

ABSTRACT

MARTINEZ PADILLA, GABRIELA ESTHER. Using Fermentable Fiber During Gestation and Early Lactation to Improve Reproductive Performance of Sows (Under the direction of Dr. Eric van Heugten).

The energy requirements of a gestating sow increase as pregnancy progresses. It is of great importance to evaluate dietary strategies to assist the sow with the energetic burden that farrowing represents to ensure an optimal lactation performance for both sow and litter. Fiber is used to control sow weight during gestation, reducing the stereotypic behaviors and it is an alternate energy source. However, the role of fiber in sow reproduction and performance, and piglet performance is an intricate topic that needs further investigation. To address this and other issues, four experiments were conducted.

The objective of experiment 1 was to determine fiber fermentation characteristics through an in vitro analysis with sow cecal contents as an inoculum. Fibers evaluated were inulin from chicory root (native and long-chain inulin with 90 and 98% fiber, respectively), pectin from citrus peel (high methoxyl pectin), resistant starch (native starch), potato starch (commercial grade), and β -glucan (β -1,3; β -1,6 yeast-derived). Cellulose and cornstarch were used as indigestible and highly digestible carbohydrates, respectively. Concentrations of acetate were greater for resistant starch, whereas butyrate was higher for potato starch and β -glucan. Propionate was increased by β -glucan. Pectin had the lowest pH and BCFA concentrations compared to the other sources, but total production of SCFA was increased by resistant starch, potato starch and β -glucan.

In experiment 2, the objective was to determine the impact of fiber supplementation throughout gestation and during the pre-farrowing period. 117 sows were randomly assigned to one of the two gestation treatments: Low fiber (9%) and High fiber (18%). Subsequently, these sows were assigned to a 2×2 factorial arrangement by BW and BCS. Factors included the level of

TDF in gestation diets (9% and 18%) and a pre-farrowing pelleted supplement (top-dress or no top-dress) and were supplemented from placement in farrowing until parturition. Fiber supplementation during gestation and pre-farrowing did not affect sow BW at weaning. Piglet performance was not affected by fiber, but piglets from sows fed the low fiber during gestation and top-dress supplement, tended to decrease the number of non-viable pigs (<3.6 kg) at weaning.

In experiment 3, two studies were conducted to evaluate the impact of fiber solubility during the pre-farrow period. The experimental design corresponds to a 2×2 factorial arrangement with a control treatment with fiber solubility: High ((SDF; 6.00%), (IDF; 31.10%)), and Low ((SDF; 4.20%), (IDF; 28.30%)) and top-dress allowance (0.45 kg, and 0.90 kg) as the factors. In experiment 3a (2-day supplementation), fiber supplementation did not affect sow BW from placement until the end of lactation, or piglet performance. Estimation of IgG was not affected by fiber source or level of supplementation. Total solids tended to increase with soluble fiber at 0.45 kg, lactose and total protein tended to be greater with fiber irrespective of the level of source and level of supplementation. In experiment 3b (7-day supplementation), fiber supplementation did not affect sow BW from placement to weaning. Soluble fiber reduced the weaning-to-estrus interval of sows regardless of the level of supplementation. Fecal scores were not impacted by fiber supplementation relative to control treatment. Glucose concentrations were higher during farrowing for sows supplemented with fiber compared to control. Estimation of IgG was not affected by fiber source or level of supplementation. Total solids tended to increase with soluble fiber at 0.45 kg, ash tended to increase with insoluble fiber at 0.45 kg, and total protein tended to increase with fiber supplementation regardless of the source and amount.

Experiment 4 aimed to determine if a longer time of fiber supplementation could improve sow and litter performance during late gestation and during the pre-farrowing period. The

experimental design corresponds to a 2×2 factorial arrangement with a control treatment with fiber solubility: High ((SDF; 9.63%), (IDF; 30.73%)), and Low ((SDF; 4.18%), (IDF; 25.25%)) and top-dress allowance (0.45 kg, and 0.90 kg) as factors. Supplementation of fiber during late gestation and during the pre-farrowing period did not affect sow BW. Sows supplemented with insoluble fiber at 0.90 kg and soluble fiber had lower weaning-to-estrus interval. Number of pigs born alive, and piglet birth weight did not differ. However, number of stillborn pigs was reduced with insoluble fiber at 0.45 kg, but higher for insoluble fiber at 0.90 kg. Furthermore, insoluble fiber at 0.45 kg increased the number of low-birth weight pigs (< 1 kg) and increased the number of non-viable pigs at weaning (<3.6 kg). Serum chemistry analysis revealed lower GGT concentrations with fiber treatments compared to control. Glucose concentrations, fetal expulsion length, and piglet vitality index were not affected by fiber.

In conclusion, these studies demonstrate that selection of a fiber source plays an important role to determine animal health and performance. Fiber during gestation does not cause a negative effect on sow and piglet performance during lactation. Fiber supplemented as a top-dress during late gestation and during the pre-farrowing period may be an alternative nutritional strategy to implement during the transition period to improve sow and piglet performance, however time of supplementation is important to consider. Further research is encouraged with an increased number of sows to determine the effects of fiber supplementation during multiple parities.

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Using Fermentable Fiber During Gestation and Early Lactation to Improve Reproductive
Performance of Sows

by
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DEDICATION

To

My parents Leticia and Luis Martinez, and my siblings Ale and Luis. This accomplishment is also yours! Thank you for being with me in every step, for your words of encouragement and for your prayers.

To my husband Fernando, thank you for joining me in this adventure, for your constant love and support and for the beautiful family we have built together.

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¡Lo logramos!

BIOGRAPHY

Gabriela Martinez was born in Honduras on September 18th, 1988. In 2011 she received her BS in animal science and agricultural production from Zamorano. In 2012 she obtained an internship with Murphy Brown LLC (Smithfield) to work in a sow farm in North Carolina. Later, she was admitted as a research scholar in the animal science department at NC State University, and subsequently, she was admitted to pursue her studies as a MS student under the direction of Dr. Eric van Heugten. She graduated in 2018 and continued with her PhD under the direction of Dr. Eric van Heugten. Her research explored the role of fermentable fiber during late gestation and early lactation in sows.

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CHAPTER I:

Literature review

Introduction

Nutrition of the pregnant and early lactating sow is still a relevant topic with many questions still to be answered in the scientific community. To date, the exact ideal nutritional program to enhance sow reproductive performance does not exist.

Up until recently, sow nutrition has gained much more attention as a means to improve sow longevity and production. There are a variety of parameters under scrutiny when formulating diets for sows, with the physiological stage (gestating or lactating) being the most important. The number of parity, age, body condition, weight, and health status influence in the formulation. Even though these parameters are different from sow to sow, and although it is not possible to exactly control them individually, investigators have placed interest in trying to meet the nutritional needs of a gestating and a lactating sow by analyzing different feed strategies. (Campos et al., 2012).

For the swine industry, the production goals are measured by increasing the conception and farrowing rates, number of pigs weaned per year per sow, litter size, optimize pig birth weight and weaning weights, and increase the number of litters per year. Maximizing these goals can be achieved when there is an understanding of sow reproductive performance and efficiency, which are tightly related to sow longevity.

The use of fermentable fiber in gestation diets can potentially help to improve the reproductive performance of sows, reduce the rate of stillborn pigs and improve the weaning weight of piglets. In addition, it can reduce stereotypic behavior of sows, improve their intestinal health and energy reserves, therefore enhancing their longevity (Brooks, 2008).

The objectives of this present review are: 1) to summarize nutrition of sows during gestation, 2) to review research related to the use of fiber as a nutrition strategy to improve sow reproductive performance, 3) evaluate the production of short-chain fatty acids from fermentable fiber and their health benefits, and 4) determine the importance of the transition period from gestation to lactation for sows, particularly when using fermentable fiber.

Sow nutrition

Genetic selection has improved prolificacy of sows, which is reflected by increase in litter size (Campos et al., 2012; Rooney et al., 2019). The average number of pigs weaned per sow per year in 2020 was estimated at 24.84 in the United States according to Pig CHAMP. This increase in litter size is also tied to a decrease in piglet birth weight, increased variation within litter, and an increased rate of mortality during the first days of lactation (Mallmann et al., 2018; Pouloupoulou et al., 2018).

As a result, the pressure in performance from sows has also increased, with the goal of growing a lean, bigger litter at the end of lactation resulting in exposure to a constant catabolic state and changes in the nutrient requirements of the sow. In consequence, physical stress from sows can lead to increased farrowing length, and it can compromise colostrum and milk composition (D'Eath et al., 2018).

The swine industry has pursued the goal to increase pig production effectively at low cost and has implemented targeted feeding strategies to reach that objective. Thus, nutrition of the gestating sow is focused on the growth of fetuses and associated tissues, the mammary gland, protein deposition, and maintenance requirements in required amounts. During this phase of production, a gestation diet that is low in energy and protein, is typically fed at a restricted amount.

In contrast during lactation, a diet which is high in protein and energy, is used to supply nutrients to piglets through milk and maintain body condition of the dam (Solà-Oriol and Gasa, 2017).

Sow nutrition: gestation period

During gestation sows are limit-fed to avoid extra weight gain. Over-conditioned sows may have problems at parturition and have a low feed intake during lactation (MacPherson et al., 2004). Gestation diets are typically low in energy, and it only satisfies 40 to 60% of voluntary intake by the sows, which triggers stereotypic behavior (Meunier-Salaün, et al., 2001). To ameliorate the stereotypic behavior, the gestation diets must rely on fibrous ingredients to maintain the low energy density while allowing satiation of the sow and minimizing welfare concerns (Close, 2003; Che et al., 2011).

As a customary practice before farrowing (2 to 3 days, depending on the production system) sows are introduced to a lactation diet (at the time they are moved from the gestation house into the farrowing facility) which is typically high in energy and protein (Guillemet et al., 2010). However, this is an abrupt change in their diets where time to adjust is rather short, in addition to preparing for the parturition process (Theil et al., 2014b; Tokach et al., 2019).

There are three gestational stages that merit close evaluation as they may help match the nutrient requirement of the gestating sow. The first phase is early pregnancy (d 0 to 30), where implantation and embryo survival are the main focus. The second phase is mid-gestation (d 30 to 75), in this period, the body reserves and body mobilization from the preceding lactation period are recovered, and maternal gain is starting to become important. The third phase is late gestation (d 75 to 115 approximately) where fetal growth, mammary development, fetal weight, and nutrient

deposition increase exponentially (Boyd et al., 2002; Kraeling and Webel, 2015). In particular, protein and energy requirements become higher during this period (Theil, 2015).

In general practice, all sows in gestation are fed a standard diet due to the easier management, and because it would be challenging to make custom diets for every sow (Solà-Oriol and Gasa, 2017). However, it is evident that nutrient requirements are lower in early gestation than late gestation. Thus, the practice of providing an equivalent nutrient distribution during gestation is not accurate (Yang et al., 2008).

Examples of nutrition strategies to meet sow nutrition needs during gestation

Moehn and Ball (2013), proposed a two-phase feeding program that would target a low nutrient requirement phase and a high nutrient requirement phase during pregnancy. Most compelling reasoning and evidence support this scheme. Macpherson and co-workers (2004) studied the dynamic changes in growth of fetuses from pregnant gilts. It was demonstrated that nutrient requirement of amino acids for fetal growth were markedly increased during late gestation (4.63 g/day for protein deposition) compared to early gestation (0.25 g/day).

Another example is the level of lysine required, which increases as pregnancy progresses (Boyd et al., 2000; Kim et al., 2009; Costa et al., 2019). Investigations by Kim et al. (2009) and Zhang et al. (2011), suggest that to support fetal weight and growth besides maintenance requirements, a sow would need to consume approximately 6 g of lysine during early gestation (d 0 to 60) and almost 9 g of lysine towards the end (d 60 to 115). Similar pattern has been observed for energy (Newcomb et al., 1991; Dourmant et al., 1994).

Certainly, it is a great challenge for the industry to apply two diets in the field, and that are customized for each sow. And it has become evident that age is another crucial aspect that

affects prolificacy as nutrient requirements for gilts and young sows are different from the requirements of a mature sow (NRC, 2012; Solà-Oriol, and Gasa., 2017).

As a matter of fact, a single gestation diet for this entire period may place the sows to a possible undernutrition-overnutrition scenario (Dourmand, 2019) where stage of pregnancy and age play a major role (Bauer et al., 1998; Campos et al., 2012; Costa et al., 2019). Rather, the developing of two diets during gestation that aim to meet the nutritional requirements during the most critical stages of sow pregnancy seems to be a good starting point onto development of more strategies to improve sow longevity.

Fiber as a nutritional strategy to improve sow reproductive performance.

Fiber definition and classification

Fiber is defined as non-starch polysaccharides that are not digested or poorly digested by enzymes in the small intestine but are mostly fermented by microbes in the large intestine. It is divided into cell wall components and non-cell wall components (Figure 1). The non-cell wall components are considered as non-starch polysaccharides (NRC, 2012; Kerr and Shurson, 2013).

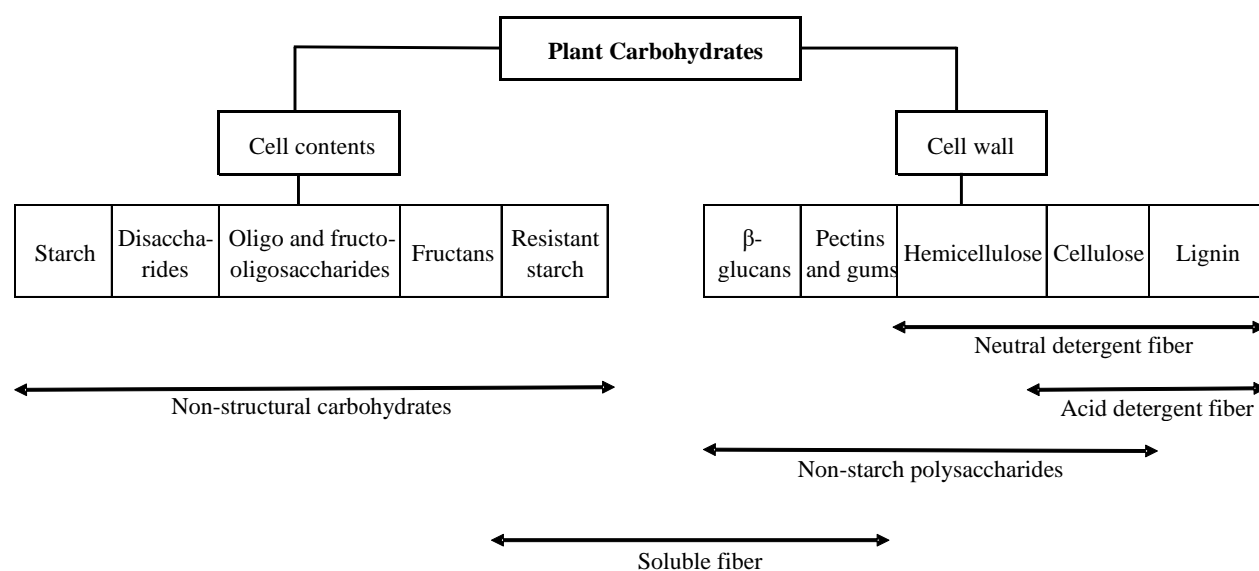


Figure 1. Plant carbohydrate fractions. Adapted from NRC (2012) and Hall and Eastridge, (2014).

