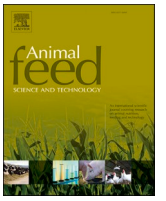
Animal Feed Science and Technology 313 (2024) 115994

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci



Exogenous xylanase increases total tract digestibility of energy and fiber in diets for gestating and lactating sows, but does not influence reproductive performance of sows

Jessica P. Acosta [a], Charmaine D. Espinosa [b,1], Gemma González-Ortiz [c], Sofia González-LasHeras [d,e], Maria J. Rodríguez-Lagunas [d,e], Francisco J. Pérez-Cano [d,e], Hans H. Stein [a,b,*]

[a] Division of Nutritional Sciences, University of Illinois, Urbana, IL 61801, USA
[b] Department of Animal Sciences, University of Illinois, Urbana, IL 61801, USA
[c] AB Vista, Marlborough, UK
[d] Physiology Section, Department of Biochemistry and Physiology, Faculty of Pharmacy and Food Science, University of Barcelona, Barcelona 08028, Spain
[e] Nutrition and Food Safety Research Institute (INSA-UB), Santa Coloma de Gramenet 08921, Spain

ARTICLE INFO

Keywords:
digestibility
energy
fiber
reproductive performance
sows
xylanase

ABSTRACT

The hypothesis that exogenous xylanase added to diets for gestating and lactating sows will increase the apparent total tract digestibility (ATTD) of gross energy (GE) and total dietary fiber (TDF), increase digestible energy (DE) and metabolizable energy, and improve the reproductive performance of sows was tested. Two diets for gestating sows and two diets for lactating sows were formulated without or with 100 g per ton of an exogenous xylanase (16,000 units/kg). Diets were fed in two consecutive reproductive cycles. From 106 animals, 48 pregnant sows, organized in 4 blocks of 12 sows (6 sows per treatment in each block), were placed for 10 days in metabolism crates starting on day 35 (mid-gestation) and again on day 95 (late-gestation) with feces and urine being collected for 4 days. Sows were moved to the lactation unit on day 106 of gestation and feeding of lactation diets was initiated. Fecal samples were collected (grab-sampling) from days 10–14 post-farrowing. The number and weight of pigs born, mummified, stillborn, and weaned per sow were recorded, and survival rate and litter average daily gain were calculated. Litters were weaned on day 20 ± 1. All animals were rebred and 46 sows were placed in metabolism crates in mid and late-gestation as in the first cycle, and treatments in the farrowing unit during the second cycle were also as in the first cycle; however, colostrum and milk samples were collected from sows in the second cycle. Results indicated that reproductive performance was not different between sows fed control diets and sows fed diets with xylanase during the two reproductive cycles. In the first gestation period, the ATTD of TDF in late-gestation was greater ($P < 0.05$) in sows fed the diet with xylanase than in sows fed the control diet. During the first lactation, sows fed the diet with xylanase had greater ($P < 0.05$) ATTD of GE and TDF,

Abbreviations: ADG, average daily gain; ANOSIM, analysis of similarities; ATTD, apparent total tract digestibility; BXU, beechwood xylanase units; DDGS, distillers dried grains with solubles; DE, digestible energy; DM, dry matter; GE, gross energy; IDF, insoluble dietary fiber; Ig, immunoglobulin; ME, metabolizable energy; NMDS, non-metric multi-dimensional scaling; SDF, soluble dietary fiber; TDF, total dietary fiber.

* Corresponding author at: Division of Nutritional Sciences, University of Illinois, Urbana, IL 61801, USA.
E-mail address: hstein@illinois.edu (H.H. Stein).
[1] Present address: EnviroFlight, Raleigh, NC, USA.

https://doi.org/10.1016/j.anifeedsci.2024.115994
Received 24 February 2024; Received in revised form 10 May 2024; Accepted 15 May 2024
Available online 18 May 2024

and greater ($P < 0.05$) DE than sows fed the control diet. During the second gestation, sows fed the diet with xylanase had greater ($P < 0.05$) DE in mid-gestation. During the second lactation, sows fed the diet with xylanase had greater ($P < 0.05$) ATTD of GE and TDF, and greater ($P < 0.05$) DE than sows fed the control diet. In conclusion, DE was greater in diets with xylanase than in control diets during the two reproductive cycles, and sows fed the lactation diet with xylanase had greater digestibility of fiber than sows fed the control diet.

1. Introduction

Carbohydrases may increase the fermentability of dietary fiber in swine diets by hydrolyzing non-starch polysaccharides into oligosaccharides and sugars (Patience and Petry, 2019). In particular, the enzyme xylanase hydrolyzes the β-(1−4) glycosidic bonds between xylose units in the backbone of arabinoxylans that are present in cereal grains and grain coproducts (Navarro et al., 2019). As a result, xylanase liberates a combination of xylose units that can be absorbed or fermented and xylo-oligosaccharides that can be fermented by intestinal microbiota (Dodd and Cann, 2009). Indeed, xylanase increased the disappearance of dietary fiber in diets for growing pigs (Passos et al., 2015; Pedersen et al., 2015a; Abelilla and Stein, 2019), increased energy digestibility (Nortey et al., 2007; Yang et al., 2016; Torres-Pitarch et al., 2019), and improved growth performance of pigs (Tsai et al., 2017; He et al., 2020; Petry et al., 2020). Xylanase also reduced pig mortality (Zier-Rush et al., 2016) and improved gut barrier integrity in nursery pigs (Tiwari et al., 2018; He et al., 2020). However, data demonstrating the efficacy of xylanase in gestating and lactating sows on reproductive performance and nutrient digestibility are limited. Inclusion of xylanase in a corn-soybean meal diet for sows increased nutrient digestibility during lactation, but no effects were observed during gestation (de Souza et al., 2007). A carbohydrase mixture added to high-fibrous diets fed to gestating and lactating sows increased digestibility of nutrients and fiber (Crome et al., 2023; Shipman et al.,

Table 1
Analyzed nutrient composition of ingredients (as-fed basis).

Item	Corn	Soybean meal	Soybean hulls	Corn distillers dried grains with solubles	Wheat middlings
Gross energy, MJ/kg	16.2	17.5	16.4	18.7	16.6
Dry matter, g/kg	876.2	895.8	907.4	873.1	886.5
Ash, g/kg	15.9	63.4	46.8	62.4	47.2
Acid-hydrolyzed ether extract, g/kg	39.6	27.8	45.1	91.7	46.4
Crude protein, g/kg	69.8	468.0	123.7	286.8	145.6
Starch, g/kg	621.0	21.0	9.6	37.0	258.0
Insoluble dietary fiber, g/kg	97.3	140.2	613.4	338.1	312.3
Soluble dietary fiber, g/kg	N.D.[a]	33.5	57.2	24.5	26.5
Total dietary fiber, g/kg	97.3	173.7	670.6	362.6	338.8
Indispensable amino acids, g/kg					
Arg	4.2	32.4	5.9	12.9	9.6
His	2.4	11.7	2.9	7.9	3.9
Ile	3.3	20.9	4.4	11.4	4.5
Leu	9.4	35.8	8.0	32.1	9.2
Lys	3.9	29.5	8.3	9.7	6.5
Met	1.9	6.2	1.4	5.4	2.3
Phe	4.2	23.7	4.8	12.2	5.8
Thr	3.3	17.8	4.3	11.3	4.9
Trp	0.7	6.2	0.7	1.7	1.3
Val	4.0	21.3	5.0	14.0	6.5
Dispensable amino acids, g/kg					
Ala	5.9	19.8	5.0	18.9	7.0
Asp	7.0	51.8	11.3	17.3	10.6
Cys	1.8	6.5	2.2	5.5	3.3
Glu	16.6	85.7	14.8	35.5	27.0
Gly	3.5	19.5	9.1	11.0	7.8
Pro	6.6	21.7	5.7	20.1	8.1
Ser	4.1	19.7	6.2	12.5	5.5
Tyr	2.3	17.6	5.1	9.3	3.8
Minerals					
Ca, g/kg	1.3	2.8	6.1	4.1	2.2
P, g/kg	3.6	7.3	1.7	11.6	11.8
K, g/kg	3.5	20.1	12.7	12.4	9.9
Mg, g/kg	0.9	2.6	2.3	3.2	3.2
Na, g/kg	0.4	0.1	0.3	3.4	0.1
Cu, mg/kg	3.2	10.2	8.7	31.1	5.6
Zn, mg/kg	57.1	161.4	359.9	86.4	137.6
Fe, mg/kg	11.1	25.2	14.8	35.9	120.7
Mn, mg/kg	97.1	46.9	40.3	117.8	82.6

[a] N.D. = Not detected.

2023). Inclusion of xylanase in a wheat-based lactation diet increased sow feed intake and nutrient digestibility and reduced sow body weight loss; however, milk yield and piglet performance were not affected (Zhou et al., 2018). There are, however, limited data on the impact of xylanase on energy and fiber digestibility in gestating and lactating sows, and it is not known how feeding xylanase during the entire reproductive cycle influences lactation performance. For growing pigs, it was demonstrated that xylanase needs to be fed for at least 28 days to have a significant impact on nutrient and energy digestibility (Petry et al., 2024). It is however, not known if sows also need a prolonged period of time for adaptation to xylanase, but if that is the case, it is expected that the response to xylanase is greater in the second reproductive cycle after start of feeding xylanase than in the first reproductive cycle. However, this hypothesis has not been experimentally verified. Therefore, an experiment was conducted to test the hypothesis that supplementation of xylanase to gestation and lactation diets will increase the apparent total tract digestibility (ATTD) of gross energy (GE), dry matter (DM), and total dietary fiber (TDF), increase digestible energy (DE) and metabolizable energy (ME), and improve reproductive performance of gestating and lactating sows fed diets containing corn, soybean meal, corn distillers dried grains with solubles (DDGS), wheat middlings, and soybean hulls during two reproductive cycles. It was also hypothesized that the effect of xylanase in diets for sows will be greater in the second than in the first reproductive cycle after start of feeding xylanase. A third hypothesis that addition of xylanase in diets for sows may influence health of the offspring by changes in immunoglobulin (Ig) composition of colostrum and milk was also tested.

2. Materials and methods

The protocol for the experiment was submitted to the Institutional Animal Care and Use Committee at the University of Illinois (Urbana, IL, USA) and the protocol was approved prior to initiation of the experiment.

