Pierce BCA Protein Assay (23225#, Thermo Fisher Scientific Inc. Rockford, IL). The samples were diluted (1:80) in PBS to reach the working range for 20 to 2,000 $\mu\text{g}/\text{mL}$. The absorbance was measured at 562 nm.

Malondialdehyde concentrations in the mucosa and serum were measured using the Thiobarbituric Acid Reactive Substance Assay Kit (STA-330, Cell Biolabs, San Diego, CA). The MDA standard was used in a working range for 0 to 125 $\mu\text{mol}/\text{L}$. Aliquots of 100 μL of each standard and sample were pipetted into a microcentrifuge tubes, followed by addition of 100 μL of SDS lysis and incubation for 5 min at room temperature. Then, 250 μL of thiobarbituric acid reagent was added into each sample and standard, and incubated at 95°C for 60 min in water bath. All tubes were cooled to room temperature in an ice bath for 5 min before being centrifuged ($10,000 \times g$ for 15 min). Aliquots of 300 μL of supernatant were transferred to another tube with 300 μL of butanol and vortex for 1 min and centrifuge for 5 min at $10,000 \times g$. Aliquots of 200 μL of samples and standards were transferred to a 96 well microplate. The absorbance was measured at 532 nm, and the MDA concentration in the serum and mucosa was expressed as $\mu\text{mol}/\text{mL}$ and $\mu\text{mol}/\text{mg}$ protein, respectively.

The concentration of protein carbonyl was measured using the ELISA kit (STA-310, Cell Biolabs, San Diego, CA). Before measurement, serum and mucosa samples were diluted in PBS to reach the protein concentration at 10 $\mu\text{g}/\text{mL}$. The standard was prepared by mixing the oxidized BSA and reduced BSA to reach the working range for 0.375 to 7.5 nmol/mg protein. Aliquots of 100 μL of standard or sample were added into the 96-well Protein Binding Plate. The content of protein carbonyl in the samples and standard were derivated to dinitrophenyl (DNP) hydrazine and probed with an anti-DNP antibody, followed by an incubation with a horseradish peroxidase (HRP) conjugated with the secondary antibody. The absorbance was measured at 450 nm, and the concentration of protein carbonyl expressed as nmol/mg protein for both serum and mucosa.

The concentrations of TNF- α in mucosa and serum were measured using the Porcine Immunoassay ELISA Kit (PTA00; R&D System Inc. Minneapolis, MN), as described by Chaytor et al. (2011). The standard was used in a working range for 0 to 1,500 pg/mL. Fifty microliter of sample, standard and control was added to microplate wells coated with capture antibody in conjunction with biotinylated antibody reagent. Detection occurred using HRP, TMB (3,3', 5,5'-tetramethylbenzidine) substrate, and a stop solution of 2 mol/L H_2SO_4 . Absorbance was read at 450 nm and 550 nm and the TNF- α concentration in serum and mucosa was expressed as pg/mL and pg/mg protein, respectively.

Analysis to detect the concentrations of IgG and IgA was previously described by Chaytor et al. (2011). The serum and mucosa samples were diluted with PBS to 1:1,600 and 1:1,000, respectively, to analyze IgG using the kit ELISA Pig IgG (E101-104, Bethyl Laboratories, Inc, Montgomery, TX). The standard was used in a working range for 0 to 500 ng/mL. The absorbance was measured at 450 nm and the concentration of IgG in the serum and mucosa was expressed as $\mu\text{g}/\text{mL}$ and $\text{mg}/\mu\text{g}$ of protein, respectively. The mucosal samples were diluted to 1:400 with PBS to analyze IgA using the kit ELISA Pig IgA (E101-102, Bethyl Laboratories, Inc). The standard was used in a working range for 0 to 1,000 ng/mL. The absorbance was measured at 450 nm and the concentration of IgA in the mucosa was expressed as $\mu\text{g}/\text{mg}$ of protein.