Fiber can be classified as follows:

Dietary fiber: found in natural feed sources (mostly plants) example: lignin, hemicellulose, cellulose, β -glucans, pectins, gums, fructo- and oligo-saccharides, and resistant starch (Jha, 2010).

Functional fiber: isolated indigestible carbohydrates that offer health benefits for humans. They may be extracted from natural sources (plants or animals (i.e., chitin)) or can be added to foods from synthetic forms. Example: fructo-oligosaccharides, resistant dextrans, chitin and chitosan polydextrose and psyllium. (Slavin, 2013; Li and Komarek, 2017).

Total fiber: is the sum of dietary and functional fiber (DeVries et al., 1999).

Fiber can be further classified based on viscosity, fermentability and solubility (Zijlstra et al., 2012; Slavin, 2013; Jha and Zijlstra, 2017) as: Soluble, viscous, fermentable fiber such as: β -glucans from oats and barley. Soluble, viscous, non-fermentable fiber such as: psyllium. Soluble, non-viscous, fermentable fiber: inulin, resistant starch, oligosaccharides. Insoluble, poorly fermentable fiber: cellulose, lignin (Figure 2). Viscosity is the ability of non-starch polysaccharides to form viscous aggregates which can delay transit time in the small intestine. Viscous fibers thicken when mixed with fluids and the grade of thickening will depend on the concentration of the polysaccharide and the chemical profile. (Dikeman and Fahey, 2007). Fermentability is more associated with large intestine function. This is the site of fermentation for non-starch polysaccharides performed by microbes. It is thought that fermentable fiber is associated with solubility. Thus, the more soluble, the more fermentable. (Agyekum, and Nyachoti, 2017).

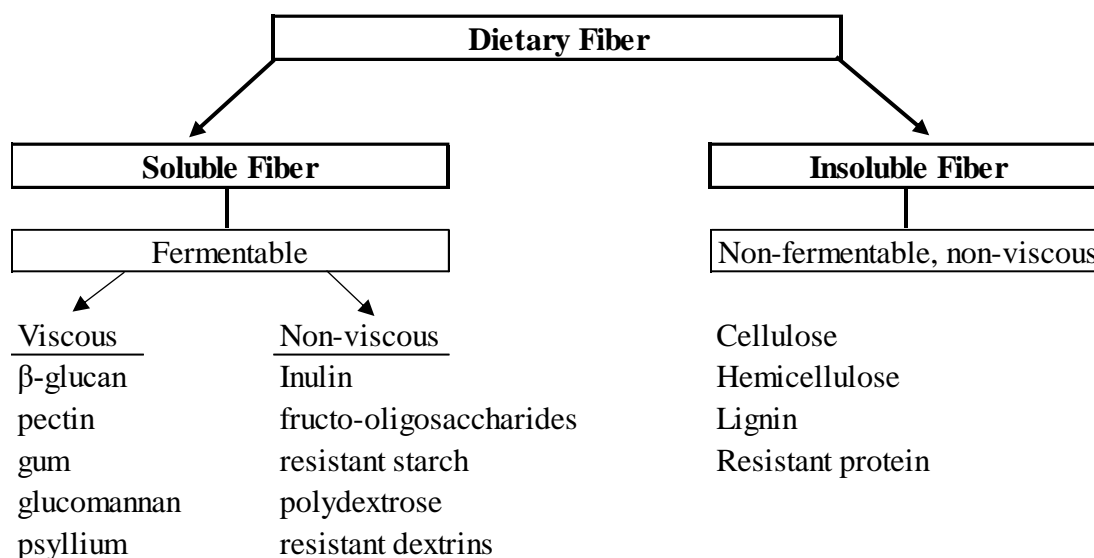


Figure 2. Fiber classification based on chemical profile. Kerr and Shurson, (2013); Lindberg, (2014); Jha and Berrocoso, (2015).

In vitro analysis, a practical method to measure fermentation of fiber

To analyze fiber and its components, there are known methods that can describe the chemical characteristics including neutral detergent fiber (NDF), acid detergent fiber (ADF) and soluble and insoluble non-starch polysaccharides. These methods can be classified in three categories: 1) Chemical-gravimetric, an example would be “crude fiber” and Van Soest (1991) methods (NDF and ADF), 2) Enzymatic-gravimetric, 3) Enzymatic-chemical. Total Dietary Fiber (TDF) is a clear example of the last two methods, because enzymes are used to stimulate what would happen in the digestive tract to quantitate this measurement. (Agyekum, and Nyachoti, 2017, Novotny et al., 2017).

To determine the fermentation characteristics of fibrous ingredients, *in vivo* methods may be expensive and laborious, whereas *in vitro* assays are a more practical way to describe in a more accurate, fast and less expensive manner, the profile of fermentation and impact of fermentable

fiber in the GI tract and provides a more controlled environment, thus, reducing human error and other factors (animal-animal and farm) (Coles et al., 2005; Pluske, 2013).

In vitro techniques are a popular tool, as they can serve as a standard procedure to determine fermentability by using a substrate (e.g., fiber), and measure microbial activity by using an inoculum. This can be fecal material or cecal contents in the case of monogastric animals or rumen content in the case of ruminants. (Williams et al., 2005). Furthermore, *in vitro* assays can measure substrate disappearance and bacterial proliferation, production of SCFA and gas, and the ability of the fiber source to generate metabolites that might influence microbial populations in pigs. (de Lange et al., 2010; Huang et al., 2018).

Generally speaking, *in vitro* assays allow the study of isolated compounds, and their possible physiological and biological action in one specific region of interest, (in the case of fiber, that would be the large intestine) while resulting in comparable results in *in vivo* scenario (Huang et al., 2018). However, *in vitro* assays have their limitations as they will never match *in vivo* conditions. Rather, the assay aims to predict the conditions closer to those of the animal which is why it is recommended to validate data observed *in vitro* with *in vivo* data.

Applications of fiber in swine (gestation diets)

Inclusion of dietary fiber in swine diets is not a new concept, and the benefits are well documented, especially when fiber is offered during the gestation period (Souza da Silva et al., 2013; Jensen et al., 2015; Zijlstra, and Beltranena, 2012; Sun et al., 2015).

It is a common practice for swine producers to limit intake of sows during gestation to avoid excessive weight gain, which can represent problems at parturition. Fiber provides the sow a satiety feeling, decreases stereotypical behavior (i.e., sham chewing, bar biting, stress) (Che et

al., 2011), and it has been incorporated in the diets with a welfare purpose; to mitigate hunger in sows. It also reduces constipation, and this is important especially at the time of parturition because constipation can represent a physical barrier to the birth canal which can lead to rectal prolapses and stillborn pigs (D'eath et al., 2018). Table 1 summarizes some of the effects observed when high fiber diets were fed to gestating sows.

When fiber is included in gestation diets, the most notable effects in sow response are reduced feeding motivation during gestation, stereotypic behaviors, increased feed intake during lactation, and heavier weights of litters at weaning (Brouns et al., 1995; Quesnel et al., 2009). During lactation the sow is faced with high energy and nutrient demands to grow her litter and feed intake is crucial. The higher the intake, the less body condition the sow loses which will better prepare the sows to be successfully bred within a normal window (which is considered between 5 to 8 days after weaning) (Schenkel et al., 2010).

Fiber has traditionally been considered to have negative impact on animal performance because its tendencies to decrease nutrient and energy digestibility (Jha et al., 2019), but recently it has gained attention due to the health and welfare benefits it provides.

The common ingredients used in gestation diets as fiber sources include wheat midds, soybean hulls, oats, alfalfa meal, sugar beet pulp, rice bran, wheat bran, distillers dried grain with solubles (DDGS), sunflower meal, and barley (NRC, 2012; Brooks, 2008; Flis et al., 2017). The recommended inclusion amounts of fiber are between 350 to 400 g/d to alleviate stereotypic behaviors, adhere to welfare policies and to obtain benefits from fermentable components in terms of performance and improvements in gut health (Reese et al., 2000; Theil, 2014).

Table 2 shows the physicochemical profiles of common ingredient sources included in gestation diets. Values of NDF, ADF, fermentation capacities are often considered when selecting ingredients.

Investigations with high fiber diets have revealed effects such as decrease net portal appearance (NPA) of glucose and insulin release, and maintaining body homeostasis (Serena et al., 2009; Knudsen, 2014). These effects are probably due, in part, to the increase in viscosity and water binding capacity of soluble fibers, which causes a delayed gastric emptying, thus, digestion and absorption are delayed as well (Hooda et al., 2010). These observations have been observed with fiber ingredients with soluble profiles like sugar beet pulp, oat hulls, soyhulls, oat β -glucans, and barley (Regmi et al., 2011; Zijlstra et al., 2012; Urriola et al., 2012). In addition, the energy derived from fiber fermentation and the production of SCFA, can meet an estimated 15% of the maintenance requirement of energy for growing pigs and 30% for gestating sows (de Leeuw et al., 2008; Jha and Berrococo, 2015; Jha et al., 2019).

Notwithstanding the above, the ability of pigs to utilize fiber, and therefore, the inclusion of fiber in the diet is age dependent. Sows and grower-finisher pigs have a fully developed digestive intestinal tract that allows for more efficient fermentation of fiber compared with young pigs. This in turn, suggests that sows have increased colonization of carbohydrate degrading microbiota population in the large intestine (Lindberg, 2014; Flis et al., 2017).

Table 1. Reported benefits of high fiber in gestation diets

Author (s)/ Fiber (%) /Duration	Performance		Social behavior		GI tract effects	
	Increased	Decreased	Increased	Decreased	Increased	Decreased
Meunier-Salaün et al., 2001. /*BD (30%)/ Gest.	Feeding time Feed intake during lactation	Feeding motivation Rectal T° before farrowing	Resting time	Stereotypic behavior aggressiveness vulva biting skin lesions	Richness and diversity of microbial population	
Guillemet et al., 2007. /*BD (12.40%)/Gest.	Litter weight at birth and at weaning	Back fat thickness				
H. Quesnel et al., 2009. /*BD (11%)/Gest.	Lactation feed intake litter weight at weaning	Back fat thickness leptin during gestation				
Che et al., 2011. /πW. B (16 and 21%)/§2CRC.	Total pigs born alive heavier pigs at weaning	Back fat thickness			Lactobacillus counts	Constipation
da Silva et al., 2013. /#DFC(10, 14, 34%)/56d. vAF.		Feeding motivation	Resting time	Explorative behavior Stereotypic behavior	Butyrate production	Constipation
Tan et al., 2015. /oK.J (2.20%)/§2CRC	Lactation feed intake heavier pigs at weaning					E. coli counts
Jensen et al., 2015. /SBP (35%)/πPG, W2-W9.		Water intake	Resting time	Explorative behavior	Plasma SCFA	Ghrelin levels
Sun et al., 2015. /UK.J (2.10%)/Gest.	Lactation feed intake heavier pigs at birth and weaning			Plasma cortisol	Concentration of SCFA and GLP-1	
Jiang et al., 2019. /φCF (7.5%)/Gest.	Litter size and pigs born alive		Resting time	Fecal, salivary cortisol	Fecal water content Fecal SCFA	Constipation

Table 1. (Continued).

*Bulky diets. These studies had more than 1 fiber ingredient and had at least 4 the following fiber ingredients in common= sugar beet pulp, wheat bran, oat hulls, soybean hulls, potato starch, rice bran, and wheat middlings.

Gest. = fed during gestation until farrowing.

⌘WB= wheat bran.

§2CRC= 2 consecutive reproductive cycles.

Fdfc= different fiber characteristics. Inulin, guar gum, resistant starch. Fed during 56 days. √AF= Adult female pigs (not pregnant).

∩KJ= konjac flour.

∪PG= partially during gestation (from week 2 to week 9 of gestation).

ϕCF= crude fiber.

Table 2
Dietary fiber commonly used in gestation diets

Fiber sources ⁴	NDF ^{1,2}	ADF ^{1,2}	TDF ¹	Fermentability ³	WHC ^{1,3}
Corn gluten feed	27.5	8.4		++	*
Dehydrated alfalfa	46.1	32.6		+++	
Grain of maize	39.2	13.9	12.2	++	*
Peas	15.8	6.8	20.0	++	**
Oat	25.3	13.7		++	**
Oat hull	73.5	35.3	65.3	+	*
Rapeseed meal	31.7	20.6	15.4	+	*
Rice bran	26.3	11.9	32.4		
Resistant starch				+++	*
Soy hulls	59.4	41.6	57.4	+++	**
Sugar beet pulp	44.9	23.5	46.0	++++	***
Sunflower meal	36.8	28.7		++	
Wheat	12.6	3.2	44.0	+	
Wheat bran	32.3	11.0	43.4	++	*
Wheat middlings	35.0	6.0	34.5		

¹NDF= neutral detergent fiber; ADF= acid detergent fiber; TDF= total dietary fiber; WHC= water holding capacity.

²Content expressed as % of DM basis.

³+, ++, +++, +++++ increasingly higher fermentation capacity.

³*, **, *** increasingly lower bulk density.

⁴Information compiled from Serena and Knudsen (2007); De Leeuw et al., (2008); Brooks, (2008); NRC (2012); Aumiller et al., (2015); Knudsen et al., (2015); Flis et al., (2017) and Zhao et al., (2019).

Benefits of fiber fermentation

Fermentation of fiber takes place in the cecum and proximal and distal colon (Macfarlane and Gibson, 1995; Nahm, 2003). Microbes degrade undigested material and endogenous secretions that reach the cecum and colon, using primarily carbohydrates, proteins or a combination of the two as substrates (Utsav et al., 2019). Fiber has been characterized for being a suitable substrate for fermentation, which leads to the production of short-chain fatty acids. The most abundant short-

chain fatty acids (also known as volatile fatty acids) from fiber fermentation are acetic, propionic, and butyric acid. Other acids include formate, valerate, caproate, in addition to gasses that are produced such as H₂, CH₄, and CO₂ (Williams et al., 2001). From protein fermentation, the end-products are branched-chain fatty acids (BCFA) (e.g., isovalerate and isobutyrate), NH₃, phenols (e.g., phenol *p*-cresol), indoles, and amines, and these compounds cause malodor in swine production facilities and contribute to pollution of the environment (Nahm, 2003; Jha and Berrocso, 2016).

Fermentation is an energy preservation process. Metabolic reactions (i.e., hydrolysis, redox, oxidation, phosphorylation) produce electrons and part of them are transferred to the substrate. As a result, energy in the form of ATP is produced and can be used by bacteria for their growth (Macfarlane and Macfarlane, 2003).

For fermentation to take place, the substrate must be depolymerized by microbial enzymes as a first step. After depolymerization, the bacteria can break down and ferment the substrate (complex carbohydrates or proteins) through glycosidases, polysaccharidases and carbohydrate esterases to yield products of fermentation. (Macfarlane and Gibson, 1997; Macfarlane and Macfarlane, 2003; Flint et al., 2012; Giuberti et al., 2015).

Short-chain fatty acids represent an important health benefit as they can be used as a source of energy when glucose from the gut decreases, by stimulating the release of satiety hormones like GLP-1 (Souza da Silva et al., 2013). Acetic acid can be absorbed across the walls of the gastrointestinal tract into the portal vein and can be used as an energy source for the brain, muscle, and heart (Williams et al., 2017; Williams et al., 2019). Butyric acid is the major fuel for colonocyte cells (epithelial cells lining the colon), whereas propionic acid is metabolized in liver and can be used for gluconeogenesis. (Williams et al., 2001; Zijlstra et al., 2012).