2.1. Experimental diets

Two gestation diets and two lactation diets were formulated to meet estimated requirements for gestating and lactating sows (NRC, 2012; Tables 1, 2, and 3). Within each stage of production, a control diet containing corn, soybean meal, corn DDGS, wheat middlings, and soybean hulls was formulated, and an additional diet was formulated by adding 0.1 g per kg of an exogenous xylanase (Econase XT; AB Vista, Marlborough, UK) to the control diet. The 0.1 g of xylanase provided 16,000 ± 3200 beechwood xylanase units (BXU) per kg. Beechwood xylanase unit is the amount of enzyme that will release 0.06 micromoles of reducing sugars (xylose equivalents) from beechwood xylan per minute at pH 5.3 and 50 °C. All diets were fed as mash diets during two consecutive reproductive cycles. Ten batches of gestation diets and 5 batches of lactation diets were mixed, and diet samples were collected for each batch of feed produced. Each batch of diets was analyzed for xylanase activity immediately after production and before feeding of the batch started to ensure diets were mixed correctly. At the conclusion of the experiment, diet samples were pooled and subsampled for chemical analysis. Diets for lactating sows contained 4 g/kg titanium dioxide as an indigestible marker, but an indigestible marker was not included in

Table 2
Ingredient composition of experimental diets, as-fed basis.

Ingredient, g/kg	Gestation		Lactation	
	Control	Xylanase[a]	Control	Xylanase
Corn	351.8	301.8	547.6	497.6
Soybean meal	60.0	60.0	200.0	200.0
Soybean hulls	150.0	150.0	100.0	100.0
Corn distillers dried grains with solubles	200.0	200.0	-	-
Wheat middlings	200.0	200.0	100.0	100.0
Soybean oil	10.0	10.0	15.0	15.0
Econase XT premix[b]	-	50.0	-	50.0
Calcium carbonate	14.0	14.0	8.0	8.0
Dicalcium phosphate	3.5	3.5	14.0	14.0
L-Lysine HCl, 788 g/kg	1.7	1.7	1.9	1.9
L-Threonine	-	-	0.5	0.5
Titanium dioxide	-	-	4.0	4.0
Sodium chloride	4.0	4.0	4.0	4.0
Vitamin-mineral premix[c]	5.0	5.0	5.0	5.0

[a] Xylanase = Econase XT; AB Vista, Marlborough, UK.
[b] The Econase-XT premix contained 320,000 BXU/kg of exogenous xylanase (0.1 kg containing 160 million BXU/kg was mixed with 49.9 kg of ground corn). At 50 g/kg inclusion, the final diets were expected to contain 16,000 BXU/kg of xylanase. BXU is the amount of enzyme that will release 0.06 micromoles of reducing sugars (xylose equivalents) from beechwood xylan per min at pH 5.3 and 50 °C.
[c] The vitamin-mineral premix provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

Table 3
Analyzed composition of experimental diets, as-fed basis.

Item	Gestation		Lactation	
	Control	Xylanase[a]	Control	Xylanase
Gross energy, MJ/kg	16.5	16.6	16.1	16.1
Dry matter, g/kg	880.1	882.4	880.1	879.0
Ash, g/kg	55.9	56.7	53.4	56.4
Acid-hydrolyzed ether extract, g/kg	55.5	56.5	42.2	38.7
Crude protein, g/kg	161.1	161.9	157.1	158.8
Starch, g/kg	299.0	282.0	369.0	386.0
Insoluble dietary fiber, g/kg	269.0	271.0	206.0	185.0
Soluble dietary fiber, g/kg	32.0	28.0	14.0	16.0
Total dietary fiber, g/kg	301.0	299.0	220.0	201.0
Indispensable amino acids, g/kg				
Arg	8.4	8.6	9.1	9.3
His	4.1	4.3	3.9	4.0
Ile	5.6	6.0	6.5	6.8
Leu	13.8	14.9	12.6	13.3
Lys	8.3	8.8	9.4	9.8
Met	2.6	2.6	2.2	2.3
Phe	6.8	7.3	7.4	7.7
Thr	5.7	6.0	6.1	6.0
Trp	1.4	1.2	1.5	1.5
Val	7.0	7.4	7.2	7.3
Dispensable amino acids, g/kg				
Ala	8.9	9.5	7.5	7.8
Asp	12.3	12.9	14.4	14.7
Cys	3.0	3.1	2.4	2.5
Glu	26.1	27.6	26.3	27.7
Gly	7.4	7.7	6.8	6.7
Pro	10.0	10.7	8.7	9.0
Ser	6.6	6.9	6.5	6.7
Tyr	5.0	5.4	5.0	5.2
Minerals				
Ca, g/kg	8.4	8.5	7.9	8.0
P, g/kg	6.6	6.4	6.1	6.1
K, g/kg	8.7	8.6	8.4	8.0
Mg, g/kg	2.3	2.2	1.7	1.7
Na, g/kg	2.6	2.3	1.8	1.5
Cu, mg/kg	51.9	36.2	22.0	23.4
Zn, mg/kg	267.2	253.7	204.9	200.3
Fe, mg/kg	97.1	95.9	63.5	69.7
Mn, mg/kg	197.5	202.0	138.4	132.4

[a] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.

gestation diets. Representative amounts of the fiber containing ingredients (i.e., corn, soybean meal, soybean hulls, corn DDGS, and wheat middlings) were also collected at each mixing, pooled at the conclusion of the experiment, and subsampled for chemical analysis.

2.2. Animals, housing, and feeding

A total of 106 animals (initial body weight: 188.7 ± 17.7 kg), 44 gilts and 62 Camborough sows (Pig Improvement Company, Hendersonville, TN, USA) were bred to Line 800 males (Pig Improvement Company). In the first cycle, sows and gilts were allotted to 4 blocks of 23–30 gilts and sows per block, using a randomized complete block design. Animals were housed individually in gestation stalls, and they were allotted to experimental diets 7 days after breeding. Gestation diets were fed until day 105 of gestation. During the gestation period, daily feed allotments were provided at 0600 h. Daily feed allowance was 1.5 times the maintenance energy requirement for gestating sows (i.e., 100 kcal ME/kg body weight$^{0.75}$; NRC, 2012), but feed allowance was adjusted every other week, if needed, to maintain or achieve ideal sow body condition by visual scoring (approximately 3.0 on a 1–5-point scale; Patience and Tacker, 1989). On day 30 post-breeding, all animals were pregnancy checked and 8 non-pregnant animals were removed. From the remaining 98 animals, 48 sows (parity 2–6) were placed in metabolism crates from day 35–45 (i.e., mid-gestation) with 12 sows per block (i.e., 6 sows per treatment in each block), providing a total of 24 sows per treatment. Crates were equipped with a self-feeder, a nipple drinker, and a fully slatted tri-bar floor. The selected 48 sows had an average parity of 2.2 ± 1.0, and an average body weight of 194.6 ± 18.3 kg when moved to the metabolism crates. A screen and a urine pan were installed under the tri-bar floor in the metabolism crates to allow for total collection of feces and urine. The initial 3 days in the metabolism crates were considered the adaptation period, which was followed by 4 days of fecal and urine collection using the marker-to-marker procedure (Adeola, 2001). Fecal collection was initiated when the first marker (i.e., ferric oxide) appeared in the feces and ceased when the second marker (i.e.,

chromium oxide) appeared (Adeola, 2001). Urine was collected in buckets that were placed under the urine pans and 50 mL of 6 *N* HCl were added to each bucket. Urine collection started at 0900 hours on day 4 and ceased at 0900 hours on day 8. Buckets were emptied daily, the weight of the collected urine was recorded, and 10% of the collected urine was stored at −20 °C until subsampling. From day 95–105 (i.e., late-gestation), the same 48 sows were moved back to the metabolism crates, and feces and urine were collected for 4 days again, following the same procedures as in mid-gestation. At the conclusion of each collection period, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before analysis (Kim et al., 2009). Fecal samples from each animal were thawed and mixed, and then dried in a 50 °C forced-air drying oven and ground using a grain mill (500 G Swing Type Grain Mill, RRH, Zhejiang, China) prior to analysis.

Twenty-one animals were removed from the experiment during gestation, but on day 106 of gestation, the remaining 77 animals were moved to the lactation unit and housed in farrowing crates (2.1 × 1.5 m) with plastic coated slatted floors. Each crate was equipped with a stainless-steel feeder and 2 nipple waterers. Sows were fed experimental lactation diets starting the day sows were moved to the lactation unit. They were fed as in gestation before farrowing but had *ad libitum* access to feed and water after farrowing. From day 14 post-farrowing, litters were offered a standard creep feed diet according to normal farm practices and this diet did not contain xylanase. During lactation, fecal samples from the same 48 sows that had been placed in metabolism crates in gestation were collected for 5 days via grab sampling starting on day 10 post-farrowing. The reason grab sampling was used is that it was not possible to place sows in metabolism crates during lactation. These samples were used to determine total tract digestibility of nutrients and energy using the index method (Adeola, 2001). Fresh fecal samples were also collected via anal stimulation in both cycles on day 1, 10, and 20 post-farrowing to assess fecal quality of sows. One sow died during lactation.

After weaning on day 20.72 ± 0.71, thirteen animals were culled following normal farm practices, and sixty-three sows (32 sows fed the control diet and 31 sows fed the diet with xylanase) were rebred when heat was observed (approximately 5 days after weaning) and housed individually in gestation stalls. Bred sows were fed the same experimental gestation diets as in the first cycle from the day after weaning and until day 106 of the second gestation period. On day 30 post-breeding, sows were pregnancy checked and 8 non-pregnant animals (2 sows fed the control diets and 6 sows fed the diet with xylanase) were removed. From the remaining 55 animals, 46 sows (24 sows fed the control diets and 22 sows fed the diet with xylanase) were placed in metabolism crates from day 35–45 and again from day 95–105 as in the first cycle and feces and urine were collected as in the first cycle. On day 106, sows were moved to the lactation unit where treatments were as in the first cycle, and fecal samples were collected for 5 days starting on day 10 as in the first cycle. Fresh fecal samples were also collected on day 1, 10 and 20 as in the first cycle.

In the second farrowing cycle, sow colostrum samples were collected within 24 hours of farrowing. Colostrum is defined as secretions from the mammary gland expressed within 24 hours of farrowing (Quesnel et al., 2015). Milk samples were collected from all functional mammary glands on day 10 post-farrowing following intramuscular administration of 1 mL of oxytocin (Bimeda-MTC Animal Health Inc., Cambridge, ON, Canada). Approximately 50 mL of colostrum or milk was collected in 50 mL conical sterile polypropylene centrifuge tubes. Colostrum and milk samples were stored at −20 ºC immediately after collection. Colostrum and milk samples were centrifuged at 2500 × g for 15 min at 4 ºC to yield lactic serum from colostrum and milk before analysis.