2.6. Histological evaluation

Two sections of jejunum per pig fixed in 10% buffered formalin were transferred to a 70% ethanol solution and sent to North Carolina State University Histology Laboratory (College of Veterinary Medicine, Raleigh, NC) for dehydration, embedment, staining and Ki-67 assay according to their internal standard protocol, for morphological evaluation and Ki-67 immunohistochemistry staining. Villus height, villus width, and crypt depth were measured

using a camera Infinity 2-2 digital CCD attached to a microscope Olympus CX31 (Lumenera Corporation, Ottawa, Canada). Lengths of 15 well-oriented intact villi and their associated crypts were measured in each slide. The villi length was measured from the top of the villi to the villi-crypt junction, the villi width measured in the middle of the villi, and the crypt depth was measured from the villi-crypt junction to the bottom of the crypt. Then, the villus height to crypt depth (VH:CD) ratio was calculated. Images of 15 intact crypts from each slide were cropped and the Image JS software was used for calculating the ratio of Ki-67 positive cells to total cells in the crypt (%). All analyses of the intestinal morphology were executed by the same person.

2.7. Statistical analyses

A randomized complete block design was used. Main effects were 2 factors (xylanase, protease) and their interaction which were handled fixed effects. Sex and initial BW were blocks which were handled random effects. Data were analyzed using the MIXED procedure in SAS version 9.4 (SAS Inc., Cary, NC, USA). The experimental unit was the pig as pigs were individually housed and fed. The means were separated using the LSMEANS statement in SAS. When an interaction between 2 factors was significant or tended to be significant, a pairwise comparison was made using the PDIF option in SAS. Statistical differences were considered significant with $P < 0.05$. Tendency was considered when $0.05 \leq P < 0.10$.

3. Results

3.1. Growth performance

The using of either xylanase or protease did not affect the BW of pigs at d 10 after weaning (Table 2). However, at d 24 after weaning, the BW was increased ($P < 0.05$) when xylanase and protease were used together, whereas it was not affected when each enzyme was used individually. In phase 1, the individual or combined use of xylanase and protease did not affect the ADG of pigs. Meanwhile, in phase 2, xylanase increased ($P < 0.05$) the ADG, however, the benefit of xylanase on the ADG was further enhanced ($P < 0.05$) when protease was used together. Overall, combinational use of xylanase and protease increased ($P < 0.05$) the ADG compared with the use of xylanase or protease alone.

The ADFI was not affected by the enzymatic supplementation during phase 1. However, during phase 2, the ADFI tended to be increased ($P = 0.063$) by the xylanase supplementation. Whereas, during the entire period, ADFI tended to be increased ($P = 0.099$) by the combinational use of xylanase and protease. There was no significant effect on G:F by dietary supplementation of either enzymes when each phase was analyzed separately, but in overall, the G:F was improved ($P < 0.05$) by protease supplementation.

3.2. Apparent ileal digestibility and digesta characteristics

The AID of dry matter (DM), GE, and CP was not affected using either enzymes (Table 3). The use of xylanase in the diet of pigs reduced the ileal digesta viscosity ($P < 0.05$), but the pH of colon digesta was not affected by the use of either enzymes.

3.3. Immune and oxidative status

Serum and mucosal concentrations of TNF- α , IgG and IgA were not affected by the use of either enzymes, individually or combined (Table 4). However, in the mucosa of jejunum, the use of xylanase reduced ($P < 0.05$) the concentration of MDA and tended to decrease ($P = 0.066$) the concentration of protein carbonyl. The using of protease in the diet of newly weaned pigs did not affect the parameters of immune and oxidative status measured in this study.

3.4. Histology and immunohistochemistry

The using of protease increased ($P < 0.05$) the villi length in jejunum, whereas the using of protease tended to increase ($P = 0.09$) it (Table 5). The individual using of xylanase and protease reduced ($P < 0.05$) the crypt depth, and crypt cells proliferation, and increased the VH:CD ratio ($P < 0.05$). The villi width was not affected by both factors. There was no interaction between 2 factors.

4. Discussion

The use of exogenous enzymes in the diet of pigs is an important tool to reduce antinutritional factors, improve digestion and nutrient absorption efficiency, and consequently enhance the growth performance (Adeola and Cowieson, 2011; Kiarie et al.,

Table 2
Performance of pigs fed diets with xylanase (Xyl) and protease (Pro) supplementation.