Fermentation in the hindgut impacts ammonia by shifting ammonia from urine to feces, such that ammonia volatilization from urine is decreased (van der Meulen et al., 1997; Nahm, 2003). In addition, fermentation of carbohydrates can decrease production of toxic metabolites such as indoles, amines, skatoles, branch-chain fatty acids (BCFA) which are end-products of protein fermentation (Williams et al., 2005; Jha and Berrococo, 2016). The breakdown of protein from feces is a slow process that can take weeks or even months compared to the degradation of urea in ammonia that can be completed in hours (Bindelle et al., 2008; Jarret and Ashworth, 2018).

Furthermore, fiber can be considered a prebiotic and may serve as an alternative for antibiotic growth promoters. By decreasing protein fermentation, fermentable fiber may serve as a substrate and preferentially stimulates the growth of “healthy bacteria” such as *Lactobacillus* and *Bifidobacteria* and decrease the proliferation of pathogenic bacteria (*Clostridium* or *Salmonella*) in the gastrointestinal tract (Macfarlane and Gibson, 1997). However, it should be noted that fermentation characteristics and health benefits will depend on the fiber source used and its physicochemical profile.

Degradation of carbohydrates by microbes

In the case of fiber fermentation, microbes break down polysaccharides into oligosaccharides, to finally yield monosaccharides. From this process only a small amount of energy is removed for microbial growth, as the substrate is not fully oxidized. Monomers are taken up by the microbial cell and enter the TCA cycle for the production of ATP (Macfarlane and Macfarlane, 2003).

Most of the anaerobic microbes residing in the large intestine use the Embden Meyerhof Parnas (EMP) pathway, also known as glycolytic pathway (Figure 3) to break down glucose to

pyruvate via glucose-6-phosphate, which when oxidized can be converted to acetate, propionate, or butyrate (Aumiller et al., 2015). Lactate, ethanol, and succinate are other intermediate products of carbohydrate fermentation, but they usually do not accumulate in the large intestine (Drochner et al., 2004).

The pentose-phosphate pathway is a side carbohydrate degradation route that converts monosaccharides into phosphoenolpyruvate (PEP) and from there is converted to fermentation products or alcohols (den Besten et al., 2013). The pH of the large intestine is acidic resulting in a preference of microbiota for a carbohydrate rather than a protein source. This facilitates the production of short-chain fatty acids, and at the same time, they can maintain the low pH causing a negative effect on pathogenic bacteria (Williams et al., 2005; Utsav et al., 2019). In the presence of sufficient amounts of fermentable carbohydrates (i.e. fiber), ammonia is removed and incorporated as microbial biomass because microbes can retain more nitrogen for their own growth (Knudsen et al., 1993).

Degradation of protein by microbes

Protein fermentation can be summarized in 2 steps: 1) protein that reaches the large intestine is partially fermented by microbes causing production of BCFA (i.e. isobutyrate, isovalerate), ammonia, malodorous compounds, and amines. All of which are derived from deamination of amino acids and from compounds consisting of indoles, phenols, and sulfur characteristics and from metabolism of BCAA (branched-chained amino acids leucine, isoleucine and valine) (Williams et al., 2001). The remaining of the BCFA are then transported to the liver and are converted to glucuronides which can be excreted in urine.

2) Protein that is not fermented in the large intestine, can be fermented in voided feces and manure. As a result, phenolic, indolic and sulfurous components are formed (Windey et al., 2012).

Sulfur components in the manure can also originate from sulfates excreted through the urine as a result of excess of sulfur amino acids (Macfarlane et al., 1992b).

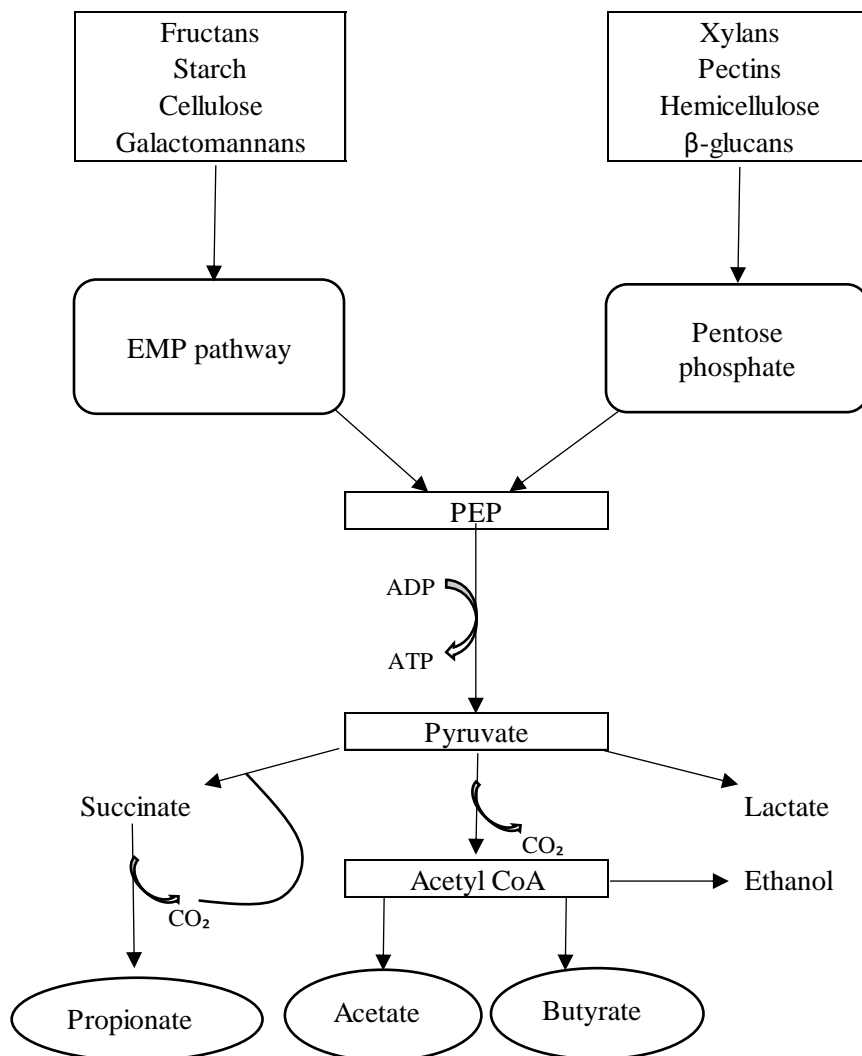


Figure 3. Products of fermentation from carbohydrate metabolism by bacteria in the large intestine. PEP= Phosphoenolpyruvate. Pyruvate and Acetyl CoA are key for anaerobic fermentation. Adapted from Macfarlane and Gibson, (1995).

Protein is always present along the entire digestive tract in the form of endogenous losses (e.g., protein from enzymes, mucus, and sloughed cells) and non-digested feed (Macfarlane et al., 1992b) and is available for fermentation once it reaches the hindgut. An increased pH in the large intestine makes protein fermentation more efficient (Williams et al., 2005). In addition, when fermentable carbohydrates are in low concentration in the large intestine, the microflora will shift to protein fermentation and will use the carbon skeleton of amino acids as energy, resulting in ammonia production (Diether and Willing, 2019). Dietary manipulations can control the substrate that reaches the large intestine and influence the activity of microflora.

Production of short-chain fatty acids (Metabolic routes)

Acetate

Acetate is the major contributor to the overall percentage of SCFA production, followed by propionic and butyric acid. (Harig et al., 1991; Macfarlane and Macfarlane, 2003; Jha and Berrocso, 2015). Production of acetate derives commonly from pyruvate (Figure 4). The pyruvate dehydrogenase complex converts pyruvate to acetyl-CoA, and the enzyme acetyl-CoA synthetase is the responsible for acetate being metabolized in various tissues such as liver, heart, and kidney (Knowles et al., 1974; Macey et al., 1978). But acetate can also be produced from long chain fatty acids, the substrate for acetate formation being carnitine palmitoyl which would increase the amounts of acetyl-CoA via β -oxidation (Yamashita et al., 2007). Pyruvate and acetyl-CoA are key determinant factors for anaerobic fermentation to take place.

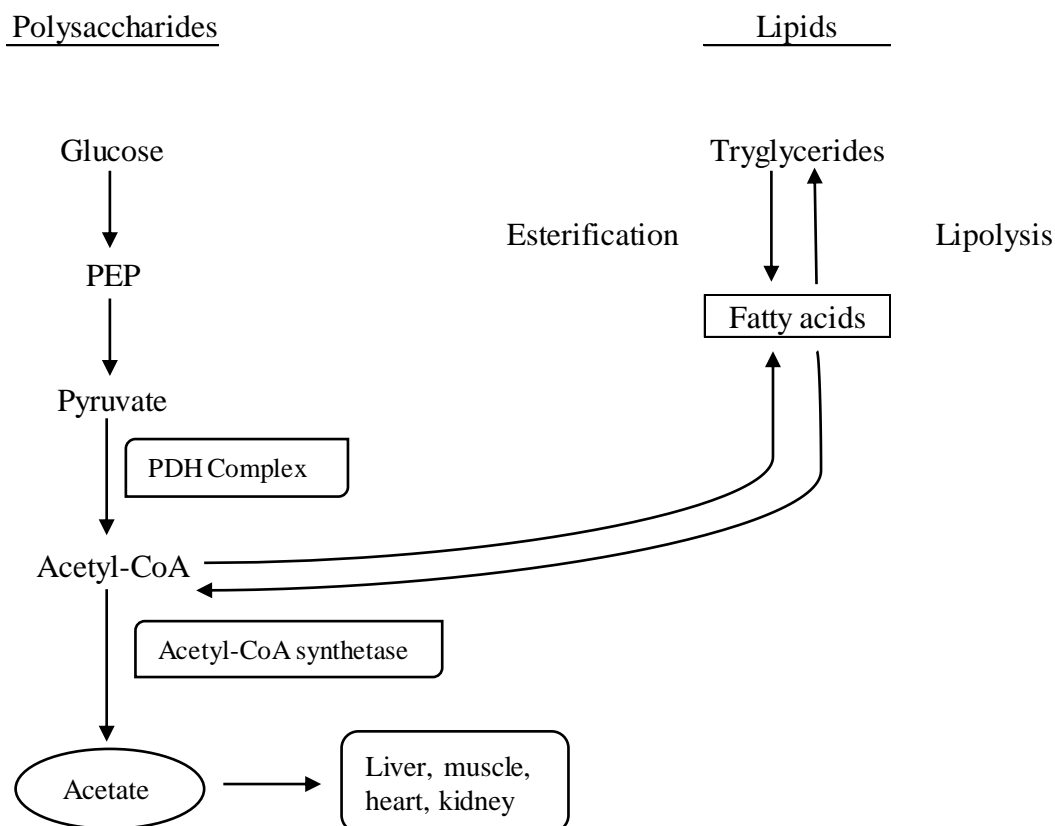


Figure 4. Diagram of acetate production from polysaccharides and lipids. Bacteria prefer the glycolytic pathway to obtain acetate. Adapted from Duncan et al., (2002).

Propionate

Propionate can be produced from three different pathways (Figure 5): the succinate pathway (most common), acrylate and propanediol pathway. (Reichardt et al., 2014).

In the succinate pathway, succinate acts as the substrate for propionate formation. Methylmalonyl-CoA is decarboxylated to propionyl-CoA and propionyl-CoA synthetase converts it to propionate (Macy et al., 1978). First, succinyl-CoA is converted to R-methylmalonyl-CoA (R-MM-CoA) by methylmalonyl-CoA mutase. Methylmalonyl-CoA racemase is needed in the configuration from R-MM-CoA to the S-MM-CoA form. Afterwards, S-MM-CoA is converted to

propionyl-CoA by propionyl-CoA carboxylase. Finally, propionyl-CoA produces propionate by propionyl-CoA synthetase.

Propionate enters the TCA cycle at the level of succinyl-CoA and from there can be integrated into gluconeogenesis (Macy et al., 1978; Reichardt et al., 2014).

The acrylate pathway uses lactate, which is converted to propionate via lactoyl-CoA (den Besten et al., 2013; Flint et al., 2014). The propanediol pathway is most relevant for the metabolism of deoxyhexose sugars (e.g. fucose and rhamnose). Some bacteria (e.g., *lachnospiraceae* family) can produce 1,2 propanediol which can be converted into propionate through propionyl-CoA (Saxena et al., 2010; Reichardt et al., 2014). This pathway is less likely to happen, because the succinate pathway dominates propionate formation (Wikoff et al., 2007; Louis et al., 2014).

Butyrate

There are two pathways from where butyrate can be synthesized from (Figure 6): the butyryl-CoA: acetate CoA transferase and the butyrate kinase pathways (Zhou et al., 2018). Most of the microbial population in the colon utilizes the butyryl CoA: acetate CoA transferase pathway. (Duncan et al., 2004; Louis and Flint, 2009). Butyrate is normally formed from two molecules of acetyl-CoA originating from pyruvate. Acetyl-CoA is further converted to butyryl-CoA and from there, in one enzyme reaction facilitated by butyryl-CoA: acetate- CoA transferase butyrate is produced. In the process, butyryl-CoA is exchanged by exogenous acetate to produce acetyl-CoA and butyrate (Miller and Wallin, 1996; Louis et al., 2004).

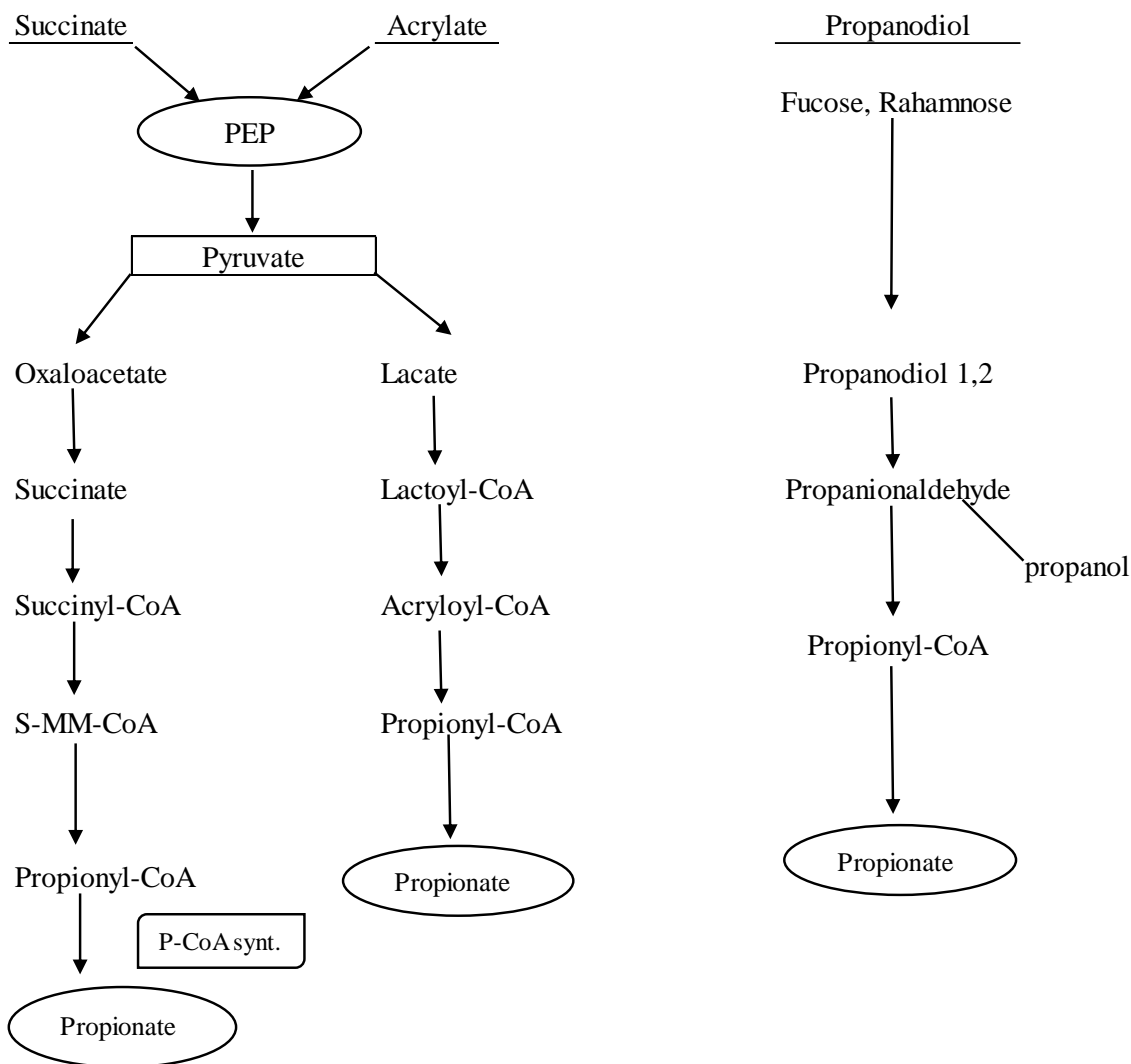


Figure 5. Metabolic routes for propionate production. The succinate pathway (on the left) is the most prevalent route for the synthesis of propionate. MM-CoA undergoes a configuration change from the "R" to "S" form with MM-CoA mutase and MM-CoA racemase respectively. MM-CoA = Methylmalonyl-CoA

P-CoA synt.= Propionyl-CoA synthetase. Adapted from Macy et al., (1978).