2.3. Data collection

In both cycles, individual body weights of sows were recorded on day 7 after breeding, when sows were moved into and out of metabolism crates, when they were moved to farrowing crates, within 24 hours after farrowing, and on the day of weaning. Daily feed intake of gestating sows and weekly feed intake during lactation were recorded as well. The number and body weight of pigs born alive, the number of mummies, stillborn pigs, and total pigs born per litter were recorded within 24 hours of farrowing. Pig body weight at birth and at cross-fostering, which was completed within 24 hours of farrowing within treatment groups, were recorded as well. Pigs were processed within 24 hours of birth, and according to normal farm practices, processing included clipping needle teeth, docking tails, castration of male pigs, administration of iron dextran (Uniferon 200, Pharmacosmos A/S, Holbaek, Denmark) and centiofur antibiotic (Excede, Zoetis, Parsippany, NJ, USA), and ear notching for identification. Following normal farm practices, pigs weighing less than 0.8 kg at birth were considered low vitality and immediately euthanized. Pig body weight at weaning was recorded, and for sows, the number of days between weaning and estrus were also recorded.

2.4. Sample analyses

Ingredients, diets, and fecal samples were analyzed for DM, which was determined by oven drying at 135 °C for 2 hours (method 930.15; AOAC Int.., 2019). Diet and ingredient samples, fecal samples, and urine samples were analyzed for GE on an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL, USA) using benzoic acid as the internal standard. Urine samples were analyzed for GE as described by Kim et al. (2009). Diets and ingredients were analyzed for ash (method 942.05; AOAC Int.., 2019). Diets and ingredients were analyzed for N by the combustion procedure (method 990.03; AOAC Int.., 2019) using a LECO FP628 (LECO Corp., Saint Joseph, MI, USA) and crude protein was calculated as N × 6.25. Starch was analyzed in diets and ingredients by the glucoamylase procedure (method 979.10; AOAC Int.., 2019). Diets and ingredients were analyzed for amino acids on a Hitachi Amino Acid Analyzer (Model No. l8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard [method 982.30 E (a, b, c); AOAC Int.., 2019]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int.., 2019]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [method 982.30 E(c); AOAC Int.., 2019]. Acid-hydrolyzed ether extract was analyzed in diets and ingredients by acid hydrolysis using 3 *N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat

extraction (method Am 5–04; AOCS, 2013) using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY, USA). Diets, ingredients, and fecal samples were analyzed for insoluble dietary fiber (IDF) and soluble dietary fiber (SDF) according to method 991.43 (AOAC Int.., 2019) using the AnkomTDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY,). Total dietary fiber was calculated as the sum of IDF and SDF. Calcium, P, K, Mg, Na, Cu, Fe, Mn, and Zn in diets and ingredients were analyzed (method 985.01 A, B and C; AOAC Int.., 2019) using inductively coupled plasma-optimal emission spectrometry (Avio 200, PerkinElmer, Waltham, MA). Sample preparation for mineral analysis included dry ashing at 600 °C for 4 hours (method 942.05; AOAC Int.., 2019) and wet digestion with nitric acid (method 3050 B; U.S. U.S. U.S. Enviromental Protection Agency, 1996). The concentration of titanium in fecal samples from lactating sows and lactation diets was analyzed following the procedure of Myers et al. (2004). Fresh fecal samples collected on day 1, 10, and 20 of lactation of both reproductive cycles were analyzed for fecal DM by oven drying at 50 °C for at least 24 hours (method 2.2.1.1; National Forage Testing Association. 1993), followed by drying at 135 °C for 2 hours (method 930.15; AOAC Int.., 2019).

Lactic serum from colostrum and milk were analyzed for IgA, IgG, and IgM using assay kits following the manufacturer's instructions (Bethyl Laboratories, Montgomery, TX, USA). These kits included the quantification of the secretory form of both IgA and IgM. Assay sensitivity was 1.37 ng/mL for IgA, 0.69 ng/mL for IgG and 1.37 ng/mL for IgM. Immunoglobulin data were analyzed using Multiskan Ascent v2.6 software (Thermo Fisher Scientific, Vienna, Austria).

2.5. Calculations and statistical analyses

At the conclusion of the experiment, data for estimated milk yield (calculated as 4 g milk per g of litter body weight gain; Close and Cole, 2000) and litter growth performance data were calculated for each sow as follows: number of total born, mummified, and still born pigs, number of pigs after cross-fostering, number of pigs weaned, and pig survival rate (i.e., calculated as the number of weaned pigs divided by the number of live born pigs after adjusting for cross-fostering). Total litter birth weight, live litter birth weight after cross-fostering, litter weight at weaning, and litter average daily gain (ADG) were calculated as well. Average pig weights and ADG for each pig were also calculated. Apparent total tract digestibility of DM, GE, IDF, SDF, and TDF were calculated for each diet, and the concentration of DE and ME in each diet were also calculated (Adeola, 2001).

With the exception of the number of pigs born alive, the number of mummies, stillborn pigs, and total pigs born per litter, and the number of days between weaning and estrus of sows, data were considered continuous variables and analyzed using the MIXED procedure (SAS Institute Inc.., 2016). The number of pigs born alive, the number of mummies, stillborn pigs, and total pigs born per litter, and the number of days between weaning and estrus of sows were considered discrete variables and analyzed using the GLIMMIX procedure (SAS Institute Inc.., 2016). Model assumptions were confirmed using the UNIVARIATE procedure, and this procedure was

Table 4
Performance of sows fed experimental diets during the first reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Parity	2.28	2.12	0.35	0.742
Body weight, kg				
Day 7 after breeding	194.3	195.8	5.38	0.839
Day 35 gestation	209.0	211.4	5.32	0.705
Day 45 gestation	220.2	218.6	5.87	0.832
Day 95 gestation	233.6	236.6	5.48	0.600
Day 105 gestation	249.2	246.5	5.36	0.653
At farrowing	223.7	225.7	4.36	0.740
At weaning	205.8	211.2	4.82	0.438
Feed intake, kg				
Day 1 to day 34, gestation	66.50	66.74	1.00	0.865
Day 35 to day 44, gestation	28.46	28.46	1.15	0.994
Day 45 to day 95, gestation	92.69	92.68	0.47	0.325
Day 96–105, gestation	30.77	30.61	1.30	0.806
Day 106–115, gestation	21.70	22.13	1.98	0.226
Total, gestation	240.12	240.37	3.05	0.838
Day 1–7, lactation	24.44	25.03	1.22	0.155
Day 8–14, lactation	40.43	40.61	0.58	0.681
Day 15–21, lactation	43.16	42.77	1.97	0.718
Total, lactation	108.03	108.41	1.38	0.794
Body weight loss during lactation	17.85	14.54	2.43	0.265
Days between weaning and estrus	5.95	5.90	0.54	0.949
Estimated total milk yield[d], kg	171.65	195.55	13.23	0.071
Estimated daily milk yield[e], kg	8.31	9.43	0.71	0.062

[a] Data are means of 24 observations per treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.
[d] Estimated milk yield was calculated as 4 g milk per 1 g of litter body weight gain (Close and Cole, 2000).
[e] Litter weight after cross-fostering was included as a covariate.

used to test for outliers. The initial statistical model for both proc MIXED and proc GLIMMIX included the fixed effect of diet, and block and replicate within block as random effects. However, for the response variables related to litter performance after cross-fostering, the litter weight after cross-fostering was included as a covariate. The LSMEANS statement was used to calculate treatment means in proc MIXED, and with inverse link option in proc GLIMMIX. Non-metric multidimensional scaling (NMDS) in R statistical software using the R package vegan was used to search clusters of similarities between groups in terms of Ig composition, and an analysis of similarities (ANOSIM) test was applied (Oksanen et al., 2022). The sow was the experimental unit for all analyses. Statistical significance and tendencies were considered at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

3. Results

3.1. Reproductive parameters

During the two reproductive cycles, differences in body weights of sows, body weight loss during lactation, and in the days between weaning and estrus between treatment groups were not observed during gestation or lactation (Tables 4 and 5). There was no difference in total feed intake of sows between treatment groups during gestation or lactation in the first cycle and during gestation of the second cycle, but sows fed the xylanase diet had less ($P = 0.021$) feed intake in week 3 of lactation of the second cycle and tended to have less ($P = 0.078$) feed intake during the entire lactation period. In the first cycle, but not in the second cycle, sows fed the xylanase diet tended to have greater ($P < 0.10$) estimated total and daily milk yields compared with sows fed the control diet. There were no differences between sows fed the control diet and sows fed the xylanase diet for the number of pigs born per litter, number of pigs born alive per litter, number of pigs per litter after cross-fostering, number of still born pigs per litter, number of mummified pigs per litter, or number of pigs weaned per litter during two reproductive cycles (Tables 6 and 7). Total litter birth weight tended to be greater ($P = 0.079$) for sows fed the control diet, and total litter weight after cross-fostering was greater ($P = 0.031$) for sows fed the control diet compared with sows fed the diet with xylanase in the first cycle. However, total litter weaning weight and litter ADG tended to be greater ($P < 0.10$) for litters from sows fed the xylanase diet compared with sows fed the control diet in the first cycle. The individual pig weights were not different between groups after cross-fostering, but greater ($P = 0.038$) at weaning for sows fed the xylanase diet compared with sows fed the control diet in the first cycle.

3.1.1. Apparent total tract digestibility of nutrients and energy of sows

Although there were no differences in DM intake during late-gestation (i.e., day 95–105) of the first gestion period, sows fed the diet

Table 5
Performance of sows fed experimental diets during the second reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Parity	2.65	2.65	0.33	0.997
Body weight, kg				
Day 7 after breeding	186.98	189.85	4.07	0.594
Day 35 gestation	191.30	193.94	4.69	0.647
Day 45 gestation	192.89	193.91	4.73	0.855
Day 95 gestation	211.13	213.41	3.90	0.688
Day 105 gestation	219.84	220.00	4.75	0.980
At farrowing	206.06	208.75	3.83	0.631
At weaning	202.46	204.11	3.83	0.767
Feed intake, kg				
Days from weaning to breeding	21.11	21.15	0.03	0.381
Day 1 to d 34, gestation	62.38	62.24	1.05	0.911
Day 35 to day 44, gestation	23.05	23.12	0.50	0.917
Day 45 to day 95, gestation	111.77	110.96	6.11	0.899
Day 96–105, gestation	33.66	35.28	1.63	0.208
Day 106–115, gestation	27.00	28.02	1.24	0.103
Total, gestation	278.86	280.99	6.81	0.794
Day 1–7, lactation	30.35	30.57	2.18	0.622
Day 8–14, lactation	49.13	48.10	2.10	0.237
Day 15–21, lactation	51.08	48.11	3.66	0.021
Total, lactation	130.57	126.75	5.12	0.078
Body weight loss during lactation	3.56	4.67	1.76	0.649
Days between weaning and estrus	5.48	5.96	0.51	0.518
Estimated total milk yield[d, 5], kg	203.68	200.31	7.19	0.703
Estimated daily milk yield[e], kg	9.84	9.73	0.35	0.777

[a] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.
[d] Estimated milk yield was calculated as 4 g milk per 1 g of litter body weight gain (Close and Cole, 2000).
[e] Litter weight after cross-fostering was included as a covariate.