Item	Treatment				SEM	P-value		
	Xyl-		Xyl+			Xyl	Pro	Xyl + Pro
	Pro-	Pro+	Pro-	Pro+				
Body weight, kg								
Initial	7.2	7.2	7.2	7.2	0.4	0.742	0.951	0.789
d 10	10.7	10.6	10.5	11.0	0.5	0.726	0.442	0.155
d 24	18.1 ^{ab}	17.7 ^b	17.8 ^b	19.3 ^a	0.7	0.142	0.243	0.046
ADG, kg/d								
d 0 to 10	0.354	0.335	0.321	0.380	0.025	0.799	0.416	0.121
d 10 to 24	0.526 ^a	0.510 ^a	0.528 ^a	0.591 ^b	0.022	0.032	0.212	0.041
d 0 to 24	0.454 ^{ab}	0.437 ^b	0.442 ^b	0.503 ^a	0.020	0.149	0.222	0.036
ADFI, kg/d								
d 0 to 10	0.414	0.390	0.391	0.445	0.028	0.536	0.566	0.132
d 10 to 24	0.713	0.674	0.723	0.773	0.033	0.063	0.842	0.121
d 0 to 24	0.589 ^{ab}	0.556 ^b	0.585 ^{ab}	0.636 ^a	0.029	0.135	0.711	0.099
G:F								
d 0 to 10	0.850	0.855	0.814	0.869	0.031	0.727	0.343	0.424
d 10 to 24	0.740	0.760	0.733	0.771	0.018	0.897	0.118	0.615
d 0 to 24	0.773	0.787	0.756	0.799	0.014	0.830	0.035	0.279

^{a, b} Within a row, means without a common superscript letter differ ($P < 0.05$).

Table 3

Apparent ileal digestibility of GE, CP and DM of diets and characteristics of digesta with xylanase (Xyl) and protease (Pro) supplementation on DM basis.

Item	Treatment				SEM	P-value		
	Xyl–		Xyl+			Xyl	Pro	Xyl + Pro
	Pro–	Pro+	Pro–	Pro+				
AID GE, %	67.2	66.1	66.7	68.8	2.9	0.705	0.855	0.586
AID CP, %	78.5	79.4	78.7	79.6	1.6	0.888	0.557	0.982
AID DM, %	67.1	61.1	64.4	60.1	3.2	0.635	0.138	0.720
pH digesta	6.27	6.35	6.30	6.45	0.10	0.529	0.258	0.725
Viscosity of digesta, mPa·s	2.67	2.71	2.48	2.24	0.14	0.016	0.452	0.307

GE = gross energy; CP = crude protein; DM = dry matter.

Table 4

Oxidative stress and immune parameters of pigs fed diets with xylanase (Xyl) and protease (Pro) supplementation.

Item	Treatment				SEM	P-value		
	Xyl–		Xyl+			Xyl	Pro	Xyl + Pro
	Pro–	Pro+	Pro–	Pro+				
Protein carbonyl								
Mucosa, nmol/mg of protein	1.15	1.07	0.96	0.79	0.12	0.066	0.322	0.724
Serum, nmol/mg of protein	0.62	0.58	0.55	0.51	0.09	0.443	0.647	0.991
MDA								
Mucosa, μ mol/mg of protein	1.21	1.07	0.98	0.92	0.11	0.022	0.212	0.500
Serum, μ mol/mL	23.12	20.85	23.42	18.46	3.91	0.763	0.301	0.699
IgG								
Mucosa, μ g/mg of protein	3.55	3.48	3.72	3.44	0.42	0.846	0.597	0.755
Serum, μ g/mL	5.34	5.17	4.76	4.82	0.49	0.288	0.895	0.791
IgA								
Mucosa, μ g/mg of protein	1.12	0.82	1.16	1.10	0.13	0.187	0.143	0.315
TNF- α								
Mucosa, pg/mg of protein	1.17	0.93	0.94	1.00	0.19	0.664	0.625	0.432
Serum, pg/mL	126.70	112.64	121.74	115.40	7.22	0.881	0.171	0.600

MDA = malondialdehyde; Ig = immunoglobulin; TNF- α = tumor necrosis factor α .**Table 5**

Jejunum morphology and the ratio of Ki-67 positive cells to total cells in the crypt of pigs fed diets with xylanase (Xyl) and protease (Pro) supplementation.