The butyrate kinase pathway follows the same reaction steps as the butyryl-CoA: acetate-CoA transferase pathway, until it reaches the formation of butyryl-CoA. From there, butyrate is produced by the enzymes phosphotransbutyrylase and butyrate-kinase. This route is limiting to some butyrate-producing bacteria due to the lack of butyrate kinase activity in many microbial species (Louis and Flint, 2009; Flint et al., 2014). This suggests that butyrate may be dependent on acetate presence for its metabolism (Duncan et al., 2002).

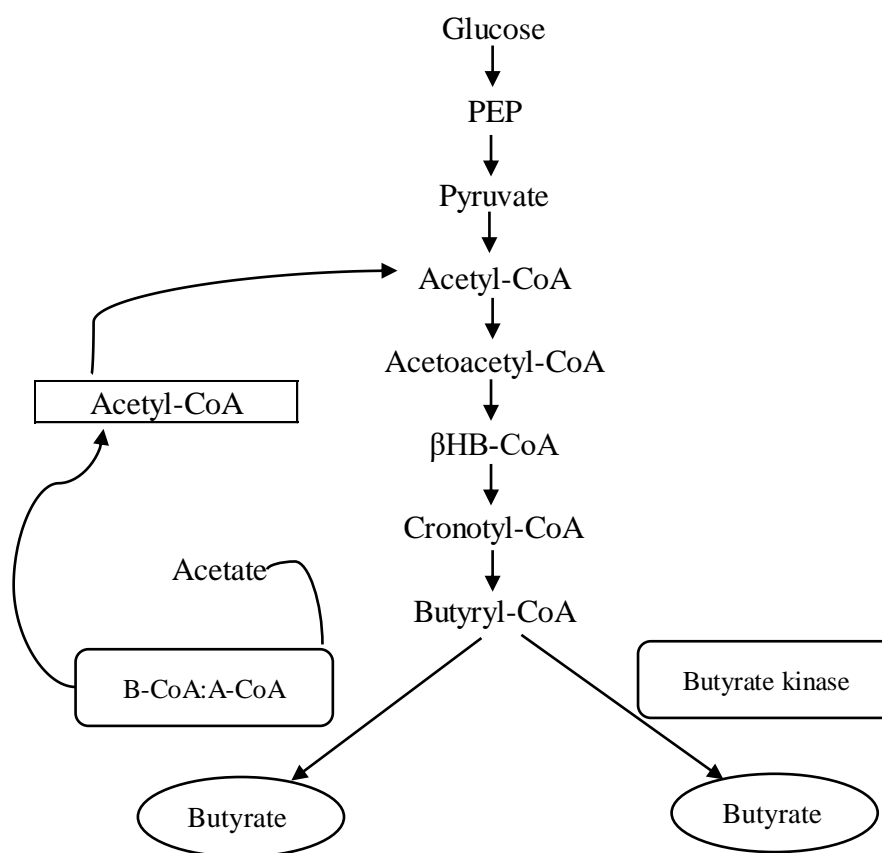


Figure 6. Diagram of butyrate production. β HB-CoA, and Crotonyl-CoA are intermediates. β HB= β -hydroxybutyrate-CoA. B-CoA:A-CoA= Butyryl-CoA: Acetate-CoA transferase. Adapted from Flint et al., (2014).

Short-chain fatty acid absorption and transport

The preferred energy substrates by epithelial cells in the colon are short-chain fatty acids, ketone bodies, amino acids, and glucose. (Williams et al., 2001). Short chain fatty acids are rapidly absorbed in the colon (90-95% absorbed, the rest is excreted in feces). Once short chain fatty acids are absorbed, they are metabolized in 3 places: 1) colon, 2) liver, and 3) skeletal and cardiac muscles (Gibson and Roberfroid, 1995).

Colonocytes utilize butyrate as their primary fuel. In the liver, propionate is used for gluconeogenesis and some residual butyrate is converted to ketone bodies. Part of acetate is used by liver cells as an energy source, but mainly acetate is metabolized in heart, cardiac and skeletal muscle (Knowles et al., 1974; Robertson et al., 2005).

The uptake of short chain fatty acids into cell membranes of colonocytes involve two mechanisms: 1) passive diffusion and 2) active transport. The active transport occurs mostly in the anionic dissociated form (more than 95%) and uses an anion exchanger (SCFA/HCO₃⁻) (Sellin, 1999). As for passive diffusion, the protonated form of short chain fatty acids is lipid soluble, thus, no transporter is required. Although only a small portion of the short chain fatty acids is present in this form (Harig et al., 1991).

Additionally, there are three proposed methods by which short chain fatty acids are transported across cell membranes of colonocytes: 1) through bicarbonate (HCO₃⁻) anion exchange, 2) transporters from the family of MCT1 (monocarboxylate transporter 1), and 3) SMCT1 (Sodium-coupled monocarboxylate transporter 1).

It is suggested that the apical membrane is the main site responsible for short chain fatty acids absorption and transport, whereas the basolateral membrane transports any unoxidized short

chain fatty acids from the colon (Macfarlane and Cummings, 1991; Kawamata et al., 2007; den Besten et al., 2013; Nakatani et al., 2018).

Physiological functions of short-chain fatty acids

By nature, the environment of the large intestine is anaerobic. One of the contributions of short chain fatty acids to intestinal health is the preservation of that anaerobic environment by maintaining an acidic pH (5.5-6.5 Macfarlane et al., 1992a; den Besten et al., 2013). The low pH does not favor proliferation of pathogenic bacteria and promotes the rise of the healthy bacteria improving intestinal health and nutrient uptake (Macfarlane and Macfarlane, 2012).

Acetate has been suggested to repress pathogenic bacteria, promote anti-inflammatory effects, reduce feeding motivation, and decrease fat accumulation in the liver (Fukuda et al., 2011; Yamashita et al., 2007). Furthermore, acetate stimulates production of satiety hormones GLP-1 (glucagon-like peptide-1), PYY (or peptide tyrosine tyrosine), improves insulin sensitivity and decreases TNF- α , a pro-inflammatory cytokine (Freeland and Wolever, 2010; Souza da Silva et al., 2013).

Butyrate has been demonstrated to reduce inflammatory diseases, for example bowel disease (Louis and Flint, 2009), improves growth and differentiation in colonic epithelial cells (Macfarlane and Macfarlane, 2012), and prevent colonic rectal cancer (Louis et al., 2014).

In addition, butyrate can obstruct histone deacetylase, which are proteins associated with DNA transcription. Butyrate keeps histones in the acetylated state, in other words “unwind” the DNA and transcription factors can access for gene activation. A histone in deacetylase state will condense DNA or “wind” DNA and transcription will not occur (Leonel and Alvarez-Leite, 2012). This can lead the way to other functions of butyrate such as control of diarrhea, increase of anti-

inflammatory activity, antioxidant effects, and tight junction integrity (Peng et al., 2009; Leonel and Alvarez-Leite, 2012; Jung et al., 2015).

Not only can propionate be incorporated into gluconeogenesis process, but it also has been observed to have anti-inflammatory activity along with butyrate by stimulating T cells that help control intestinal inflammation (Louis et al., 2014). Moreover, propionate can interact with acetate in reducing lipolysis and regulation of cholesterol and fatty acid metabolism, thus, preventing free fatty acids circulating in blood stream (Al-Lahham et al., 2010; Macfarlane and Macfarlane, 2012).

The examples mentioned above, are some of the benefits observed by the short-chain fatty acids and action of the intestinal microbiota. Not to mention that short-chain fatty acid production is increased with the presence of dietary fiber. Therein lies the importance of fiber inclusion in sow gestation diets, and during the pre-farrowing period.

Importance of transition feeding for gestating sows

Transition feeding during the pre-farrowing period and early lactation

Transition feeding is a relatively new concept that has caught the attention of the scientific community in recent years. Transition feeding is associated with the transition period of sows, which is defined as the last 10 days of gestation and the first 10 days of lactation (Theil, 2015; Theil et al., 2022).

Fetal growth occurs exponentially in the last third of pregnancy, but this growth is more evident in the last 10 to 25 days of gestation. Fetal weight gain increases, as well as nutrient retention (Noblet et al., 1985, Akdag et al., 2009; Cabrera et al., 2012, Tan et al., 2015).

In this short period of time, a series of biological and physiological events take place, and they can represent a critical input that dictates potential success during lactation for the sow and

the progeny, piglet performance during nursery, and perhaps growing-finishing stages (Tan et al., 2015).

A summary of the important biological events for the sow and the newborn piglet has been made below to highlight the importance of meeting the nutritional needs of the sow during this dynamic and important period, and how fiber can contribute through the production of short-chain fatty acids to support the metabolic changes during the transition period.

Impact of biological events in late gestation: for sows

For the sow, during late gestation there is an increased requirement for nutrients. At the time of parturition, the sow changes from an anabolic metabolism to a catabolic metabolism (Mosnier et al., 2010, Hansen et al., 2012). Moreover, the sows develop a progressive decrease in insulin sensitivity towards the end of gestation, and this may be accentuated in lactation, where glucose is needed in lactose synthesis for milk production (Père and Etienne, 2007). An increase in glucose concentration is observed during the last days of gestation while insulin does not increase at the same rate, which is negatively correlated with feed intake during lactation, as well as energy balance (Mosnier et al., 2010). Portal blood flow to the liver increases at the end of gestation to help maintain glucose concentrations to provide energy to the sow and support the growth of fetal tissues (Hansen et al., 2012). The liver also switches from a glucose utilization (i.e., glycolysis, glycogenesis) to a glucose production state (i.e., gluconeogenesis, glycogenolysis) during late gestation and it is closely related to the energetic status of the sow (König et al., 2012; Theil, 2015).

Uterine blood flow and the diameter of uterine artery increases as pregnancy progresses, allowing the transfer of substrates to the product of conceptus. However, this adaptation in uterine

blood flow is not able to keep pace with the exponential fetal growth during late gestation. This could explain the low energy reserves of the neonate at birth (Père and Etienne, 2000).

Mammary growth increases exponentially in the last third of pregnancy, with noticeable changes beginning at day 75 (Ji et al., 2006). There is an increased accumulation of mammary tissue and DNA concentration. In addition, there is an increased in weight of the mammary glands from day 45 to 112 of gestation (Ji et al., 2006), and a change in the composition of the mammary tissue going from a lipid content to a protein content in the last third of gestation (King et al., 1996). The mammary tissue is composed mainly of adipose tissue but the shift from lipid to protein is more observed during the last third of pregnancy.

Milk-producing cells are more abundant between days 90 and 105 of gestation, consisting with preparation for the lactation process (Kensinger et al., 1982, 1986a). Development of mammary glands is continuous during the first 10 days of lactation, where it could represent a change in nutrient requirements (Noblet et al., 1985, Kim et al., 1999a); however, there is little information in regard to how nutrition strategies can affect mammary development during the transition period.

It is unknown when exactly the colostrum starts being produced by the sow, but a study from Dodd et al, (1994) concluded that the first component of colostrum detected at day 80 of gestation is β -lactoglobulin. In the last week of gestation, α -lactalbumin is detected. Moreover, Hartmann et al. (1984b) found that lactose production begins 4 days prior to parturition. Colostrum intake is very important for the survival of the piglet. The main components of colostrum are proteins (mostly as immunoglobulins), fat, lactose, and amino acids (Theil et al., 2014a).

Fat and lactose are important in transferring energy to the newborn while immunoglobulins provide passive immunity. Altered nutrition during the last weeks of gestation could improve

colostrum production and perhaps yield of colostrum although this has not clearly been established.

For example, a study by Theil et al., (2014b) where sows were fed high fiber diets containing sugar beet pulp, potato pulp or pectin residue (32% to 40% DF) from mating until day 108 of gestation vs a conventional gestation diet (17% dietary fiber) increased colostrum intake of piglets (estimated by the D₂O technique and two blood samplings, 520 vs 504 g/piglet respectively) with pectin residues or sugar beet pulp treatments compared to potato pulp and the control treatment (393 vs 414 g/piglet respectively).

Furthermore, Loisel et al., (2013) found an increase in colostrum consumption of 60% in piglets weighing less than 900 g and an increase in lipids in colostrum of 29% from sows fed high fiber diets during gestation. The method for estimation of colostrum consumption by the piglet followed a proposed equation from Devillers et al. (2004) where they establish the time elapsed from the birth of the pig, to when the pig starts to suckle. Their hypothesis is that the ability to begin nursing relatively quickly, is one of the reasons of the increase colostrum intake for low-birth weight pigs.

Milk production is a determinant aspect that influences the daily nutrient requirement of the lactating sow. Mammary activity increases in the last days of gestation, and factors like genetics, body condition, feed composition, feeding level, sow metabolic status, parity, stage of lactation, and litter size can impact milk yield. (Theil et al., 2004).

A study from Tan et al. (2018) reported higher feed intakes for sows fed high fiber diets using sugar beet pulp and konjac flour compared to the control sows for two consecutive reproductive cycles. Quesnel et al. (2009), observed an increased consumption of lactation feed of 0.94 kg/ day for sows fed high fiber (11% crude fiber) during gestation compared to the control

sows. Similarly, Liu et al. (2021) reported a higher lactation intake for sows fed alfalfa meal during gestation relative to the control treatment (8.76 kg vs. 7.75 kg, respectively).

Stimulating a high feed intake during lactation is a priority to support the maintenance needs of the sow, support milk production and reduce as much as possible tissue mobilization (Einarsson and Rojkittikhun, 1993).