Table 6
Performance of litters from sows fed experimental diets during the first reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Pigs per litter, n				
Total born	15.81	15.06	1.03	0.513
Born alive	14.75	14.08	0.84	0.547
After cross-fostering	13.13	12.50	0.74	0.549
Still born	0.80	0.81	0.27	0.995
Mummified	0.18	0.18	0.11	1.000
Weaned	11.79	11.50	0.76	0.769
Litter weight, kg				
Total at birth	21.32	19.35	1.18	0.079
After cross-fostering	19.64	17.63	1.08	0.031
At weaning[d]	61.55	67.52	3.31	0.071
Litter average daily gain[d], kg	2.08	2.36	0.18	0.062
Individual pig weight, kg				
After cross-fostering	1.51	1.41	0.05	0.134
At weaning[d]	5.37	5.72	0.17	0.038
Survival rate[e]	0.898	0.919	0.035	0.685

[a] Data are means of 24 observations per treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.
[d] Litter weight after cross-fostering was included as a covariate.
[e] Survival rate was calculated as the number of weaned pigs divided by the number of live born pigs after adjusting for cross-fostering.

Table 7
Performance of litters from sows fed experimental diets during the second reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Pigs per litter, n				
Total born	14.31	15.13	0.91	0.475
Born alive	13.79	14.37	0.80	0.603
After cross-fostering	12.00	12.14	0.73	0.895
Still born	0.43	0.50	0.18	0.731
Mummified	0.08	0.23	0.12	0.257
Weaned	11.38	11.36	0.70	0.991
Litter weight, kg				
Total at birth	17.48	17.72	0.88	0.841
After cross-fostering	15.22	15.35	0.80	0.878
At weaning[d]	66.07	65.54	2.43	0.842
Litter average daily gain[d], kg	2.46	2.43	0.09	0.777
Individual pig weight, kg				
After cross-fostering	1.27	1.25	0.05	0.730
At weaning[d]	5.85	5.71	0.18	0.412
Survival rate[e]	0.946	0.940	0.018	0.777

[a] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.
[d] Litter weight after cross-fostering was included as a covariate.
[e] Survival rate was calculated as the number of weaned pigs divided by the number of live born pigs after adjusting for cross-fostering.

with xylanase in late-gestation had less ($P = 0.016$) fecal DM output and greater ($P = 0.028$) ATTD of DM compared with sows fed the control diet (Table 8). Fecal GE output in late-gestation tended to be less ($P = 0.083$) from sows fed the diet with xylanase compared with sows fed the control diet. Sows fed the xylanase diet had greater ($P < 0.001$) ATTD of DM, and GE, and greater ($P < 0.001$) DE than sows fed the control diet during the first lactation period. Intake, fecal output, and ATTD of IDF, SDF, and TDF in mid-gestation of the first cycle were not different between diets (Table 9). Sows fed the control diets had greater ($P < 0.001$) IDF fecal output than sows fed the xylanase diet; therefore, the ATTD of IDF in late-gestation was greater ($P < 0.001$) for sows fed the diet with xylanase. Fecal output of TDF was reduced ($P < 0.001$) from sows fed the diet with xylanase compared with sows fed the control diet, resulting in a greater ($P < 0.001$) ATTD of TDF in late-gestation. Sows fed the xylanase diet also had greater ($P < 0.001$) ATTD of IDF and TDF than sows fed the control diet during the first lactation period.

During the second reproductive cycle, there was a tendency for greater ($P = 0.090$) ATTD of DM in mid-gestation for sows fed the diet with xylanase compared with sows fed the control diet (Table 10), and the ATTD of GE and concentrations of DE in mid-gestation were greater ($P = 0.048$) by sows fed the diet with xylanase than by sows fed the control diet. Sows fed the diet with xylanase also had

Table 8
Apparent total tract digestibility (ATTD) of dry matter (DM) and gross energy (GE), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets fed to sows during the first reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Mid-gestation (i.e., day 35–45)				
DM intake, kg/day	2.36	2.40	0.04	0.427
DM fecal output, kg/day	0.37	0.38	0.02	0.639
ATTD of DM	0.841	0.841	0.006	0.977
GE intake, MJ/day	44.29	45.08	0.80	0.427
GE fecal output, MJ/day	6.73	6.85	0.32	0.653
GE urine output, MJ/day	1.23	1.16	0.15	0.518
ATTD of GE	0.848	0.848	0.006	0.961
DE, MJ/kg	14.04	14.04	0.09	0.961
ME, MJ/kg	13.58	13.62	0.13	0.616
Late-gestation (i.e., day 95–105)				
DM intake, kg/day	2.57	2.58	0.05	0.844
DM in fecal output, kg/day	0.44	0.40	0.02	0.016
ATTD of DM	0.829	0.844	0.007	0.028
GE intake, MJ/day	48.19	48.42	1.01	0.844
GE fecal output, MJ/day	7.93	7.51	0.28	0.083
GE urine output, MJ/day	1.28	1.40	0.09	0.292
ATTD of GE	0.835	0.844	0.007	0.142
DE, MJ/kg	13.83	13.97	0.11	0.142
ME, MJ/kg	13.39	13.49	0.13	0.300
Lactation				
ATTD of DM	0.814	0.833	0.005	<0.001
ATTD of GE	0.807	0.828	0.006	<0.001
DE, MJ/kg	12.98	13.32	0.10	<0.001

[a] Data are means of 24 observations per treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.

Table 9
Apparent total tract digestibility (ATTD) of insoluble dietary fiber (IDF), soluble dietary fiber (SDF) and total dietary fiber (TDF) in experimental diets fed to sows during the first reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Mid-gestation (i.e., day 35–45)				
IDF intake, kg/day	0.72	0.74	0.01	0.427
IDF fecal output, kg/day	0.18	0.19	0.01	0.153
ATTD of IDF	0.751	0.737	0.011	0.176
SDF intake, kg/day	0.08	0.08	0.01	0.427
SDF fecal output, kg/day	0.01	0.02	0.01	0.381
ATTD of SDF	0.822	0.813	0.018	0.493
TDF intake, kg/day	0.80	0.82	0.01	0.427
TDF fecal output, kg/day	0.19	0.21	0.01	0.151
ATTD of TDF	0.758	0.745	0.011	0.172
Late-gestation (i.e., day 95–105)				
IDF intake, kg/day	0.79	0.80	0.01	0.844
IDF fecal output, kg/day	0.22	0.17	0.01	< 0.001
ATTD of IDF	0.719	0.781	0.017	< 0.001
SDF intake, kg/day	0.09	0.09	0.01	0.844
SDF fecal output, kg/day	0.01	0.01	0.01	0.968
ATTD of SDF	0.835	0.835	0.009	0.954
TDF intake, kg/day	0.87	0.88	0.01	0.844
TDF fecal output, kg/day	0.23	0.19	0.01	< 0.001
ATTD of TDF	0.730	0.787	0.015	< 0.001
Lactation				
ATTD of IDF	0.630	0.677	0.009	< 0.001
ATTD of SDF	0.685	0.633	0.059	0.136
ATTD of TDF	0.634	0.674	0.011	0.001

[a] Data are means of 24 observations per treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.

greater (P = 0.014) ATTD of DM compared with sows fed the control diet. The ATTD of GE was not different between diets in late-gestation, but DE tended to be greater (P = 0.096) in late-gestation for sows fed the diet with xylanase than for sows fed the control diet. During the second lactation period, sows fed the diet with xylanase had greater (P = 0.004) ATTD of DM and GE than sows fed the control diet, and DE was also greater (P = 0.031) for sows fed the diet with xylanase compared with sows fed the control diet. The ATTD of SDF in late-gestation tended to be greater (P = 0.091) for sows fed the diet with xylanase than for sows fed the control diet (Table 11). Sows fed the diet with xylanase also had greater (P < 0.05) ATTD of IDF and TDF than sows fed the control diet during the second lactation period.

3.2. Fecal dry matter

On day 10 and day 20, sows fed the control diet had greater (P < 0.05) fecal DM than sows fed the diet with xylanase (Table 12). The amount of SDF was greater (P = 0.013) in feces on day 10 from sows fed the diet with xylanase than in feces from sows fed the control diet. On day 10 of lactation of the second reproductive cycle, sows fed the diet with xylanase had reduced (P = 0.017) fecal DM compared with sows fed the control diet.

3.2.1. Immunoglobulins in colostrum and milk

The concentration of IgA, IgG, and IgM in the colostrum and milk were not different between sows fed the control diet and those fed the diet with xylanase (Table 13). There were also no differences in the analyzed IgA, IgG, and IgM pattern displayed in NMDS between colostrum of sows fed the control diet compared with colostrum of sows fed the diet with xylanase (Fig. 1A), as the ellipses overlapped. The same lack of differential clustering was observed in the analyzed IgA, IgG, and IgM pattern displayed in NMDS from milk of sows fed the control diet compared with colostrum of sows fed the diet with xylanase (Fig. 1B). The IgA, IgG, and IgM analysis of both colostrum and milk samples, allows for distinguishing two types of clusters (stress 0.6576, ANOSIM P < 0.001), corresponding to the time of milk collection (Fig. 1C), but no effects were observed between dietary treatments.