Item	Treatment				SEM	P-value		
	Xyl–		Xyl+			Xyl	Pro	Xyl + Pro
	Pro–	Pro+	Pro–	Pro+				
Villus height, μ m	422.1	474.1	456.3	512.5	21.4	0.092	0.014	0.919
Villus width, μ m	97.1	98.1	101.6	97.0	3.9	0.649	0.624	0.439
Crypt depth, μ m	238	202	220	176	9	0.019	<0.001	0.695
VH:CD ratio ¹	1.77	2.38	2.12	2.94	0.12	<0.001	<0.001	0.346
Ki-67 positive, % ²	23.3	18.3	19.7	15.5	1.4	0.011	<0.001	0.739

¹ Villus height to crypt depth ratio.² Ratio of Ki-67 positive cells to total cells in the crypt.

2013). However, the data related to the use of xylanase and protease shown in the literature is not consistent yet. Apparently, this is due the interactions between the age of the animals, diet composition and the way in which enzymes are used, individually or combined (Adeola and Cowieson, 2011; Kerr and Shurson, 2013; Kiarie et al., 2013; Lindberg, 2014).

This study showed that the final BW enhanced only when xylanase and protease were used together. This effect was due the ADG has similar effect in second phase and in overall. The improvement in the ADG can be partially explained by the tendency of enhancement in the ADFI in the phase 2 using xylanase and in overall when both enzymes were used together, as well as by the higher feed efficiency promoted by the use of protease in overall.

One of the factors that influence the feed intake are the physicochemical properties of the NSP, as water solubility and fermentability and their interactions (Kerr and Shurson, 2013). In

corn-soybean diets, the major fraction of NSP is insoluble (Gutierrez et al., 2014; Jaworski et al., 2015; Ngoc et al., 2012). The insoluble NSP acts preventing the digestive enzymatic activity on nutrients inside of the plant cell wall (Nortey et al., 2007; O'Neill et al., 2012; Owusu-Asiedu et al., 2010; Tervilä-Wilo et al., 1996) and improving the digesta passage rate and the chyme bulk (Jha and Berrocoso, 2015; Nortey et al., 2007). On the other hand, soluble NSP have high water holding capacity and viscosity which can improve the digesta bulk (Berrocoso et al., 2015; Jha and Berrocoso, 2015; McDonald et al., 2001). It is important to emphasize that there is a crescent availability and use of coproducts, such as dried distillers grains and soluble (DDGS) to feed, and the NSP content in this ingredients is higher than in the respectively unprocessed grain (Choct, 2015; Gutierrez et al., 2014; Jaworski et al., 2015). The distention in wall of the digestive tract due the improvement of the digesta bulk stimulates the production of cholecystokinin (CCK), an hormone that acts in the control of satiety, as well as stimulates the

pancreatic synthesis and secretion (McDonald et al., 2010). This could improve endogenous losses, and consequently affects the growth performance (Agyekum et al., 2015; Agyekum and Nyachoti, 2017). Thus, the ADG improvement in the phase 2 due the use of xylanase can be explained by the degradation of the arabinoxylan which was proven by the reduction of 13% of the ileal digesta viscosity. The capacity to improve the viscosity has been related to the deleterious effect of NSP in the intestinal lumen (Choct et al., 2004; McDonald et al., 2001; Wellock et al., 2008). Besides that, the partial hydrolysis of the NSP results in oligosaccharides that can act as prebiotics, as well as releasing encapsulated nutrients from the cell (Agyekum et al., 2015; Montagne et al., 2003; Pedersen et al., 2012), what can also improve the growth performance (Kiarie et al., 2016, 2013).

Another factor is the content of glycinin and β -conglycinin in the corn-soybean diet of pigs (Zhao et al., 2008). Nishi et al. (2003) demonstrated, in rats, that β -conglycinin binds some components of the gastrointestinal cell wall and stimulates the synthesis of CCK. Thus, the protease supplementation, capable of hydrolyzing proteins with disulfide bonds and reducing their effects on the intestinal mucosa, may increase feed intake (Zuo et al., 2015). However, the effect of protease used in the current study on the ADFI tended to be higher when combined with xylanase, due the reduction of viscosity, since, according to Adeola e Cowieson (2011), the higher viscosity reduces the access of enzymes to substrates.