Impact of biological events in late gestation: for the neonatal pig

The number of weaned pigs per sow is a very important production trait. Piglet vitality relies on sow nutrition and her ability to support and grow her litter. If the dam is not fed correctly, or if the nutrient requirements are not met, it can lead to mobilization of body reserves to replace the nutrient deficiency. This mobilization might not be sufficient and may result in low survival of the piglet (Edwards and Baxter, 2015). The first survival barrier the fetus encounter is competition within the uterine space in gestation. And this will depend on the body composition of the sow, the number of parities, genetic and her previous maternal influence during the previous farrowing.

Stillborn piglets, and low vitality live-born piglets, are closely related to these prenatal traits and they can lead to a compromised postnatal survival rate (Foxcroft et al., 2006).

Farrowing length is another factor that could be related to stillborn pigs, and up to certain extent it might be improved by optimizing sow feeding in late gestation. Thus, late gestation feeding strategies have the potential to decrease the number of stillborn pigs and maximize piglet survival, and this is an area of research that needs much more scientific attention (Oliviero, et al., 2010).

In addition, neonatal mortality can also be explained due to a low energy supply, related to low glycogen reserves at birth (Tan et al., 2015). Fetuses can retain glycogen during the last third of pregnancy, and these glycogen depots serve to provide an immediate source of energy to the neonatal pig (Père, 2003). The newborn pig utilizes glycogen reserves in liver, muscle and colostrum as an energy source to cope with the change in extra-uterine environment. Newborn pigs lack brown adipose tissue; thus, glycogen reserves help them regulate their body temperature (Theil et al., 2011, Theil et al., 2014b).

As previously mentioned, colostrum intake is of vital importance for piglet survival, and colostrum must be consumed as soon as the pig is born (Quesnel et al., 2012). After 12 hours of onset of farrowing colostrum starts to decrease, which makes small pigs (i.e, weighing less than 900 g) the perfect candidate to die of starvation, from hypothermia or being crushed by the sow (Theil et al., 2014a).

Crushing by the sow could be masking hypothermia as the direct reason of piglet death. But it is not easily possible to determine the exact cause of death without monitoring rectal temperatures, and in farms is more practical to record “crushing by the sow” (Edwards and Baxter, 2015).

An altered maternal nutrition during late gestation could be an alternative to improve the energetic conditions of the sow in preparation for the onset of parturition, colostrum and milk production and to improve the vitality of the newborn pig, ultimately increasing the survival rate during lactation.

Scope of this Dissertation

Nutrition of the modern hyperprolific sow has gained attention in the recent years as a means to improve sow longevity and productivity. Gestation is a crucial phase for fetal growth and development being most noticeable during the last third of pregnancy and being more evident during the transition period. The transition period has been colloquially defined as the last 10 days of gestation and the first 10 days of lactation (Theil et al., 2022). During this period the sow undergoes simultaneous metabolic and physiological changes in preparation for parturition, colostrum and milk production and to the increased supply of nutrients to meet the demands from the fetus. Nutritional strategies such as supplementation of fiber have been studied during the recent years as a means to provide the sow an alternate energy source through the fermentation process that yields of short chain fatty acids (SCFA) which have been observed to improve gut health (Metzler-Zebeli et al., 2019; Jha et al., 2019). The energy derived from SCFA could improve the energetic status of the sow during late gestation (Peltoniemi et al., 2021). In addition, fiber supplementation during gestation and the pre-farrowing period decreased the constipation of sows (Liu et al., 2021), which might reduce farrowing duration and potentially reduce the number of stillborn pigs (Feyera et al., 2017). Thus, fiber supplementation may positively impact piglet survivability and ultimately improve sow and litter performance during lactation to have a successful subsequent reproductive cycle (Sun et al., 2015; Jiang et al., 2019; Liu et al., 2021).

The present dissertation will evaluate the impact of fermentable fiber inclusion in sow diets during gestation, and fiber supplementation during the pre-farrowing period on sow reproductive performance. The pre-farrowing period herein is defined as the period that sows are transferred from gestation to the farrowing facility until parturition. **Chapter I** presents a literature review of sow nutrition during gestation, the applications of fiber in gestating sows, the production of SCFA

through fermentation of fiber and the health benefits it provides, and the importance of the transition period in sows and what this represents for the fetus. **Chapter II** evaluates the fermentation characteristics of purified fermentable fiber sources using sow cecal content as the inoculum. **Chapter III** evaluates the inclusion of high fiber in gestation diets and during the pre-farrowing period of sows primarily using soybean hulls and wheat middlings to evaluate sow and litter performance. **Chapter IV** evaluates the impact of fiber solubility (soluble fiber derived from sugar beet pulp or insoluble fiber from soybean hulls) and amount of fiber supplemented during the pre-farrowing period on sow and litter performance, colostrum composition, sow constipation, glucose status of the newborn piglets, and estimated IgG concentrations in colostrum on site using a brix refractometer. **Chapter V** focused on the evaluation of fiber solubility (soluble vs. insoluble) and level of supplementation during late gestation and during the pre-farrowing period on sow and litter performance, serum chemistry of sows during late gestation, farrowing duration, and piglet vitality at birth.

Literature cited

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CHAPTER II:

**In vitro evaluation of purified fiber sources for the production of short-chain fatty acids
using sow cecal content as an inoculum**

ABSTRACT: This study evaluated short-chain fatty acid (SCFA) production from purified fiber sources when fermented in vitro using pig cecal contents as an inoculum. Fiber sources of interest were inulin from chicory root (native and long-chain inulin with 90 and 98% fiber, respectively), pectin from citrus peel (high methoxyl pectin), resistant starch (native starch), potato starch (commercial grade), and β -glucan (β -1,3; β -1,6 yeast-derived). Cellulose and cornstarch were used as indigestible and highly digestible carbohydrates, respectively. Triplicate samples of substrates (2 g) were subjected to enzymatic hydrolysis with pepsin and pancreatin for 6 h. Subsequently, hydrolyzed residues (200 mg) were incubated under anaerobic conditions at 39°C with 30 mL solution of cecal inoculum collected from 3 sows fed a standard commercial diet and buffered mineral solution. After 48 h of incubation, solutions from fermented samples were analyzed for pH, SCFA, and branched-chain fatty acids (BCFA) using gas-liquid chromatography. Enzymatic hydrolysis had no effect on digestion of β -glucan, but total SCFA concentration after fermentation was highest (26.13 mmol/g) followed by resistant starch (22.61 mmol/g) and potato starch (22.20 mmol/g) and was lowest for cellulose (13.91 mmol/g). In contrast, native inulin was highly digested during enzymatic hydrolysis, resulting in the lowest substrate remaining for fermentation (11.84%) and the highest pH (5.98). Enzymatic hydrolysis and fermentation of resistant starch increased ($P < 0.001$) concentrations of acetate (600 μ g/g), whereas potato starch and β -glucan yielded more butyrate (600 and 540 μ g/g respectively), and β -glucan resulted in greater ($P < 0.001$) propionate concentrations (690 μ g/g). Pectin resulted in the highest fermentation (82.38% substrate disappearance) and the lowest pH (4.03) compared to the other fiber sources ($P < 0.001$) and yielded the lowest BCFA concentration (50 μ g/g, $P < 0.001$). Results suggest that fermentation of resistant starch, potato starch, and β -glucan produced higher SCFA concentrations, while pectin resulted in a decreased pH of the fermentation solution.

Key words: fiber, fermentation, cecal inoculum, in vitro model, swine

Introduction

Dietary fiber is of popular interest in both animal and human nutrition (Williams et al., 2019). Dietary fiber is fermented by the microbes residing in the large intestine, specifically in the cecum and colon, resulting in the production of metabolites of which the short-chain fatty acids (SCFA) acetate, propionate and butyrate are the main end-products (Williams et al., 2001; den Besten et al., 2013). These SCFA have shown to improve gut health by stimulating the growth of beneficial bacteria over pathogenic bacteria, lessening the negative impact of pathogenic bacteria on intestinal barrier function (Macfarlane and Gibson, 1997; Davidson and McDonald, 1998). In addition, carbohydrate fermentation which stimulates production of SCFA contributes to reduce protein fermentation thereby reducing production of toxic metabolites such as BCFA, ammonia, phenols, indoles and that are harmful for the gut environment (Macfarlane et al., 1992a; Windey et al., 2012; Jha and Berrocso, 2016). Furthermore, SCFA are an alternate energy source when glucose from the gut decreases by stimulating satiety hormones such as GLP-1 via entero-endocrine cells present in the large intestine. Peptide hormones such as GLP-1 may have a direct effect in decreasing transit time of digesta, allowing absorption of nutrients and, reducing the appetite feeling (Souza da Silva et al., 2013), resulting in delayed insulin release storing glucose to be later used as energy.

Butyrate is the major fuel for colonocyte cells (epithelial cells lining the colon). Acetate can be used as a substrate for lipid metabolism (synthesis of cholesterol, ketone bodies, long-chain fatty acids) and can be used as a source of energy for the brain, muscle, and heart (den Besten et al., 2013b; Williams et al., 2017). Propionate is metabolized in liver and can be used for

gluconeogenesis (Williams et al., 2001; Zijlstra et al., 2012). Controlling the substrate that reaches the large intestine, is a way to modulate the actions of the resident microbial population (Bindelle et al., 2008), because the preferred substrate for bacteria in the large intestine is of carbohydrate origin. Ensuring a continuous supply of saccharolytic substrate will enhance the production of SCFA, which can improve the energetic balance and intestinal health of the host (Samuel et al., 2008).

In vitro fermentation techniques are practical and rapid tools that allow evaluation of by-products (in isolation), often rich in fiber material, at the same time. (Boisen and Fernández, 1997; Williams et al., 2005). In vitro fermentation can offer a fair screening of the possible products of fermentation a feedstuff might stimulate in an animal by simulating in vivo scenarios, by using inoculum either from feces or from cecum material as they contain live microbes. In vitro techniques are relatively low cost, and the results offer accuracy and precision (Jha and Tiwari, 2016; Zeng et al., 2019). Thus, in vitro techniques are widely used to help determine fiber fermentation characteristics.

Therefore, the objective of this study was to evaluate short-chain fatty acid (SCFA) production from purified fiber sources when fermented in vitro using pig cecal contents as an inoculum.

Materials and methods

Eight sources of isolated fermentable fiber were used for this analysis: β -glucan (MacroGard® β 1-3, β 1-6, yeast derived), was obtained from Trouw Nutrition (IL, USA). Pectin (Unipectine™ high methoxyl pectin from apple pomace), inulin (Oligo-Fiber® from chickory

root: native and long-chain inulin with 90 and 98% fiber, respectively), and resistant starch (potato starch corresponding to RS type 2, and RS type 3 C*Gel 03420 denominated as “resistant starch” for the purpose of this study), were obtained from Cargill (Minneapolis, MN, USA). Cellulose (Solka-floc®) and cornstarch were obtained from Sigma-Aldrich (St. Louis, MN, USA).

Enzymatic hydrolysis

Fiber sources were subjected to an enzymatic hydrolysis treatment using pepsin and pancreatin, and this process lasted for 6 hours. These procedures followed protocols from Boisen and Fernandez (1997) and Jha et.al (2011), with the exception that for the present study, there was no dilution factor practiced to the source of inoculum, and there was no application of any agent to prevent bacterial growth during hydrolysis.

Fiber sources (2 g) were weighed in triplicate into 50 mL round bottom tubes where a phosphate buffer solution (100 ml, 0.1 M, pH 6) and HCL (40 ml, 0.2 M) solution was added. Once the pH was adjusted to 2 using 1 M HCL or 1 M NaOH, pepsin (4 mL, 20 g/l porcine pepsin, Sigma P-0609) was incorporated into the tubes and they were placed in a water bath at 39 °C for 2 hours and, gently stirred manually. Two blank tubes (with no fiber source) were included to verify accuracy of the pre-digestion process.

Subsequently, 40 mL of phosphate buffer (0.2 M, pH 6.8) and 20 mL of 0.6 M NaOH were poured into the solution to adjust the pH to 6.8 using 1 M HCL or 1 M NaOH. Next, pancreatin (2 mL, 100g /l pancreatin, Sigma P-1750) was added to the tubes and hydrolysis continued in a water bath at 39 °C for 4 hours.

After hydrolysis, the tubes were centrifuged at $3,000 \times g$ for 5 minutes to obtain the pellet. The pellets were stored in a cooler at a temperature of 4 °C to prevent enzyme activity until

subsequent in vitro fermentation. A subsample of the pellets was used to determine substrate disappearance by drying the pellets at 60 °C for 48 hours. After 48 hours were completed, the in vitro substrate disappearance during the pepsin and pancreatin hydrolysis was calculated using the following formula:

$$\text{IVSDh\%} = \frac{\text{Dry weight of the substrate before hydrolysis (g)} - (\text{dry weight of residue (g)} - \text{blank})}{\text{Dry weight of the substrate before hydrolysis (g)}} \times 100$$

Where: IVSDh% is the percentage of the hydrolyzed material during enzymatic hydrolysis

In vitro fermentation

Prior to adding the inoculum, tubes with the residue following in vitro enzymatic digestion were placed at room temperature. A 30 mL buffer solution (NaHCO₃ and (NH₄) HCO₃) containing macro and micro minerals (Na₂HPO₄, KH₂PO₄, MgSO₄ · 7 H₂O; CaCl₂ · 2 H₂O; MnCl₂ · 4 H₂O; CoCl₂ · 6 H₂O; FeCl₃ · 6 H₂O) adapted from Menke and Steingass, (1988) was prepared. Tubes containing the residue (200 mg) were incubated at 39 °C with the buffer solution and cecal contents as inoculum. Three blank tubes (with inoculum only) were used to verify the accuracy of the fermentation process. Cecal contents were obtained by opening the abdominal cavity of 3 cull sows obtained from Bass Farms (Spring Hope, NC, USA) fed a standard commercial diet. The cecum was clamped off at both ends and then collected in its entirety. Each cecum was placed into pre-warmed thermos at a temperature of 39 °C.

Contents of the cecum (1 L) was placed in a pre-warmed buffer solution (containing the same macro and micro minerals, placed into a 1L glass Erlenmeyer flask) achieving a 1:1 ratio between cecal contents and buffer solution, and flushed with CO₂ gas to maintain the anaerobic

environment. Then, 30 mL of mixed cecal contents with buffer solution were added to each bottle containing the residue. Bottles were purged with CO₂ during the addition of the inoculum, capped with a rubber stopper and placed in 39 °C water bath for incubation. One subset of tubes was used to measure pH at the beginning of the incubation, these tubes did not continue under the 48-hour fermentation procedure and were labeled as “after hydrolysis” to allow comparison between initial fermentation and final fermentation pH. Fermentation was stopped at 48 hours of incubation by placing the bottles in the cooler at a temperature of 4 °C. The experimental scheme was as follows: 8 fiber sources × 3 replicates + 3 blanks (inoculum only). At the end of fermentation, pH was measured, and tubes were centrifuged at 5,000 × g for 5 minutes to collect a clean supernatant.

Then, 1 mL of clean supernatant was added to a 1.5 mL centrifuge tube with 200 µL of metaphosphoric acid and 2-ethylbutyric acid as internal standard for SCFA analysis to precipitate protein. Afterwards tubes containing the samples were centrifuged at 21,000 × g for 10 minutes to collect a clear supernatant and were then transferred into 1.5 mL sterile glass vials for subsequent analysis of SCFA and BCFA using gas liquid chromatography (Varian CP 3380). The remaining tubes (containing substrate and inoculum) used for the *in vitro* fermentation were used to calculate the material that was fermented during the incubation period by drying the contents of the tubes at 60 °C for 48 hours. After 48 hours were completed, the *in vitro* substrate disappearance during the fermentation process was calculated by subtracting the (dry weight of hydrolysis residue (g) – fermentation residue (g) – blank) divided by dry weight of hydrolysis residue (g)

Statistical Analysis

Data were analyzed using the Glimmix procedure of SAS (SAS Inst. Inc., Cary, NC). The model included the effect of fiber source and period (after hydrolysis, and after fermentation).