4. Discussion

4.1. Ingredients and diets composition

To test the hypothesis that a long adaptation period is needed to obtain the full benefits of microbial xylanase in diets for sows due to a slow adjustment of the intestinal microbiome, sows were fed xylanase for two consecutive reproductive cycles. To account for loss of sows that did not get pregnant after breeding and sows that had to be removed from the experiment due to normal farm practices, a

Table 10
Apparent total tract digestibility (ATTD) of dry matter (DM) and gross energy (GE), and concentrations of digestible energy (DE) and metabolizable energy (ME) in experimental diets fed to sows during the second reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Mid-gestation (i.e., day 35–45)				
DM intake, kg/day	2.26	2.27	0.04	0.810
DM fecal output, kg/day	0.39	0.38	0.01	0.219
ATTD of DM	0.825	0.834	0.004	0.090
GE intake, MJ/day	42.43	42.71	0.90	0.810
GE fecal output, MJ/day	7.15	6.82	0.19	0.145
GE urine output, MJ/day	2.01	2.11	0.15	0.459
ATTD of GE	0.831	0.840	0.003	0.048
DE, MJ/kg	13.76	13.91	0.06	0.048
ME, MJ/kg	12.97	13.11	0.08	0.124
Late-gestation (i.e., day 95–105)				
DM intake, kg/day	2.43	2.52	0.08	0.331
DM in fecal output, kg/day	0.43	0.42	0.01	0.543
ATTD of DM	0.822	0.833	0.003	0.014
GE intake, MJ/day	45.64	47.39	1.43	0.330
GE fecal output, MJ/day	8.03	8.00	0.26	0.926
GE urine output, MJ/day	1.94	1.96	0.11	0.855
ATTD of GE	0.824	0.831	0.003	0.103
DE, MJ/kg	13.64	13.76	0.05	0.096
ME, MJ/kg	12.94	13.08	0.07	0.108
Lactation				
ATTD of DM	0.820	0.835	0.004	0.004
ATTD of GE	0.815	0.827	0.004	0.031
DE, MJ/kg	13.10	13.31	0.07	0.031

[a] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.

Table 11
Apparent total tract digestibility (ATTD) of insoluble dietary fiber (IDF), soluble dietary fiber (SDF), and total dietary fiber (TDF) in experimental diets fed to sows during the second reproductive cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Mid-gestation (i.e., day 35–45)				
IDF intake, kg/day	0.69	0.70	0.01	0.810
IDF fecal output, kg/day	0.19	0.18	0.01	0.206
ATTD of IDF	0.726	0.740	0.007	0.177
SDF intake, kg/day	0.08	0.08	0.01	0.810
SDF fecal output, kg/day	0.01	0.01	0.01	0.858
ATTD of SDF	0.840	0.837	0.018	0.835
TDF intake, kg/day	0.77	0.77	0.01	0.810
TDF fecal output, kg/day	0.20	0.19	0.01	0.252
ATTD of TDF	0.737	0.751	0.007	0.170
Late-gestation (i.e., day 95–105)				
IDF intake, kg/day	0.74	0.77	0.02	0.332
IDF fecal output, kg/day	0.21	0.23	0.01	0.204
ATTD of IDF	0.715	0.705	0.01	0.306
SDF intake, kg/day	0.08	0.09	0.01	0.332
SDF fecal output, kg/day	0.01	0.01	0.01	0.107
ATTD of SDF	0.844	0.873	0.01	0.091
TDF intake, kg/day	0.83	0.86	0.02	0.332
TDF fecal output, kg/day	0.23	0.24	0.01	0.281
ATTD of TDF	0.727	0.722	0.009	0.534
Lactation				
ATTD of IDF	0.668	0.696	0.010	0.048
ATTD of SDF	0.588	0.631	0.037	0.156
ATTD of TDF	0.663	0.692	0.011	0.035

[a] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.

Table 12
Fecal dry matter (**DM**), insoluble dietary fiber (**IDF**), soluble dietary fiber (**SDF**), and total dietary fiber (**TDF**) content assessment in sows fed lactation experimental diets.

Item	Diet		SEM[b]	P-value
	Control	Xylanase[a]		
First cycle[c]				
DM, day 1, g/kg	615.3	607.9	10.2	0.467
DM, day 10, g/kg	685.3	673.0	6.7	0.014
DM, day 20, g/kg	691.6	678.7	4.2	< 0.001
IDF[d], g/kg	390.4	377.3	9.2	0.141
SDF[d], g/kg	25.3	32.7	4.1	0.013
TDF[d], g/kg	415.7	410.0	6.4	0.487
Second cycle[e]				
DM, day 1, g/kg	632.1	615.5	8.0	0.150
DM, day 10, g/kg	684.7	664.4	8.6	0.017
DM, day 20, g/kg	684.6	676.4	9.2	0.187
IDF, g/kg	369.5	362.8	8.8	0.494
SDF, g/kg	35.1	34.2	3.2	0.727
TDF, g/kg	404.9	396.4	11.3	0.397

[a] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[b] SEM = standard error of the mean.
[c] Data are means of 24 observations per treatment.
[d] Composition of fiber portions was calculated on a dry matter basis in feces collected on d 10.
[e] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.

much larger number of sows than needed in the second cycle were fed treatment diets from the start of the experiment. Although sows were randomly allotted to treatments, differences between treatments occurred due to removal of sows. Likewise, some of the sows that were used in parity 2 had not been used in parity 1 although they had been fed treatment diets and as a consequence, the average parity of sows was not increased from cycle 1 to cycle 2 and the average body weight of sows was less in cycle 2 than in cycle 1. However, because sows were randomly allotted to treatments and because all sows used in cycle 2 also had been fed treatment diets in cycle 1, these differences did not impact results of the experiment.

Sows derive more energy from fibrous feed ingredients than growing pigs due to prolonged digesta retention in the hindgut and a

Table 13
Concentration of immunoglobulin (**Ig**) A, IgM, and IgG of colostrum and milk from sows fed lactation experimental diets in the second cycle[a].

Item	Diet		SEM[c]	P-value
	Control	Xylanase[b]		
Colostrum				
IgA, mg/mL	13.99	15.96	1.14	0.233
IgG, mg/mL	87.83	85.26	5.99	0.737
IgM, mg/mL	20.52	18.96	8.75	0.901
Milk				
IgA, mg/mL	11.80	13.70	1.40	0.263
IgG, mg/mL	1.73	1.55	0.12	0.307
IgM, mg/mL	1.45	1.19	0.18	0.281

[a] Data are means of 24 observations for the control treatment and 22 observations for the xylanase treatment.
[b] Xylanase = Econase XT 25 (16,000 BXU/kg complete feed); AB Vista, Marlborough, UK.
[c] SEM = standard error of the mean.

greater capacity to ferment fiber (Jørgensen et al., 2007), which results in beneficial effects for gestating sows (i.e., increased satiety, decreased stress, and reduced constipation; Meunier-Salaün et al., 2001). However, high inclusion of dietary fiber may reduce energy and nutrient utilization and decrease reproductive performance (Holt et al., 2006; Feyera et al., 2021); therefore, it was hypothesized that addition of xylanase to diets for sows may increase fiber fermentation and consequently will increase efficiency of energy utilization in ingredients. In this experiment, corn, soybean meal, corn DDGS, wheat middlings, and soybean hulls resulted in diets containing 300 g/kg and 210 g/kg of TDF in gestation and lactation, respectively. The majority of fiber in corn, corn DDGS, and wheat middlings consists of arabinoxylans (Navarro et al., 2019), and approximately 500 g/kg of dietary fiber from soybean hulls consists of hemicelluloses containing xylan polymers (Middelbos and Fahey, 2008). Xylanase hydrolyzes the backbone of xylans; therefore, feed ingredients used in this experiment provided the substrate for the xylanase enzyme.

Concentrations of DM, crude protein, amino acids, GE, starch, TDF, ash, and acid-hydrolyzed ether extract of ingredients were in agreement with reported values (NRC, 2012). The nutrient composition of diets were also in agreement with calculated values. The average xylanase activity for the control diets did not exceed the detection limit (2000 BXU/kg) and the average xylanase activity in the diets with added xylanase were 16,830 for the gestation diets and 18,640 for the lactation diets, which was in agreement with expected values.

4.2. Sow and litter performance

Gestating sows were fed limited amount of feed according to the visual assessment of body condition of sows to prevent excessive body weight gain (de Leeuw et al., 2008). The observation that sow body weight and feed intake during gestation in both reproductive cycles did not differ between control and xylanase sows indicates that xylanase did not release sufficient energy to impact these parameters.

Lactating sows generally mobilize body reserves to sustain milk production because of insufficient intake of energy and nutrients (Aherne and Williams, 1992). The observation that feed intake and body weight loss was not different between treatments in the first lactation is in agreement with results from other experiments with lactating sows fed a carbohydrase (Walsh et al., 2012; Zhe et al., 2022), although reduced body weight loss of sows during lactation also has been reported (Cozannet et al., 2018; Zhou et al., 2018; Lee et al., 2019). Excess weight loss during lactation has been associated with longer weaning to service intervals (Trottier and Johnston, 2001). The observation that days between weaning and estrus were not different is likely due to the lack of differences in body weight loss in lactation and is in agreement with previous data (Walsh et al., 2012).

The increased feed intake of sows during lactation in the second cycle compared with the first cycle is likely a result of the fact that during the first cycle, sows farrowed during the summer and therefore were heat stressed, which likely limited feed intake. In contrast, during the second cycle, sows farrowed in the winter where temperatures were lower and sows were not heat stressed.

The observation that sows fed the xylanase diet had decreased feed intake in week 3 of lactation during the second cycle is in contrast with data indicating that added xylanase increased feed intake during lactation (Walsh et al., 2012; Zhou et al., 2018). This observation is likely due to the increased ATTD of TDF in lactation, which resulted in increased absorption of short-chain fatty acids that were used for energy. Addition of carbohydrases to sow diets also resulted in increased nutrient digestibility during lactation in a previous experiment (de Souza et al., 2007).