The improvement of feed efficiency with the using of protease in this study indicates a reduction of the maintenance nutritional requirements due the degradation of glycinin and β -conglycinin. Beyond stimulating the CCK secretion, the presence of that globulins in the diet can activate the immune system and it causes damage on enterocytes, reduces villi length, improves crypts depth and the proliferation of enterocyte (Jun et al., 2009; Pluske et al., 1997; Zhang et al., 2013; Zhao et al., 2010). This induces the organism to mobilize nutrients to repair the intestinal epithelium, to immune function and to the cell proliferation (Xu, 2014).

Even with enhanced growth performance observed in this study, the dietary supplementation with xylanase and protease did not affect the AID of DM, CP or GE. Although many studies have reported that the use of xylanase (Cadogan and Choct, 2015; Passos et al., 2015; Yin et al., 2001) and protease (Chen et al., 2017; Wang et al., 2011; Yin et al., 2001; Zuo et al., 2015) in the swine diet improves the nutrient digestibility. This can be due the high ratio between insoluble and soluble NSP in corn-soybean meal diets, since, according to Urriola e Stein (2010), insoluble NSP interfere less in the digestibility than soluble NSP. Besides that, the short chain fat acid (SCFA) produced by the fermentation of carbohydrates are not totally counted in the analysis of AID, although they contribute to the growth performance (Owusu-Asiedu et al., 2010, 2006). The major part of the NSP fermentation occurs in the cecum-colon portion (Montagne et al., 2003; Serena et al., 2008), mainly in newly weaned pigs (Knudsen et al., 2012), because they do not have the digestive tract totally developed and have high digesta passage rate (Cadogan and Choct, 2015; Lindberg, 2014).

The dietary supplementation with xylanase and protease did not affect the immune status of the pigs, despite the reduction in the viscosity which is correlated to the decrease in the pathogenic microorganism proliferation in the small intestine (Agyekum et al., 2015; Agyekum and Nyachoti, 2017; Kim et al., 2012; McDonald et al., 2001; Montagne et al., 2003). Probably, this is due the high ratio between insoluble and soluble NSP, as well as the high digesta passage rate in pigs, that reduces the proliferation of microorganism in the small intestine (Choct, 1997; Molist et al., 2014; Montagne et al., 2003).

However, the physicochemical properties of the digesta, due the NSP and low digestibility proteins content (Adeola and Cowieson,

2011), can act directly on molecules in the cell wall of the intestine (Ruemmele et al., 2002). This can explain the reduction of the oxidative stress due the supplementation with xylanase. The MDA and the protein carbonyl are the final product of the oxidation of lipids and proteins, respectively (Kwiecien et al., 2014) that have been used as indicators of oxidative stress (Shacter, 2000).

Products of the oxidative stress can affect important compounds in the cell wall, such as lipids and proteins, causing the cell destruction and, consequently, reduction of villi length (Assimakopoulos et al., 2011; 2007; Sido et al., 2017). According to Pluske et al. (1997), the villi reduction caused by the increasing of cell losses is associated to the improvement of the crypt cells proliferation and, consequently, the crypt depth. Thus, the reduction of the oxidative stress found in this study due the xylanase supplementation can explain the enhancement in the morphology in jejunum, such as the tendency to improve villi length and the decrease of crypt depth and cell proliferation. Also, the enterocyte proliferation may have been reduced by the use of xylanase due the decrease in the viscosity, once the lower viscosity results in a lower production of SCFA (Serena et al., 2008). Some fatty acids in the lumen stimulate the enterocyte proliferation (Knudsen et al., 2012).

The protease was more efficient in the intestinal morphology maintenance than the xylanase in this study, once it increases the villi length and reduces the crypt depth and cell proliferation. According to Chen et al. (2011), the content of β -conglycinin on the intestinal cell stimulates the synthesis of mitogen-activated protein kinases 8 (MAPK8), which induces both apoptosis and enterocyte proliferation (Rao, 2001). This was confirmed by Zhao et al. (2010), who observed an increasing in the proliferation rate, apoptosis and enterocyte migration when adding glycinin and β -conglycinin in the diets of pigs.

5. Conclusion

Supplementation of xylanase (45,000 XU/kg) enhanced growth performance and gut morphology, reduced digesta viscosity, and reduced intestinal oxidative stress. Supplementation of protease (300,000 U/kg) enhanced feed efficiency and the gut morphology. The combined use of xylanase and protease enhanced the growth performance of newly weaned pigs.

Conflicts of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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