LSMeans were reported and compared using Tukey's test, and statistical significance was defined as $P \leq 0.05$ and tendencies as $0.05 < P \leq 0.10$.

Results and discussion

In vitro fermentation techniques have been used as a convenient tool to help characterize the fermentation profile of fiber (Huang et al., 2018) by simulating conditions of the intestinal tract of an animal. This study evaluated the production of SCFA from purified fiber sources when fermented in vitro using sow cecum contents as an inoculum. The reason for using cecal contents as opposed to fecal material as inoculum, was to obtain results based on a more true-close scenario given that the cecum is the main site of fermentation in monogastrics (Knudsen et al., 1993; Wang et al., 2004) Cornstarch and cellulose were included in the experimental design to verify if the assay worked as expected with cornstarch being a rapidly fermentable source and cellulose being most resistant to fermentation.

Each fiber source had different rates of substrate disappearance during the enzymatic hydrolysis process which resulted in different substrate availability for subsequent fermentation, which impacted metabolite production at the end of fermentation. This was expected as we implemented mostly soluble, fermentable fibers and as reported by Bindelle et al. (2007), the enzymatic hydrolysis process results in the disappearance of a portion of soluble fiber fractions during in vitro analysis. Such observations were found for inulin long-chain (98% purity) pectin, potato starch, and resistant starch (Table 1). These fibers are characterized for being slow fermenters, therefore, a rapid degradation in the small intestine is unlikely to occur (Ellegård et al.,

1997; Macfarlane et al., 2006; van de Wiele et al., 2007; Bindels et al., 2015; Williams et al., 2017; Uerlings et al., 2019).

However, the high percentage of disappearance of inulin native with 90% of purity obtained with the enzymatic hydrolysis compared to the other sources was still surprising (Table 1). It is worth noting that inulin is often classified as a fructooligosaccharide and its fermentation can begin even before reaching the large intestine as observed by Stewart et al., (2008). We can speculate that inulin native in this experiment could have a profile of short-chain fructans which would be easy to ferment and may have been the cause for its rapid degradation during the enzymatic hydrolysis (Patterson et al., 2010; Williams et al., 2019).

On the other hand, β -glucan did not undergo any degradation during the enzymatic hydrolysis. This is not uncommon as β -glucans generally have high water binding capacity, which increases gel formation which allowing it to reach the large intestine intact (Knudsen et al., 1993; Dikeman and Fahey, 2007; Daou and Zhang, 2012). Pectin had greater percent of degradation compared with β -glucan despite sharing the characteristic of being viscous soluble fibers (Slavin and Greene, 2007). However, pectins do not belong to the glucose polymers, rather, they are polymers of galacturonic acid (Drochner et al., 2004; Rubio et al., 2015). Similarly, resistant starches were minimally altered by the enzymatic hydrolysis process probably due to the amylose polymers that characterize this type of fiber (Nielsen et al., 2014; Metzler-Zebeli et al., 2019).

Fermentation characteristics were different for all fiber sources (Table 2). In part, this is explained by the substrate disappearance from the enzymatic hydrolysis (i.e the substrate available for fermentation), but also is attributed to the different structures (sugar and linkages) of each fiber source (Jonathan et al., 2012) and the ability of the microbiota to degrade different fiber types. Although we did not measure the microbiota population, the importance of bacterial fermentation

to produce SCFA has been recognized which are stimulated by the presence of fiber (Hernot et al., 2009; Vetvicka and Oliviera, 2014, Louis et al., 2014; Carlson et al., 2017).

Concentrations of acetate and butyrate were elevated by resistant starch and potato starch. Previous investigations by He et al. (2017) reported increased concentrations of butyrate and acetate and low production of BCFA in vitro when using corn resistant starch. Similarly, Giuberti et al. (2013) evaluated different sources of resistant starch and found that in general all sources increased the concentrations of butyrate after in vitro fermentation. Likewise, β -glucan increased concentrations of butyrate, and propionate in the present study which is in line with findings from Knudsen et al. (1993) in cannulated pigs fed with different sources of fiber rich in β -glucan. Metzler-Zebeli et al. (2011) observed high concentrations of butyrate and a tendency to increase propionate in digesta of nursery pigs fed with 8.9% β -glucan. In human nutrition, β -glucan has become a subject of interest because of its cholesterol-lowering effects (Queenan et al., 2007; Daou and Zhang, 2012; Dong et al., 2020) and protection against bowel inflammatory disease (Karimi et al., 2020).

Total concentrations of SCFA were highest for β -glucan, followed by resistant starch and potato starch (Table 3). Our results are consistent with others (Regmi et al., 2011; Jha et al., 2011; Jha and Leterme 2012; Jonathan et al., 2012; Bang et al., 2018) where total SCFA concentration was increased through fiber types that are characterized for being soluble and fermentable. Collectively, these findings suggest that resistant starch, potato starch and β -glucan stimulate butyrate, propionate and acetate-producing bacteria which can result in enhanced production of these SFCA, potentially contributing to gut health (Haenen et al., 2013).

The individual and total production of SCFA for both sources of inulin were lower in comparison with the other fibers (Table 2, Table 3, respectively). At least for inulin native this was

not surprising as it had limited substrate remaining after enzymatic hydrolysis to ferment. However, our results are in agreement with previous information (Uerlings et al., 2019) where inulin produced the lowest amount of SCFA during the first 24 hours of fermentation compared with pectin-based ingredients. In addition, it has been observed that inulin was among the lowest acetate and propionate producers (Hernot et al., 2009) when fermentation characteristics were determined using the in vitro fermentation gas production technique. In our study, both sources of inulin were on the lower side of acetate and butyrate production, but inulin long-chain increased propionate concentrations along with β -glucan. In contrast, Jonathan et al. (2012) reported increased concentrations of butyric acid by inulin, thereby providing energy for colonocytes (Wang and Gibson, 1993).

Further, increased total SCFA production with inulin (Nyman, 2002; Guarner 2005) and decreased p-cresol, one of the products of protein fermentation have been reported (Macfarlane et al., 1992b; Jha and Berrococo, 2016). It is worth noting that inulin may have a significant impact on the integrity of the small intestine depending on the chain length (Loh et al., 2006; Patterson et al., 2010) as there is some degradation at the jejunum (Loh et al., 2006) which is similar to what we observed in our in vitro analysis.

Pectin also resulted in a low concentration of total SCFA at the end of fermentation (Table 3). The structure of pectin is very complex and industrial pectin sources are subject to different extraction processes (Beukema et al., 2020) which may affect the degree of esterification (Drochner et al., 2004). This in turn can affect the ability to stimulate pectin-degrading microbiota (Uerlings et al., 2019), leading to a low SCFA production. However, pectin was the primary source able to reduce considerably the pH as opposed to inulin native and cellulose (Table 4), this outcome was not anticipated, and we cannot explain the exact mechanism of the low pH with a low total

SCFA production. The environment of the large intestine is acidic by nature, and one of the functions of fiber is to maintain that acidic environment helping to decrease the risk of protein fermentation in the hindgut and stimulate proliferation of beneficial bacteria over the pathogenic microbiota (Knudsen, 2001; den Besten et al., 2013; Zhou et al., 2018; Jha et al., 2019). On this account, pH is an important parameter to analyze when conducting in vitro analysis. In addition, pectin resulted in the lowest concentration of BCFA (Table 3), and the highest percent of fermented material compared to the rest of fiber sources (Table 1). BCFA are a product of protein fermentation which leads to the rise of toxic metabolites such as ammonia, indoles, phenols among others (Windey et al., 2012; Jha and Berrocoso, 2016). Ammonia in particular is excreted in the urine causing an increase in NH_3 into the environment (Nahm, 2003; Philippe et al., 2015). Hence, maintaining a low concentration of BCFA contributes to decrease the environmental pollution.

Lastly, cornstarch and cellulose were used as our reference sources considering cornstarch to be a soluble, and rapid fermentable source (Weaver et al., 1992), whereas cellulose was expected to be an insoluble source and not rapid fermentable (Williams et al., 2019). Cornstarch was degraded similarly to the other fermentable fiber sources, and the production of total and individual SCFA was comparable with β -glucan, resistant starch, and potato starch, which was expected based on previous reports (Fernandes et al., 2000; Rink et al., 2011). The enzymatic hydrolysis caused minimal degradation of cellulose, and at the end of fermentation, little of the cellulose disappeared. Furthermore, cellulose did not impact pH values and produced the lowest concentrations of total SCFA and individual metabolites. This is in agreement with the findings of Bai et al. (2021), who compared cellulose with β -glucan, glucomannan, and arabinoxylan using pig fecal microbiota in vitro. In that study, cellulose produced the lowest SCFA concentrations and highest pH during fermentation.

In conclusion, it is difficult to standardize fiber characteristics of fermentation because all fibers differ in their physico-chemical structures (Wang et al., 2004; Jha, 2010; Jha and Zijlstra 2019) which can produce different amounts of SCFA as observed in this study. Nevertheless, resistant starches, potato starches and β -glucan fibers increased concentrations of acetate, butyrate and propionate as well as total SCFA. Pectin decreased the pH during fermentation compared to inulin native and cellulose, which resulted in the highest pH. Production of BCFA from purified fibers was also reduced especially by pectin.

The use of fermentable fibers in swine diets is increasing as a functional nutrition strategy (Pi et al., 2021). Resistant starches, β -glucans, and pectins should be considered for further analysis in combination with in vitro and in vivo scenarios to clarify their net contributions on gut health and how they affect and support animal performance.

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Table 1

Substrate utilization during enzymatic hydrolysis and fermentation

Fiber source	SRF ¹ (%)	Fermented ² (%)
Cellulose	97.05 ^b	10.75 ^e
Cornstarch	86.60 ^b	41.33 ^b
Inulin Native	11.84 ^c	95.44 ^a
Inulin XL	83.00 ^b	45.36 ^b
Pectin	80.70 ^b	82.38 ^a
Potato starch	88.21 ^b	40.15 ^d
Resistant starch	86.49 ^b	41.59 ^b
β-glucan	100 ^a	58.45 ^b
SE	4.06	3.31

¹ Substrate remaining for fermentation after enzymatic hydrolysis.² Substrate fermented after 48 hours of incubation.

Treatment effect P < 0.001.

Period effect P < 0.001.

Treatment (period) effect P < 0.0001.

^{abcd} Means with different superscripts are significantly different (P < 0.05).

Table 2

Production of individual SCFA by fiber source after fermentation (48 hrs)

Fiber source	$\mu\text{g/g}$ of carbohydrate fermented			
	Acetate	Butyrate	Propionate	BCFA ¹
Cellulose	380 ^c	150 ^{cd}	330 ^d	70 ^{ab}
Cornstarch	500 ^b	560 ^a	310 ^d	60 ^c
Inulin native	400 ^c	220 ^c	440 ^c	80 ^a
Inulin long-chain	400 ^c	250 ^c	570 ^b	70 ^{ab}
Pectin	350 ^c	410 ^b	220 ^{ef}	50 ^c
Potato starch	490 ^b	600 ^a	280 ^{de}	60 ^c
Resistant starch	600 ^a	490 ^{ab}	300 ^d	70 ^{ab}
β -glucan	410 ^c	540 ^a	690 ^a	80 ^a
SE	0.01	0.02	0.01	0.002
P value	<0.0001	<0.0001	<0.0001	<0.0001

¹ Branched chain fatty acids (sum of iso-butyrate and iso-valerate).^{abcdef} Means with different superscripts within the columns are significantly different ($P < 0.05$).

Table 3

Production of total SCFA by fiber source after fermentation

Fiber source	mmol/g of CHO fermented	
	After hydrolysis (0hrs)	After fermentation (48hrs)
Cellulose	6.09	13.91 ^d
Cornstarch	6.33	22.82 ^{ab}
Inulin Native	6.49	17.50 ^{dc}
Inulin XL	6.10	19.77 ^b
Pectin	6.17	15.75 ^d
Potato starch	6.49	22.2 ^b
Resistant starch	6.30	22.61 ^{ab}
β-glucan	6.32	26.13 ^a
SE	0.08	0.76
P value	>0.05	<0.0001

^{abcd} Means with different superscripts within the columns are significantly different (P< 0.05).

Table 4

Evaluation of pH after hydrolysis and after fermentation

Fiber source	After hydrolysis (0hrs)	After fermentation (48hrs)
Cellulose	6.94 ^b	6.33 ^b
Cornstarch	6.76 ^b	4.86 ^e
Inulin native	6.76 ^b	5.98 ^d
Inulin long-chain	6.81 ^b	4.94 ^e
Pectin	6.57 ^{bc}	4.03 ^f
Potato starch	6.78 ^b	4.76 ^e
Resistant starch	6.90 ^b	4.77 ^e
β-glucan	6.65 ^{bc}	4.66 ^e
SE	0.07	0.06

Treatment effect P< 0.0001.

Period effect P< 0.0001.

Treatment * period effect P< 0.0001.

Means with different superscripts within the columns are significantly different (P< 0.05).

CHAPTER III:

Effects of increasing total dietary fiber intake during gestation and the pre-farrowing period on sow and litter performance in lactation

ABSTRACT: This study evaluated the effects of increasing total dietary fiber (TDF) during gestation and the pre-farrowing period to improve sow and litter performance. Sows (n=117) were assigned to a 2×2 factorial arrangement consisting of the following factors: 1) gestation diet with low fiber (9% TDF) or high fiber (18% TDF) using primarily wheat middlings and soyhulls as the fiber sources; and 2) pre-farrowing pelleted supplement (no top-dress or top-dress). The top-dress was formulated to contain 43% TDF, using soyhulls and wheat middlings as the fiber sources and was provided at 0.91 kg daily on top of the normal feed allotment from the time sows were transferred into the farrowing house (112 ± 1 d of gestation) until parturition. Fiber composition of the gestation diet and additional fiber from the top-dress fed pre-farrowing did not impact sow BW at placement ($P= 0.84$) or at weaning ($P= 0.86$). The number of pigs born alive tended ($P= 0.10$) to be greater for sows fed the top-dress (13.03 and 12.88, within low and high fiber diets, respectively) compared to sows not receiving top-dress (11.89 and 11.42). Number of stillborn pigs (1.58, 1.26, 1.30, and 1.64 for the high fiber without and with top-dress, and low fiber without and with top-dress, respectively, $P= 0.75$) and number of weaned pigs (9.96, 10.30, 9.56, and 9.72) were not impacted by dietary treatments ($P= 0.64$). However, number of small weaned pigs tended to be lower ($P= 0.05$) when top-dress was provided to sows fed low fiber diets compared to top-dress supplementation to high fiber diets (0.33 vs 1.30; interaction, $P= 0.02$). Results suggest that high fiber supplementation during gestation and additional fiber fed immediately pre-farrowing did not influence sow BW, whereas top-dress tended to increase the number of pigs born alive and decreased the number of non-viable pigs at weaning when added to low fiber diets.

Key words: pre-farrowing period, fiber, sows, stillborn, born alive

Introduction

The use of dietary fiber in swine has been a subject of controversy for many years. Initially, it was seen as an antinutritional factor because of the tendencies to decrease energy and nutrient digestibility (Lindberg, 2014; Agyekum and Nyachoti, 2017). However, the potential benefits of fiber in terms of animal welfare and animal health have been recognized (Davidson and McDonald, 1998; Li and Komarek, 2017).