Inclusion of fiber ingredients in gestation and lactation diets has been associated with a reduced number of stillborn pigs, increased pig weights at birth, and increased weaning weights (Feyera et al., 2017; Jarrett and Ashworth, 2018). However, the lack of effects of xylanase supplementation on litter performance at birth observed in this experiment is in agreement with Walsh et al. (2012) and Zhou et al. (2018) indicating that supplementation of xylanase to sow diets does not impact total born and live born pigs at parturition. In contrast, in diets based on corn and SBM, pigs from sows fed diets with carbohydrases during lactation had greater ADG and greater body weight at weaning compared with pigs from sows fed no exogenous enzymes (Lee et al., 2019). The observed tendency for greater ADG and greater litter weight at weaning for litters from sows fed the diet with xylanase during the first reproductive cycle is possibly due to the observed reduction in the number of pigs per litter after cross-fostering and may also have been the reason for the tendency for higher production of milk estimated in sows fed xylanase. However, the decrease in feed intake of sows fed the diet with xylanase in

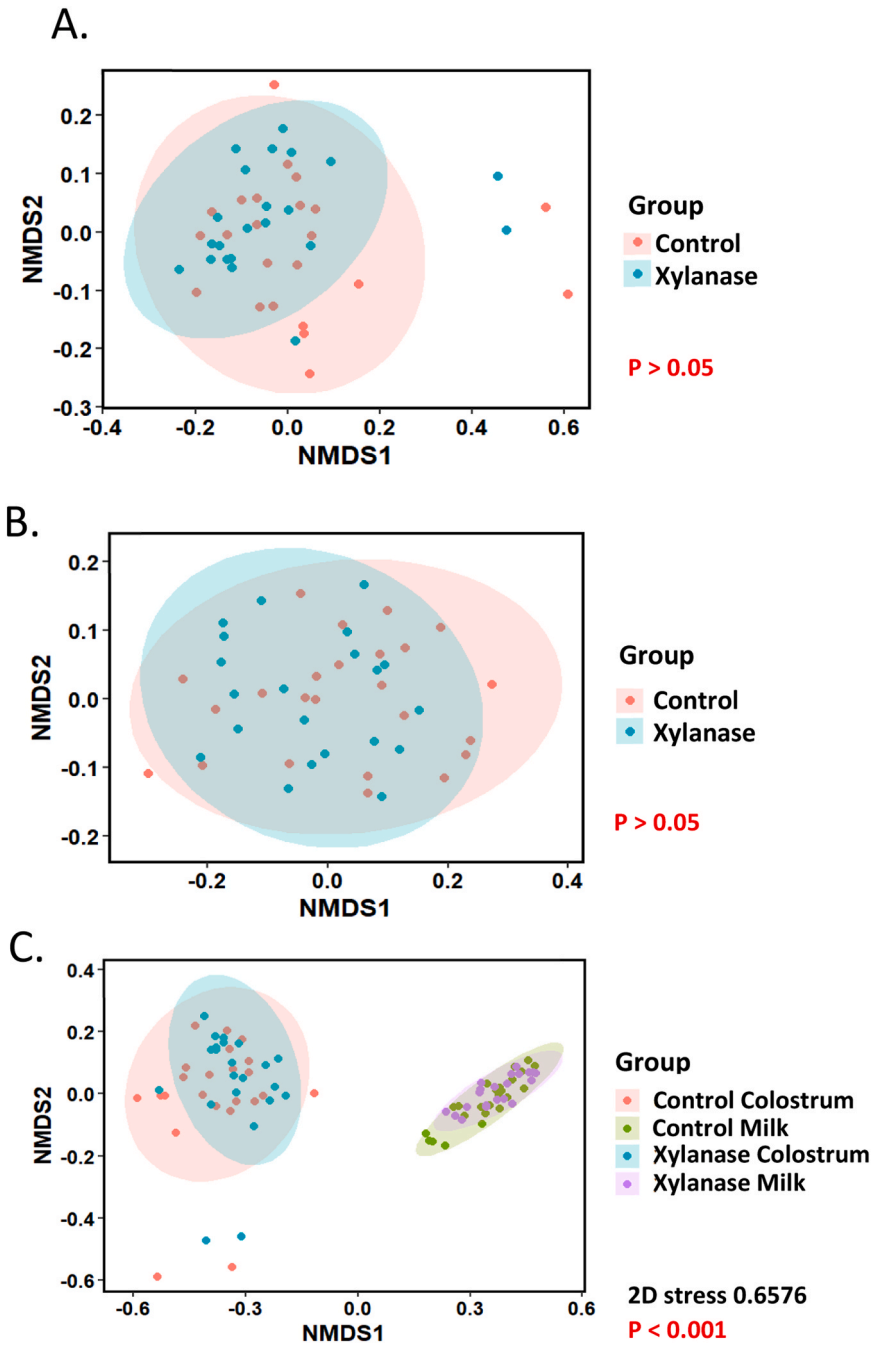


Fig. 1. Non-metric multi-dimensional scaling (NMDS) of immunoglobulin A, M and G (in colostrum samples; A, in milk samples; B, in colostrum and milk samples together; C).

the second lactation did not influence litter gain, which indicates that the decreased feed intake was caused by increased energy availability in the diet with xylanase.

4.3. Energy and nutrient digestibility, and fiber utilization

Sows have greater fermentability of dietary fiber compared with growing pigs (Le Goff et al., 2002; Jørgensen et al., 2007), but there are limited data on effects of xylanase in diets for gestating sows. The lack of effect of xylanase on nutrient digestibility during mid-gestation of the first cycle likely indicates that a long adaptation time is needed to increase effects of xylanase as has been reported for growing pigs (Lan et al., 2017; Petry et al., 2024). This is because an increased adaptation time of xylanase shifts fiber digestion into

the small intestine. This may promote intestinal absorption of xylose and arabinose, reducing energy loss from microbial fermentation (Huntley and Patience, 2018).

The increased ATTD of DM, IDF, and TDF by supplemental xylanase in late gestation of the first cycle is in agreement with data (Crome et al., 2023; Shipman et al., 2023) indicating that a carbohydrase mixture in high-fibrous diets fed to gestating sows increased ATTD of nutrients and fiber. However, the observation that there was no effect of xylanase supplementation on the ATTD of GE, and concentrations of DE and ME is in contrast with reports where supplementation of xylanase improved energy concentrations in growing pigs (Abelilla and Stein., 2019; Petry et al., 2020; Crome et al., 2023), this is likely because although insoluble fiber appears to be more solubilized in gestating sows fed the xylanase diet, the energy produced by fermentation of soluble fiber is not enough to increase the digestibility of energy of the diet.

The greater ATTD of DM, GE, IDF, and TDF, and greater DE in lactation of both reproductive cycles that was observed for sows fed the xylanase diet is in agreement with data indicating that addition of xylanase in lactation diets increased digestibility of DM, crude protein, energy, and fiber (de Souza et al., 2007; Cozannet et al., 2018; Zhou et al., 2018). Xylanase may enhance the fermentation of fiber by hydrolyzing the arabinoxylan backbone to release xylo-oligosaccharides and some monosaccharides (Pedersen et al., 2015b). The smaller fiber fractions produced by xylanase are more fermentable and soluble; therefore, the fermentability of IDF fragments is also enhanced (Adeola and Cowieson, 2011). Xylanase may also degrade the physical fiber matrix, which releases trapped nutrients, and therefore, increases access of endogenous digestive enzymes to these nutrients (de Lange et al., 2010). Xylanase may also mitigate the negative physiochemical properties of fiber (e.g., decrease digesta viscosity; Raza et al., 2019), which can increase nutrient and energy digestibility (de Vries et al., 2012; Gonzalez-Ortiz et al., 2016). The xylo-oligosaccharides produced as the result of xylanase action on arabinoxylans may act as stimbiotic that change the composition of the substrate that hindgut microbiota can access, and this may cause a shift in the microbial population that causes pathogenic bacteria to starve (Bedford and Cowieson, 2012; Tiwari et al., 2020). Stimbiotics stimulate the fiber-degrading microbiome, resulting in an increase in fiber utilization and fermentability even though the compound itself contributes quantitatively very little to short-chain fatty acid production (Ribeiro et al., 2018; Gonzalez-Ortiz et al., 2019). Improvements in digestibility of DM, energy, and concentrations of DE observed in this experiment are likely due to hydrolysis of insoluble fiber, and possibly because of the combination of the mechanisms of action working simultaneously to hydrolyze dietary fiber directly or indirectly. However, because the microbiome was not characterized in this experiment, this hypothesis cannot be confirmed.

The reason the digestibility of IDF and TDF did not increase in sows fed diets with xylanase during the second gestation period although differences in digestibility of GE and DM were observed likely is that xylanase may have released non-fiber nutrients that may have been trapped in the fiber matrix. Those nutrients subsequently increased DE of the diet. Because there were no consistent improvements in digestibility of nutrients and energy in gestating sows from the first to the second cycle, the hypothesis that feeding of xylanase for two cycles is needed to obtain the full benefits of xylanase was rejected. It appears that sows adapt pretty quickly to the added xylanase by increasing digestibility of fiber and other nutrients. Indeed, the highly significant increases in energy and DM digestibility in lactation in the first cycle as a result of dietary xylanase demonstrates that sows do not need to be fed xylanase for two cycles to increase digestibility. It is, however, acknowledged that because of inclusion of soybean hulls and wheat middlings in the lactation diets, the DE was lower than what is sometimes observed in commercial diets.

4.4. Fecal dry matter

Fecal DM was determined on three separate days in lactation to document the differences occurring throughout lactation. The observation that fecal DM was less on day 1 than on days 10 and 20 demonstrates that sows may have differences in water absorption or in digestibility during early lactation compared with later lactation.

The reason DM in feces of sows fed the xylanase diet on days 10 and 20 of lactation in the first cycle and on day 10 in the second cycle was reduced is likely that xylanase may mitigate the negative physicochemical properties of fiber (de Vries et al., 2012; Raza et al., 2019). By hydrolyzing the xylose backbone, xylanase may increase the solubility of fiber in the digestive tract. Soluble fragments bind to more water and increase viscosity to a greater extent than intact fiber (Urriola et al., 2012). The major part of arabinoxylans is water-unextractable due to covalent bonds or non-covalent interactions between individual arabinoxylans-molecules or arabinoxylans-molecules and other cell wall constituents (Courtin and Delcour, 2002). Xylanase may release bound water molecules from the water-unextractable arabinoxylans after hydrolysis of the xylose backbone, reducing the overall water retention capacity, which results in the release of water (Leys et al., 2020). Because sows fed xylanase had more SDF and more water in the feces, it is likely that the overall effect of xylanase was an increase in water released and bound to soluble fiber in the feces. However, because physicochemical analysis were not determined, this hypothesis cannot be verified, but warrants further research.

4.5. Colostrum and milk immunoglobulins

The reduced concentration of IgG and IgM in milk samples compared with colostrum is in agreement with data indicating that IgG and IgM are predominant in colostrum, but their concentrations drop drastically during lactation (Hurley, 2014). Also, IgA was the predominant Ig in milk, as observed in previous research (Hurley, 2014; Nuntapaitoon, 2022). It was hypothesized that increased DE for lactating sows by the addition of xylanase in the diets may influence the Ig composition of colostrum and milk. However, xylanase did not impact the Ig composition of colostrum and milk, which is in contrast with other dietary interventions, such as arabinoxylans, xylo-oligosaccharides or mannan-oligosaccharides that induce an immunoenhancing effect (Czech et al., 2010; Akhtar et al., 2012; Loisel et al., 2013; Zhenping et al., 2013).

5. Conclusions

Addition of xylanase to diets for gestating and lactating sows had no effects on sow body weight changes, number of pigs per litter, or birth weights of pigs during two consecutive reproductive cycles, and xylanase did not impact the immunoglobulin composition of colostrum and milk during the second cycle. However, in late gestation of the first cycle, xylanase increased the digestibility of dry matter, insoluble dietary fiber, and total dietary fiber, and in the second cycle, xylanase increased the digestibility of dry matter, gross energy, and concentrations of digestible energy. Xylanase also increased the digestibility of dry matter, gross energy, insoluble dietary fiber, and total dietary fiber, and concentrations of digestible energy in lactation in both cycles, which indicates there is an opportunity to include more fibrous ingredients in diets for lactating sows with the addition of xylanase. More research is needed to understand the action of xylanase in diets for gestating and lactating sows, with different types of dietary fiber to enhance the action of xylanase. Research to determine the mechanism of action of xylanase in sow performance in lactation is also warranted.

CRediT authorship contribution statement

JPA, CDE, GGO, and HHS conceptualized the experiment. JPA conducted the animal part and summarized data. JPA and CDE analyzed data. JPA, CDE, and HHS contributed with data interpretation. SGL, MJRL, and FJPC conducted the immunoglobulins analysis, summarized immunoglobulins data, analyzed immunoglobulins data, and interpreted immunoglobulins data. JPA wrote the first draft of the manuscript. CDE, GGO, FJPC, and HHS edited the final version of the manuscript. HHS supervised the project.

Declaration of Competing Interest

Gemma Gonzalez-Ortiz is an employee of AB Vista, Marlborough, UK, a global supplier of enzymes to the swine industry. The other authors have no conflicts of interest.

Acknowledgment

Funding for this research by AB Vista, Marlborough, UK, is greatly appreciated.

References

Abelilla, J.J., Stein, H.H., 2019. Degradation of dietary fiber in the stomach, small intestine, and large intestine of growing pigs fed corn- or wheat-based diets without or with microbial xylanase. J. Anim. Sci. 97, 338–352. https://doi.org/10.1093/jas/sky403.

Adeola, O., 2001. Digestion and balance techniques in pigs. In: Lewis, J., Southern, L.L. (Eds.), Swine Nutrition. CRC Press, Washington, D.C., USA, pp. 903–916.

Adeola, O., Cowieson, A.J., 2011. Board-invited review: opportunities and challenges in using exogenous enzymes to improve nonruminant animal production. J. Anim. Sci. 89, 3189–3218. https://doi.org/10.2527/jas.2010-3715.

Aherne, F.X., Williams, I.H., 1992. Nutrition for optimizing breeding herd performance. Vet. Clin. North Am. Food Anim. Pract. 8, 589–608. https://doi.org/10.1016/S0749-0720(15)30706-4.

Akhtar, M., Tariq, A.F., Awais, M.M., Iqbal, Z., Muhammad, F., Shahid, M., Hiszczynska-Sawicka, E., 2012. Studies on wheat bran arabinoxylan for its immunostimulatory and protective effects against avian coccidiosis. Carbohydr. Polym. 90, 333–339. https://doi.org/10.1016/j.carbpol.2012.05.048.

AOAC Int, 2019. Official methods of analysis. 21st ed. AOAC Int., Rockville, MD, USA.

AOCS, 2013. Official Method Am 5-04. Rapid determination of oil/fat utilizing high-temperature solvent extraction, in: Firestone, D. (Ed.), Official methods and recommended practices of the AOCS. 6th ed. AOCS Press, Urbana, IL, USA.

Bedford, M.R., Cowieson, A.J., 2012. Exogenous enzymes and their effects on intestinal microbiology. Anim. Feed Sci. Technol. 173, 76–85. https://doi.org/10.1016/j.anifeedsci.2011.12.018.

Close, W.H., Cole, D.J.A., 2000. Nutrition of sows and boars. Nottingham University Press, Nottingham, United Kingdom.

Courtin, C.M., Delcour, J.A., 2002. Arabinoxylans and endoxylanases in wheat flour bread-making. J. Cereal Sci. 35, 225–243. https://doi.org/10.1006/jcrs.2001.0433.

Cozannet, P., Lawlor, P.G., Leterme, P., Devillard, E., Geraert, P.A., Rouffineau, F., Preynat, A., 2018. Reducing BW loss during lactation in sows: a meta-analysis on the use of a nonstarch polysaccharide-hydrolyzing enzyme supplement. J. Anim. Sci. 96, 2777–2788. https://doi.org/10.1093/jas/sky045.

Crome, T.A., Giesemann, M.A., Miller, H.E., Petry, A.L., 2023. Influence of fiber type and carbohydrase supplementation on nutrient digestibility, energy and nitrogen balance, and physiology of sows at mid and late gestation. J. Anim. Sci. 101, skad390 https://doi.org/10.1093/jas/skad390.

Czech, A., Grela, E.R., Mokrzycka, A., Pejsak, Z., 2010. Efficacy of mannanoligosaccharides additive to sows diets on colostrum, blood immunoglobulin content and production parameters of piglets. Pol. J. Vet. Sci. 13, 525–531.

Dodd, D., Cann, I.K., 2009. Enzymatic deconstruction of xylan for biofuel production. Glob. Change Biol. Bioenergy 1, 2–17. https://doi.org/10.1111/j.1757-1707.2009.01004.x.

Feyera, T., Højgaard, C.K., Vinther, J., Bruun, T.S., Theil, P.K., 2017. Dietary supplement rich in fiber fed to late gestating sows during transition reduces rate of stillborn piglets. J. Anim. Sci. 95, 5430–5438. https://doi.org/10.2527/jas2017.2110.

Feyera, T., Hu, L., Eskildsen, M., Bruun, T.S., Theil, P.K., 2021. Impact of four fiber-rich supplements on nutrient digestibility, colostrum production, and farrowing performance in sows. J. Anim. Sci. 99, skab247 https://doi.org/10.1093/jas/skab247.

Gonzalez-Ortiz, G., Olukosi, O., Bedford, M.R., 2016. Evaluation of the effect of different wheats and xylanase supplementation on performance, nutrient and energy utilisation in broiler chicks. Anim. Nutr. 2, 173–179. https://doi.org/10.1016/j.aninu.2016.06.005.

Gonzalez-Ortiz, G., Gomes, G.A., Dos Santos, T.T., Bedford, M.R., 2019. New strategies influencing gut functionality and animal performance. In: Gonzalez-Ortiz, G., Bedford, M.R., Bach Knudsen, K.E., Courtin, C., Classen, H.L. (Eds.), The value of fibre - engaging the second brain for animal nutrition. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 233–254.

He, X., Yu, B., He, J., Huang, Z., Mao, X., Zheng, P., Luo, Y., Luo, J., Wang, Q., Wang, H., Yu, J., Chen, D., 2020. Effects of xylanase on growth performance, nutrients digestibility and intestinal health in weaned piglets. Livest. Sci. 233, 103940 https://doi.org/10.1016/j.livsci.2020.103940.

Holt, J.P., Johnston, L.J., Baidoo, S.K., Shurson, G.C., 2006. Effects of a high-fiber diet and frequent feeding on behavior, reproductive performance, and nutrient digestibility in gestating sows. J. Anim. Sci. 84, 946–955. https://doi.org/10.2527/2006.844946x.

Huntley, N.F., Patience, J.F., 2018. Xylose metabolism in the pig. PLoS One 13, e0205913. https://doi.org/10.1371/journal.pone.0205913.