In swine production, it is a common practice among producers to limit feed intake of the sow during gestation (Brouns et al., 1995; Che et al., 2011; Jarret and Ashworth, 2018). It has been observed that when sows have a feed intake above their requirement especially during late gestation, the sow is likely to have locomotion problems, negative effects on lactation feed intake, trouble to farrow probably because the piglets are too big for the birth canal, and increased farrowing length which in turn, may increase the risk of stillborn pigs, and even sudden death of the sow (Coffey et al., 1994; Weldon et al., 1994; Guillemet et al, 2007; Quesnel et al., 2009).

A common gestation diet with little to no fiber inclusion can only satisfy between 40 to 60% of sow's voluntary intake (Meunier-Salaün et al., 2001). If a sow is not feeling satisfied after a meal, signs of stereotypic behavior will appear such as bar biting, false mastication, floor licking (McGlone et al., 2004), which adds stress to the sow (Reese, 1997; Leeuw et al., 2008).

Fiber is a complex carbohydrate that is typically not digested in the small intestine due to the lack of endogenous enzymes, but it can be degraded by the bacteria residing in the large intestine as a good substrate for fermentation. Through fermentation, SCFA are produced which provide energy and have been demonstrated to cause positive effects on intestinal health (Slavin

and Green, 2007; Serena et al., 2009; Jha and Berrocso, 2015; D'Eath et al., 2018). Inclusion of different fiber ingredients (or a bulky diet) during gestation in sows are linked to heavier piglet weights at birth, increased feed intake of sows during lactation, and a tendency to increase weaning piglet weights (Matte et al., 1994; Reese et al., 2008; Guillemet et al., 2007).

The pre-farrowing period is extremely important for the sow and fetal growth. During this period, the sow is subject to many physiological and metabolic changes such as lactogenesis, increased fetus growth, onset of farrowing, and milk production; all are dynamic and occur simultaneously (Quesnel et al., 2009; Feyera and Theil, 2017; Pedersen et al., 2020). Fiber has been proposed as a nutritional strategy to help the sow cope with metabolic and physiological changes.

Therefore, the objective of this study was to evaluate the effectiveness of increasing dietary fiber intake during gestation and during the pre-farrowing period to improve sow and litter performance in lactation.

Materials and Methods

This experiment was conducted on a 2,600-sow commercial farm owned and operated by the Hanor Family of Companies (Mooreland, Oklahoma). Protocols for animal use and care were under the supervision of licensed veterinarians.

A total of 117 sows (Camborough, PIC, Hendersonville, TN) were assigned to one of the two treatments in gestation: 1) low fiber diet (Lofi) containing 9% of total dietary fiber (TDF), and 2) high fiber (Hifi) containing 18% of TDF. Wheat midds and soy hulls were used as the main fiber source and soybean oil was used to maintain caloric density of the diets (Table 1). Diets were formulated to meet or exceed the NRC (2012) nutrient recommendations and were manufactured

at a feed mill owned by Hanor company. Diets were color coded for visual confirmation and sows started to consume the experimental diets after they were inseminated throughout gestation.

At the time sows were moved from gestation into the farrowing house (at 112 ± 1 d of gestation) the same sows were assigned to either a control (no top-dress supplement) or a top-dress supplement feed (0.91 kg) during the pre-farrowing period within each of the original gestation treatments, resulting in a 2×2 factorial arrangement.

The top-dress pelleted supplement was formulated to achieve a targeted daily allowance of 600 g/d of TDF using soy hulls and wheat middlings as the fiber sources (Table 2). The top-dress was manufactured by the feed mill owned and operated by Hanor company (Table 3).

Measurements

Sows were weighed individually when they entered the farrowing house at 112 ± 1 d of gestation (in groups of 25 to 30 sows per group) and at the end of lactation. Between placement and farrowing, the sows received the top-dress pelleted supplement (5 ± 1 d before expected farrowing date) using an automated feed system (Howema, Big Dutchman, Vechta Germany) on top of the normal feed allotment. After farrowing, sows received a standard lactation diet and were allowed to eat ad libitum and had free access to water via water nipples.

After farrowing, the number of pigs born alive, mummies, and stillborn pigs were recorded. Cross-fostering was done after at least the first 24 hours after farrowing, to allow colostrum consumption by piglets from their own dam. Handling and processing of the litters was performed according to standard farm practices under supervision of licensed veterinarians. Piglets did not receive milk replacer or creep feed during the experiment. Mortality of pigs was recorded during

lactation. Pigs were weaned at (21 ± 1 d). Number of pigs weaned, and the number of non-viable pigs (pigs weighing less than 3.6 kg) was also recorded via electronic data collection.

Sows that died, were euthanized, culled, returned to estrus, aborted, and nurse sows were recorded. These sows (n= 7) were excluded from the statistical analysis and corresponds to Hifi + no top-dress (n= 1), Hifi + top-dress (n= 3), Lofi + no top-dress (n= 2) and Lofi + top-dress (n= 1).

Statistical analysis

Sow weight was analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). The model included fixed effects of fiber level during gestation, top-dress during the pre-farrowing period, and their interactions. Group of sows (4 groups) entering the farrowing house were used as a random effect. The number of pigs born, stillborn pigs, mummies, number of weaned pigs, and number of non-viable pigs at weaning were analyzed with using Proc GLIMMIX of SAS (9.4 SAS Inst. Inc., Cary, NC). Least square means were reported and compared with the Tukey-Kramer multiple comparison test. Differences of $P \leq 0.05$ were considered significant. Tendencies were considered when $0.05 < P \leq 0.10$.

Results

Sow body weight at placement was not affected by fiber level in gestation diets or the top-dress fiber supplement that was fed during the pre-farrowing period after the sows had been placed ($P= 0.84$). Similarly sow body weight at weaning ($P= 0.86$) and lactation length ($P= 0.72$) were not different between dietary treatments at weaning.

The number of pigs born alive tended to be greater ($P= 0.10$) for the high fiber during gestation with top-dress supplement and low fiber with top-dress supplement treatment compared to the treatments where the top-dress supplement was not offered. The number of stillborn pigs ($P= 0.75$), and pigs weaned per litter ($P= 0.64$) were not significantly different. However, the number of non-viable pigs at weaning (pigs weighing less than 3.6 kg) tended to be lower ($P= 0.05$) when sows received a low fiber diet in gestation and the top-dress supplement compared to the sows fed the high fiber diet with the top-dress supplement treatment (interaction, $P = 0.02$).

Discussion

Sows are restrictedly fed during gestation to keep them within optimal body weight and body condition score to avoid excess weight gains that will represent a problem at farrowing. Supplementation of fiber in gestation diets is a practical strategy to provide the sow with an adequate energy requirement without increasing energy density and without causing a negative impact on body condition (Brooks, 2008; Oelke et al., 2018).

The current study was conducted to supplement fiber during gestation and during the pre-farrowing period with the purpose of influencing the number of total pigs born, birth weights and improve sow performance. While our results did not improve litter size and litter weights, we do support that the weight of the sow and piglet is not negatively impacted by fiber at least up to 18% used during the gestation period, or 43% during the pre-farrowing period and it may be possible to increase the number of piglets born alive. Our results agree with outcomes by Huang et al. (2020), which revealed that a 5% of resistant starch or 5% of fermented soybean fiber did not impact litter size, or sow body weight during gestation. Further, Darroch et al. (2008) reported that inclusion of 20% of soybean hulls or 30% of psyllium included in gestation diets were not effective

to increase litter size at birth, and sow weight remained unaffected as well, which is similar to what we found, and supported by the investigation of Guillemet et al. (2007) where no difference in sow body weight, litter size and performance was detected with high fiber diets were supplemented to sows during gestation and until farrowing.

Even though the number of weaned pigs was not influenced by fiber supplementation during gestation and during the pre-farrowing period in our study, it did reveal a trend of reducing the number of non-viable pigs at weaning (being the pigs weighing less than 3.5 kg) for the sows receiving the low fiber treatment during gestation and the top-dress pelleted supplement during the pre-farrowing period. This intriguingly result is comparable to a study by Che et al. (2011) where dietary fiber was provided to gestating sows at 10.8%, 15.8%, or 20.8% (low, medium, and high fiber, respectively) and reported higher litter weights at day 22 of lactation for sows under the low and medium level of fiber treatment for the first reproductive cycle. Although in that particular study, fiber was offered from day 1 to 90 of gestation, after day 90 and until farrowing sows consumed a standard gestation diet. And for the high fiber treatment, piglet survival was greater and litter weights were higher at day 22 of lactation on the second reproductive cycle compared to the low and medium fiber treatments.

Further, in a regional experiment by Veum et al. (2009), who evaluated the use of wheat straw during gestation in sow diets for three consecutive reproductive cycles, found that sows receiving wheat straw increased the number of pigs born alive by 0.51 pigs per litter and weaning weights increased by 3.6 kg compared to the control treatment. Perhaps the differences detected may be attributed to the continuity of the dietary treatments for more than one reproductive cycle, allowing the sow to adjust accordingly to their physiological state (i.e., gestation, lactation). Another point of consideration is the additional 13.36% of ground wheat straw to the diet, having

a 0.30 kg daily consumption for that treatment, unlike our study as the sows receiving high fiber during gestation consumed the same amount of feed (2.5 kg) as the control sows during the entire gestation period, which means the sows fed fiber consumed less energy. In similar fashion, Matte et al. (1994) evaluated gestation diets with different fibrous ingredients (i.e., oat hulls, wheat bran, corn cobs) for two consecutive reproductive cycles and determined that weaning weights of litters from sows receiving high fiber diets were heavier at the second reproductive cycle. This might suggest that consecutive production cycles of sows is worthy of consideration to verify if these positive outcomes for sow and litter performance provide consistency across studies.

Late gestating sows experience catabolic events as they are preparing for the parturition process, and the production of colostrum and milk (Battaglia and Meschia, 1978; Noblet et al., 1985; Einarson and Rojkittikhun, 1993). It has been observed that fiber through the fermentation products (SCFA, which are the main group) can contribute up to 15 % of additional energy for maintenance requirements for growing pigs, and approximately 30 % for sows (Jha et al., 2019). In addition, bulky diets (rich in fibrous material) are linked to a reduction in sow constipation, as it is associated to enhance peristaltic movements in the intestine (Peltoniemi et al., 2016). The constipation relieving properties may help the sow to reduce farrowing duration by having a birth canal free of obstruction, reducing the risk of infections by exposing the birth canal to an open environment (Wenk et al., 2001; Renteria-Flores et al., 2008a).

Hence, our purpose of fiber supplementation during the pre-farrowing period was to increase the energy reserve for sows, alleviate constipation with the aim of reducing the number of stillborn pigs, which is contrary to our findings. In their study, Feyera et al. (2017) indicated a reduction in stillborn pigs from 8.8 to 6.6% with a fiber rich supplement offered during the last two weeks of gestation. Moreover, a reduced piglet vitality at birth was found when sows received

the fiber rich supplement during the pre-farrowing period compared to the control treatment. In the same line, an investigation conducted by Deng et al. (2021) supplemented either 15% or 30% of wheat aleurone in sow gestation diets and reported a reduction in rate of stillborn pigs for sows having 15% in comparison with 30% of wheat aleurone (6% vs 8%, respectively).

Collectively, these data suggest that high fiber in gestation diets can be included as no negative impact for sow body weight, or litter performance were observed in our current investigation and are in agreement with previous findings (Loisel et al., 2013). The supplementation of fiber during the pre-farrowing period may positively affect piglet survival, and litter quality at weaning, however, to influence litter size at such late stage of gestation it is very difficult as the number of fully formed fetuses has already been established.

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Table 1Composition of gestation diets with low and high fiber (as fed basis)¹

Item	Low fiber (9%)¹	High fiber (18%)¹
Ingredients, %		
Sorghum	80.56	47.49
Wheat middlings	8.85	35.00
Soybean meal	3.90	7.60
Soybean oil	1.00	3.00
Soy hulls	1.50	3.55
Limestone	1.25	1.25
Monocalcium phosphate	0.92	0.51
Dynamate ²	0.50	0.50
Salt	0.48	0.45
L-Lysine	0.30	0.07
Vitamin and mineral premix ³	0.20	0.20
Choline	0.13	0.13
L-Threonine	0.09	-
Toxin Binder ⁴	0.10	0.10
L-Methionine	0.08	-
Organic mineral source [Zn-Mn-Cu] ⁵	0.08	0.08
Active microbial product ⁶	0.05	0.05
Enzyme blend	0.04	0.04
Calculated nutrient composition		
ME, kcal/ kg	3,295	3,296
Standardized ileal digestibility lysine, %	0.56	0.559
Neutral detergent fiber, %	12.39	18.26
Total dietary fiber, %	9.00	18.01
Sol Fiber, %	1.07	2.12
Insol Fiber, %	7.93	15.89
InSol:Sol, ratio	7.39	7.50

¹Diets were formulated to meet or exceed NRC (2012).²Mosaic, Plymouth, MN added as a laxative.

Table 1. (Continued).

³Supplied per kg of complete diet: vitamin A, 11,023 IU; vitamin D₃, 1,763.7 IU; vitamin E, 51 IU; pyridoxine, 3.3 mg; folic acid, 1.21 mg; biotin, 0.28 mg; vitamin K, 4.4 mg; vitamin B₁₂, 0.044 mg; riboflavin, 8.8 mg; d-pantothenate, 26.5 mg; niacin 55.1 mg; thiamine, 3.3 mg.

⁴Zeolite aluminosilicate mineral clay (Kemin Industries, Inc., Des Moines, IA).

⁵Supplied per kg of complete diet: Zn, 125 mg; Fe, 100 mg; Mn, 50 mg; Cu, 25.0 mg; I, 0.7 mg; Se, 0.3 mg; phytase, 661 FTU; (Phyzyme, Danisco A/S, Copenhagen, Denmark), and chromium, 0.4 mg/kg.

⁶Med CloStat (Kemin Industries, Inc., Des Moines, IA).

Table 2Ingredient composition of the top-dress pelleted fiber supplement¹

Fiber	Inclusion (%)
Soybean hulls	64
Wheat middlings	15
Sorghum	10
Cereal fines	10
Soybean oil	1

¹Provided during the pre-farrow period only (5 ± 1 d before expected farrowing) at 0.90 kg on top of the normal lactation diet.

Table 3Calculated composition of the overall dietary treatments (as fed basis)¹

Gestation	HiFi ²		LoFi ²		
	No Top-dress	0.91 kg Top-dress ³	No Top-dress	0.91 kg Top-dress ³	
Pre-farrowing					
TDF ⁴	%	18.00	43.10	9.00	43.10
Soluble Fiber	%	2.10	5.50	1.10	5.50
Insoluble Fiber	%	15.90	37.60	7.90	37.60
InSol:Sol Fiber	%	7.50	6.84	7.40	6.84

¹Treatments provided in gestation were used to distribute sows to the pre-farrowing treatment.² High fiber during gestation (18 %), Low fiber during gestation (9 %).³Top-dress provided at 0.90 kg.⁴Total dietary fiber.