Hurley, W.L., 2014. Composition of sow colostrum and milk. In: Farmer, C. (Ed.), The gestating and lactating sow. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 193–230.
Jarrett, S., Ashworth, C.J., 2018. The role of dietary fibre in pig production, with a particular emphasis on reproduction. J. Anim. Sci. Biotechnol. 9, 59. https://doi.org/10.1186/s40104-018-0270-0.
Jørgensen, H., Serena, A., Hedemann, M.S., Bach Knudsen, K.E., 2007. The fermentative capacity of growing pigs and adult sows fed diets with contrasting type and level of dietary fibre. Livest. Sci. 109, 111–114. https://doi.org/10.1016/j.livsci.2007.01.102.
Kim, B.G., Petersen, G.I., Hinson, R.B., Allee, G.L., Stein, H.H., 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87, 4013–4021. https://doi.org/10.2527/jas.2009-2060.
Lan, R., Li, T., Kim, I., 2017. Effects of xylanase supplementation on growth performance, nutrient digestibility, blood parameters, fecal microbiota, fecal score and fecal noxious gas emission of weanling pigs fed corn-soybean meal-based diets. Anim. Sci. J. 88, 1398–1405. https://doi.org/10.1111/asj.12771.
de Lange, C.F.M., Pluske, J., Gong, J., Nyachoti, C.M., 2010. Strategic use of feed ingredients and feed additives to stimulate gut health and development in young pigs. Livest. Sci. 134, 124–132. https://doi.org/10.1016/j.livsci.2010.06.117.
Le Goff, G., van Milgen, J., Noblet, J., 2002. Influence of dietary fibre on digestive utilization and rate of passage in growing pigs, finishing pigs and adult sows. Anim. Sci. 74, 503–515. https://doi.org/10.1017/S1357729800052668.
Lee, J.J., Choi, S.H., Cho, J.H., Choe, J., Kang, J., Kim, S., Park, S., Kyoung, H., Seo, D., Cho, J.Y., Park, I.H., Oh, S., Kim, H.B., Song, M., 2019. Effects of dietary carbohydrases on productive performance and immune responses of lactating sows and their piglets. J. Anim. Sci. Technol. 61, 359–365. https://doi.org/10.5187/jast.2019.61.6.359.
de Leeuw, J.A., Bolhuis, J.E., Bosch, G., Gerrits, W.J., 2008. Effects of dietary fibre on behaviour and satiety in pigs. Proc. Nutr. Soc. 67, 334–342. https://doi.org/10.1017/S002966510800863X.
Leys, S., De Bondt, Y., Bosmans, G., Courtin, C.M., 2020. Assessing the impact of xylanase activity on the water distribution in wheat dough: a 1H NMR study. Food Chem. 325, 126828 https://doi.org/10.1016/j.foodchem.2020.126828.
Loisel, F., Farmer, C., Ramaekers, P., Quesnel, H., 2013. Effects of high fiber intake during late pregnancy on sow physiology, colostrum production, and piglet performance. J. Anim. Sci. 91, 5269–5279. https://doi.org/10.2527/jas.2013-6526.
Meunier-Salaün, M.C., Edwards, S.A., Robert, S., 2001. Effect of dietary fibre on the behaviour and health of the restricted fed sow. Anim. Feed Sci. Technol. 90, 53–69. https://doi.org/10.1016/S0377-8401(01)00196-1.
Middelbos, I.S., Fahey, G.C., 2008. Soybean carbohydrates. In: Johnson, L.A., White, P.J., Galloway, R. (Eds.), Soybeans. Chemistry, production, processing, and utilization. Academic Press and AOCS Press, Urbana, IL, USA, pp. 269–296. https://doi.org/10.1016/B978-1-893997-64-6.50012-3.
Myers, W.D., Ludden, P.A., Nayigihugu, V., Hess, B.W., 2004. Technical note: a procedure for the preparation and quantitative analysis of samples for titanium dioxide. J. Anim. Sci. 82, 179–183. https://doi.org/10.2527/2004.821179x.
National Forage Testing Association, 1993. Forage analyses procedures. Omaha, NE, USA. ⟨https://www.foragetesting.org/lab-procedures⟩ (Accessed 2 December 2022).
Navarro, D.M.D.L., Abelilla, J.J., Stein, H.H., 2019. Structures and characteristics of carbohydrates in diets fed to pigs: a review. J. Anim. Sci. Biotechnol. 10, 39. https://doi.org/10.1186/s40104-019-0345-6.
Nortey, T.N., Patience, J.F., Sands, J.S., Zijlstra, R.T., 2007. Xylanase supplementation improves energy digestibility of wheat by-products in grower pigs. Livest. Sci. 109, 96–99. https://doi.org/10.1016/j.livsci.2007.01.092.
NRC, 2012. Nutrient requirements of swine, 11th rev. ed. Natl. Acad. Press, Washington, D.C., USA.
Nuntapaitoon, M., 2022. Colostrum and milk in sow. In: Chaiyabutr, N. (Ed.), Milk protein - New research approaches. IntechOpen, London. United Kingdom. https://doi.org/10.5772/intechopen.102890.
Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M., Lahti, L., McGlinn, D., Ouellette, M., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C., Weedon, J., 2022. Vegan: Community Ecology Package. R package (version 2.6-4). ⟨https://CRAN.R-project.org/package=vegan⟩.
Passos, A., Park, I., Ferket, P., von Heimendahl, E., Kim, S.W., 2015. Effect of dietary supplementation of xylanase on apparent ileal digestibility of nutrients, viscosity of digesta, and intestinal morphology of growing pigs fed corn and soybean meal-based diet. Anim. Nutr. 2015, 19–23. https://doi.org/10.1016/j.aninu.2015.02.006.
Patience, J.F., Petry, A.L., 2019. Susceptibility of fibre to exogenous carbohydrases and impact on performance in swine. In: Gonzalez-Ortiz, G., Bedford, M.R., Bach Knudsen, K.E., Courtin, C., Classen, H.L. (Eds.), The value of fibre - engaging the second brain for animal nutrition. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 99–116.
Patience, J.F., Tacker, P.A., 1989. Swine nutrition guide. Prairie swine center. Saskatoon, SK, Canada.
Pedersen, M.B., Yu, S., Arent, S., Dalsgaard, S., Bach Knudsen, K.E., Lærke, H.N., 2015b. Xylanase increased the ileal digestibility of nonstarch polysaccharides and concentration of low molecular weight nondigestible carbohydrates in pigs fed high levels of wheat distillers dried grains with solubles. J. Anim. Sci. 93, 2885–2893. https://doi.org/10.2527/jas.2014-8829.
Pedersen, M.B., Dalsgaard, S., Arent, S., Lorentsen, R., Bach Knudsen, K.E., Yu, S., Lærke, H.N., 2015a. Xylanase and protease increase solubilization of non-starch polysaccharides and nutrient release of corn-and wheat distillers dried grains with solubles. Biochem. Eng. J. 98, 99–106. https://doi.org/10.1016/j.bej.2015.02.036.
Petry, A.L., Huntley, N.F., Bedford, M.R., Patience, J.F., 2020. Xylanase increased the energetic contribution of fiber and improved the oxidative status, gut barrier integrity, and growth performance of growing pigs fed insoluble corn-based fiber. J. Anim. Sci. 98, skaa233 https://doi.org/10.1093/jas/skaa233.
Petry, A.L., Huntley, N.F., Bedford, M.R., Patience, J.F., 2024. Unveiling the influence of adaptation time on xylanase and arabinoxylan-oligossacharide efficacy: a study on nutrient digestibility, viscosity, and scanning electron microscopy in the small and large intestine of growing pigs fed insoluble fiber. J. Anim. Sci. 102, 1–13. https://doi.org/10.1093/jas/skad378.
Quesnel, H., Farmer, C., Theil, P.K., 2015. Colostrum and milk production. In: Farmer, C. (Ed.), The gestating and lactating sow. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 173–192. https://doi.org/10.3920/9789086868032_009.
Raza, A., Bashir, S., Tabassum, R., 2019. An update on carbohydrases: growth performance and intestinal health of poultry. Heliyon 5, e01437. https://doi.org/10.1016/j.heliyon.2019.e01437.
Ribeiro, T., Cardoso, V., Ferreira, L.M.A., Lordelo, M.M.S., Coelho, E., Moreira, A.S.P., Domingues, M.R.M., Coimbra, M.A., Bedford, M.R., Fontes, C.M.G.A., 2018. Xylo-oligosaccharides display a prebiotic activity when used to supplement wheat or corn-based diets for broilers. Poult. Sci. 97, 4330–4341. https://doi.org/10.3382/ps/pey336.
SAS Institute Inc, 2016. SAS® 9.4 SQL Procedure user's guide, Fourth ed.,. SAS Institute Inc, Cary, NC, USA.
Shipman, G., Perez-Palencia, J.Y., Rogiewicz, A., Patterson, R., Levesque, C.L., 2023. Evaluation of multienzyme supplementation and fiber levels on nutrient and energy digestibility of diets fed to gestating sows and growing pigs. J. Anim. Sci. 101, 1–11. https://doi.org/10.1093/jas/skad375.
de Souza, A.L.P., Lindemann, M.D., Cromwell, G.L., 2007. Supplementation of dietary enzymes has varying effects on apparent protein and amino acid digestibility in reproducing sows. Livest. Sci. 109, 122–124. https://doi.org/10.1016/j.livsci.2007.01.113.
Tiwari, U.P., Chen, H., Kim, S.W., Jha, R., 2018. Supplemental effect of xylanase and mannanase on nutrient digestibility and gut health of nursery pigs studied using both *in vivo* and *in vitro* models. Anim. Feed Sci. Technol. 245, 77–90. https://doi.org/10.1016/j.anifeedsci.2018.07.002.
Tiwari, U.P., Fleming, S.A., Abdul-Rasheed, M.S., Jha, R., Dilger, R.N., 2020. The role of oligosaccharides and polysaccharides of xylan and mannan in gut health of monogastric animals. J. Nutr. Sci. 9, e21 https://doi.org/10.1017/jns.2020.14.
Torres-Pitarch, A., Manzanillaac, E.G., Gardiner, G.E., O'Doherty, J.V., Lawlor, P.G., 2019. Systematic review and meta-analysis of the effect of feed enzymes on growth and nutrient digestibility in grow-finisher pigs: effect of enzyme type and cereal source. Anim. Feed Sci. Technol. 251, 153–165. https://doi.org/10.1016/j.anifeedsci.2018.12.007.

Trottier, N.L., Johnston, L.J., 2001. Feeding gilts during development and sows during gestation and lactation. In: Lewis, A.J., Southern, L.L. (Eds.), Swine nutrition. CRC Press, Boca Raton, FL, USA, pp. 725–770. https://doi.org/10.1201/9781420041842.

Tsai, T., Dove, C.R., Cline, P.M., Owusu-Asiedu, A., Walsh, M.C., Azain, M., 2017. The effect of adding xylanase or β-glucanase to diets with corn distillers dried grains with solubles (CDDGS) on growth performance and nutrient digestibility in nursery pigs. Livest. Sci. 197, 4–52. https://doi.org/10.1016/j.livsci.2017.01.008.

U.S. Enviromental Protection Agency, 1996. Method 3050B: Acid digestion of sediments, sludges, and soils. Revision 2. Washington, DC. USA.

Urriola, P., Cervantes-Pahm, S.K., Stein, H.H., 2012. Fiber in Swine Nutrition. In: Chiba, L.I. (Ed.), Sustainable swine nutrition. John Wiley and Sons Inc, Ames, IA, USA, pp. 255–276. https://doi.org/10.1002/9781118491454.ch11.

de Vries, S., Pustjens, A.M., Schols, H.A., Hendriks, W.H., Gerrits, W.J.J., 2012. Improving digestive utilization of fiber-rich feedstuffs in pigs and poultry by processing and enzyme technologies: a review. Anim. Feed Sci. Technol. 178, 123–138. https://doi.org/10.1016/j.anifeedsci.2012.10.004.

Walsh, M.C., Geraert, P.A., Maillard, R., Kluess, J., Lawlor, P.G., 2012. The effect of a non-starch polysaccharide-hydrolysing enzyme (Rovabio® Excel) on feed intake and body condition of sows during lactation and on progeny growth performance. Animal 6, 1627–1633. https://doi.org/10.1017/S1751731112000237.

Yang, X., Walsh, M.C., Kiarie, E., Tekeste, A., Baidoo, S.K., 2016. Effects of xylanase on growth performance and digestibility of fiber and energy in growing pigs fed corn, corn DDGS and soybean meal based diet supplemented with phytase. J. Anim. Sci. 94 (Suppl. 2), 131. https://doi.org/10.2527/msasas2016-279.

Zhe, L., Zhou, R., Theil, P.K., Krogh, U., Yang, L., Zhuo, Y., Lin, Y., Xu, S., Jiang, X., Huang, L., Che, L., Feng, B., Wu, D., Fang, Z., 2022. The impact of enhancing diet quality or dietary supplementation of flavor and multi-enzymes on primiparous lactating sows. Animals 12, 1493. https://doi.org/10.3390/ani12121493.

Zhenping, S., Wenting, L., Ruikui, Y., Jia, L., Honghong, L., Wei, S., Zhongmie, W., Jingpan, L., Zhe, S., Yuling, Q., 2013. Effect of a straw-derived xylooligosaccharide on broiler growth performance, endocrine metabolism, and immune response. Can. J. Vet. Res. 77, 105–109.

Zhou, P., Nuntapaitoon, M., Pedersen, T.F., Bruun, T.S., Fisker, B., Theil, P.K., 2018. Effects of mono-component xylanase supplementation on nutrient digestibility and performance of lactating sows fed a coarsely ground diet. J. Anim. Sci. 96, 181–193. https://doi.org/10.1093/jas/skx042.

Zier-Rush, C.E., Groom, C., Tillman, M., Remus, J., Boyd, R.D., 2016. The feed enzyme xylanase improves finish pig viability and carcass feed efficiency. J. Anim. Sci. 94 (Suppl. 2), 115. https://doi.org/10.2527/msasas2016-244.