Table 4

Effect of supplementing dietary fiber during gestation and the pre-farrowing period on sow and litter performance

Item	Treatments ¹				SEM	P-values
	HiFi	HiFi + TD ¹	LoFi	LoFi + TD ¹		
Sows, n ²	30	32	28	28		
BW at placement, kg	296.99	298.09	294.38	293.96	8.50	0.84
Number of pigs born alive per litter	11.89	13.04	11.42	12.88	0.78	0.10
Number of stillborn pigs per litter	1.58	1.26	1.30	1.64	0.30	0.75
Number of pigs weaned per litter	9.96	10.30	9.56	9.72	0.43	0.64
Small weaned pigs (<3.6 kg) ³	0.60	1.30	0.78	0.33	0.24	0.05
Litter wean weight, kg	66.53	57.04	55.70	57.32	6.17	0.22
Sow BW at weaning, kg	256.11	255.22	258.39	251.82	11.65	0.86
Lactation length, d	20.71	20.63	20.36	21.00	0.39	0.72

¹HiFi= high fiber; HiFi + TD= High fiber + top-dress; LoFi= Low fiber; LoFi + TD= Low fiber + top-dress

²Values represent least square means for n sows for sows.

The experiment was conducted from June-September 2020.

³Number of small weaned within each litter were counted. Tendency to reduce number of small weaned by LoFi + TD, compared to HiFi + TD (interaction fiber*pellet P= 0.02).

CHAPTER IV:

Impact of solubility of dietary fiber fed during the pre-farrowing period on sow and litter performance during lactation

ABSTRACT: Two studies were conducted to evaluate the impact of level and solubility of dietary fiber on sow and litter performance when fed during the pre-farrowing period and different time of supplementation, 2-day supplementation (experiment 3a) and 7-day supplementation (experiment 3b). Both studies were designed as a 2×2 factorial arrangement plus a control treatment (regular lactation diet; 11.30% TDF) with the following factors: 1) Fiber solubility of the top-dress using a high soluble dietary fiber formulation (soluble and insoluble dietary fiber levels of 5.91 28.28% respectively, and total dietary fiber (TDF) of 34.21%) and a high insoluble dietary fiber formulation (soluble and insoluble dietary fiber levels of 4.19 and 31.11% respectively, and TDF of 35.31%) and 2) Supplementation level of a fiber top-dress added to the lactation feed (0.45 vs 0.90 kg). The top-dress supplements were formulated to meet target fiber levels using sugar beet pulp and soyhulls. In experiment 3a, a total of 82 sows were used. Sows were transferred into the farrowing house at approximately 113 (\pm 1 d) days of gestation and experimental treatments were implemented from placement until parturition. Piglet birth weight ($P= 0.35$), stillborn pigs ($P= 0.76$), number of pigs born per litter ($P= 0.42$), and number of pigs born below 1 kg ($P= 0.89$) did not differ between treatments. Wean weight of piglets was not different between treatments ($P= 0.84$). Estimation of IgG in colostrum using a brix refractometer did not change due to top-dress fiber supplement ($P= 0.30$). Soluble fiber at 0.45 kg tended to increase total solids in colostrum ($P= 0.10$), and fiber supplementation tended to increase total protein ($P= 0.10$), and lactose ($P= 0.10$). In experiment 3b, a total of 85 sows were used. Sows began their dietary treatments during gestation (109 ± 1 d) and when transferred to farrowing house (112 ± 1 d), treatments continued until farrowing. Fiber solubility and top-dress level had no effects on sow BW during the pre-farrowing period and lactation ($P > 0.05$). Soluble fiber reduced the weaning-to-estrus interval irrespective of supplementation level (5.15 and 6.87 vs 7.33 days, for

soluble fiber, insoluble fiber, and control, respectively). Piglet birth weight ($P = 0.36$), stillborn pigs ($P = 0.49$), number of pigs born below 1 kg ($P = 0.63$) and wean weights ($P = 0.85$) did not differ between treatments. Fecal constipation scores were not influenced by fiber supplements ($P > 0.05$). Glucose measurements during farrowing remained higher with the fiber top-dress supplements compared to control ($P = 0.0013$), but fiber solubility or allowance was not different from each other. Estimation of IgG in colostrum using a brix refractometer did not differ between treatments ($P = 0.14$). Fiber at 0.45 kg tended to increase total solids ($P = 0.10$), whereas insoluble at 0.45 kg tended to increase ash ($P = 0.06$), and fiber supplementation regardless of the source and level of supplementation tended to increase total protein ($P = 0.10$). Results suggests that short-term supplementation (2-day) of fiber immediately prior to farrowing, along with fiber solubility was not an effective strategy to improve sow performance during lactation. And a 7-day fiber supplementation did seem to cause an effect on sow performance at the end of lactation. Moreover, fiber had a minor effect on sow colostrum composition, estimation of IgG did not change. Yet, a 7-day supplementation of fiber indicates that glucose status during the farrowing can provide the sow extra energy during this demanding event. However, further research is needed to determine if the effects observed in glucose concentration are constant during parturition, and if the effects observed in lactation performance are due to fiber and if depends on the level of inclusion.

Key words: fiber solubility, pre-farrowing, sows, born alive, stillborn pigs

Introduction

Fiber has been implemented in gestation diets to improve satiety and welfare in sows (Matte et al., 1994; Girard et al., 1995). During the transition from gestation to lactation, fiber addition has been shown to stabilize glucose peaks and insulin release (Hooda 2010; Souza da Silva et al., 2013). This suggests that fiber may function as a longer-term energy source when glucose availability from the gut decreases, ensuring the sow maintain a high energy status, which may prevent the sow mobilizing tissue reserves to support fetal growth (de Leeuw et al., 2004; Sun et al., 2014). Fiber during the pre-farrowing period can have further beneficial impacts by reducing the number of stillborn pigs (Feyera et al., 2017) due to a decrease in farrowing duration (Feyera et al., 2018), and by reducing the incidence of constipation in sows (Oliviero et al., 2009), which positively impacts lactation performance.

The type of fiber (soluble vs. insoluble) is proposed to impact on sow lactation performance through different mechanisms (Ngalavu et al., 2020). Sources like sugar beet pulp (soluble fiber 18%, insoluble fiber 28%; Ai et al., 2020; Huang et al., 2020), and soyhulls (soluble fiber 7.4%, insoluble fiber 50%) (Kim et al., 2015; Yang et al., 2020), have shown positive effects in reducing stereotypical behavior in sows, reducing constipation, improving feed intake during lactation, increasing litter birth weight, and weaning weight, and reducing pre-weaning mortality when included in gestation diets (Ramonet et al., 1999; de Leeuw et al., 2004; Zhao et al., 2015; Shang et al., 2019).

When sows are transferred from the gestation house to the farrowing facility, they experience a drastic change in diet as well as environment. The lactation diet becomes more energy dense, with more protein and fat (Coffey et al., 1994; Boyd et al., 2002; P ere, 2003; Pedersen et

al., 2020). It is still offered in restricted amounts and ad libitum consumption is typically not employed until after parturition.

Therefore, the objectives of the present study are: 1) evaluate the effects of fiber supplementation during the pre-farrowing period of the sow until parturition; and 2) determine the amount and source of fiber that could be effectively used during the transition period to improve sow lactation performance and litter performance during the suckling period until weaning.

Materials and methods

Two experiments were conducted at a 2,600-sow commercial farm owned by the Hanor Family of Companies located in Mooreland, Oklahoma. Protocols for animal use were approved and monitored by licensed veterinarians.

Each experiment consisted of a 2×2 treatment arrangement, plus a control treatment. Factors included: 1) Supplementation of a fiber supplement (Table 1) added in addition to the lactation feed as a top-dress at 2 levels (0.45 kg vs. 0.90 kg); and 2) Fiber solubility of the top-dress using a high soluble dietary fiber formulation (soluble and insoluble dietary fiber levels of 5.91 and 28.28% respectively, and total dietary fiber (TDF) of 34.21%) and a high insoluble dietary fiber formulation (soluble and insoluble dietary fiber levels of 4.19 and 31.11% respectively, and TDF of 35.31%).

The top-dress pellet was formulated to achieve a targeted daily allowance of 365 g/d and 525 g/d of TDF using primarily soyhulls as the insoluble fiber, and 360 g/d and 515 g/d of TDF using primarily sugar beet pulp as the soluble fiber source (Table 1). The top-dress was manufactured by the feed mill owned and operated by the company (Table 2) and was pelleted to

avoid sorting by the sow. Pens of the sows receiving the top-dress were color coded for visual confirmation and proper treatment assignments.

The top-dress pelleted supplement was provided to sows between placement and farrowing using an automated feeding system (Howema, Big Dutchman, Vechta Germany) on top of the normal lactation feed allotment. After farrowing, sows received a standard lactation diet and were allowed to eat ad libitum and had free water access by installed water nipples. Sows assigned to the control treatment did not receive any supplement and were fed the standard lactation diet.

In experiment 3a, sows ($n= 82$) entered the farrowing house (113 ± 1 d) in groups of 22 to 30 sows per group. Within each group sows were randomly assigned to one of the 5 experimental treatments (control, insoluble top-dress provided at 0.45 kg and 0.90 kg, and soluble top-dress provided at 0.45 kg and 0.90 kg). The experimental design was considered as a generalized linear mixed model and was balanced by body condition score at placement in farrowing. In experiment 3b, sows ($n= 85$) were assigned according by body condition score in groups of 25 to 30 sows per group and within each group sows were randomly assigned to one of the 5 treatments and the experimental design was considered as a generalized linear mixed model. Supplementation of the top-dress was initiated at day 109 ± 1 d of gestation. Gestation boxes were adjusted accordingly to body condition score and were color coded for visual identification. The top-dress was provided at targeted levels manually once per day, and when the sows were transferred to the farrowing house (112 ± 1 d) the top-dress treatment continued to be provided using an automated feeding system as described for Exp. 3a.

After farrowing, number and weight of pigs born alive, number of stillborn pigs, and mummies, were recorded. Cross-fostering was done at least 24 hours after farrowing, to allow colostrum consumption. Handling and processing of the litters was performed according to

standard farm practices under the supervision of licensed veterinarians. Farrowing was not induced, and piglets did not receive milk replacers or creep feed during the experiments. Mortality of pigs was recorded during lactation. Pigs were weaned following the farm production schedule (at 21 ± 1 d). Number of sows, pigs weaned, weight of weaned pigs and number of non-viable pigs (less than 3.6 kg) were also recorded (subset of sows $n= 40$, from all groups of sows entering the farrowing house (13 sows per group) for both experiments). Estrus detection and artificial insemination were performed following the standard operating procedures of the farm. Sow events were recorded including sows that died, were euthanized, culled, aborted, and sows used as nurse sows. These sows were excluded from the statistical analysis. For experiment 3a excluded sows ($n= 11$) corresponds to treatment control ($n= 6$), insoluble fiber at 0.45 kg ($n= 2$), insoluble fiber at 0.90 kg ($n= 3$). For experiment 3b excluded sows ($n= 6$) corresponds to treatment control ($n= 2$), insoluble fiber at 0.45 kg ($n=1$), insoluble fiber at 0.90 kg ($n= 2$), and soluble fiber at 0.90 kg ($n= 1$).

Colostrum analysis and brix refractometer reading

Colostrum (20 mL) samples were manually collected from all functional teats ($n= 40$ in Exp. 3a; $n= 32$ in Exp. 3b) opportunistically including: immediately prior to parturition, at the birth of the first piglet, or during parturition. Collected colostrum samples were analyzed to determine fat, total protein, total solids, ash, and lactose (Dairy One Laboratory, Ithaca, New York). In addition, a fresh 0.3 mL sample of colostrum was collected and analyzed using a commercial digital brix refractometer (digital hand-held pocket refractometer, Atago, Tokyo, Japan), with a range of 0-53% Brix, to estimate IgG content in colostrum on-farm.

Fecal consistency

Sow constipation was visually assessed in Exp. 2 from 45 sows total (9 per treatment) for a 7-day period that covered the 3 days prior to farrowing, during farrowing and the first 3 days after farrowing. The scoring scale was adapted from Oliviero et al. (2009) and consisted of the following: 0= dry feces, 1= dry to normal, 2= normal and soft, 3= normal and wet (still formed but not firm) and 4= wet feces (not formed and liquid).

Glucose concentration during farrowing

In Exp. 2, glucose was monitored during farrowing by carefully extracting blood from the umbilical cord of the newborn piglets to monitor the glucose status of the sow and the piglet. A 3 mL syringe was used, and the collected blood was placed into a glucose meter (Precision Xtra, Abbott, CA, USA) to perform the analysis on site. A total of 82 pigs (from 15 sows total) were evaluated, and glucose readings were taken for 3 time points during farrowing: at birth of the first pigs, those that were born mid-parturition, and those that were born last. The piglet samples did not follow birth order as they were taken opportunistically. These piglets were allowed to consume colostrum after the measurement was taken.

Statistical analysis

Sow and litter performance were analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). The model included fixed effects of control, fiber source (insoluble, soluble) and level of supplementation (0.45 kg and 0.90 kg) during the pre-farrow period, and their interactions. Group of sows entering the farrowing house (Exp. 3a groups = 3; Exp. 3b groups = 3), were considered as a random effect for pigs born alive, stillborn pigs, and mummies. Piglet birth weight,

pigs with low- birth- weight (below 1 kg body weight) wean piglet weight, and number of non-viable pigs at weaning (below 3.6 kg body weight) were analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC).

Fecal scores, colostrum composition, brix IgG readings and glucose monitoring were analyzed using Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). All models included fixed effects of control, fiber solubility and level of supplementation and their interactions. Day was used as a repeated measure for fecal scores and modeled as a sequence of random effect with covariance structure following an autoregressive process of order 1. For colostrum composition, a contrast analysis was included to observe the day effect of supplementation (2 days for Exp.3a; 7 days for Exp.3b), for fiber solubility and level of supplementation.

Least square means were reported and compared using multiple comparison test Tukey-Kramer, and for the control treatment Dunnett's test was used to identify meaningful comparisons. Differences of $P \leq 0.05$ were considered significant. Tendencies were considered when $0.05 < P \leq 0.10$.

Results

Experiment 3a

Fiber solubility and level of top-dress supplementation had no influence (Table 3) on sow body weight at placement or at weaning ($P > 0.05$). Likewise, piglet birth weight ($P = 0.35$) and number of pigs born per litter ($P = 0.42$), number of stillborn pigs ($P = 0.76$), and number of low-birth weight pigs weighing less than 1 kg ($P = 0.89$), were not affected by dietary treatments during the pre-farrowing period.

No differences were detected in piglet weaning weight ($P = 0.84$), number of pigs weaned per litter ($P = 0.44$) and number of non-viable pigs at weaning (pigs weighing less than 3.6 kg) per litter ($P = 0.20$).

A total of 40 samples of colostrum were taken either before farrowing, after the birth of the first piglet, or during farrowing to assess content of IgG percentage in colostrum of sows using the brix refractometer as a means to provide a rapid on-site estimate. Estimated concentrations of IgG (Table 4) were not different between fiber solubility treatments or level of top-dress supplementation ($P = 0.30$).

Nutritional composition of colostrum samples (Table 5) for fat, total protein, total solids, ash, and lactose had similar results for most of the components. For ash, there was an effect for day of supplementation ($P < 0.001$) where it is higher at 7 days (Exp. 3b, 0.77%) compared to 2 days (Exp. 3a, 0.69%), where it tended to be increased by fiber solubility ($P = 0.09$).

Casein and fat were not affected by the top-dress pelleted supplement and were not influenced by fiber solubility ($P > 0.05$). But soluble fiber provided at 0.45 kg had a tendency ($P = 0.10$) to increase total solids (%). Fiber supplementation irrespective of the source and amount, tended to increase lactose compared to control ($P = 0.10$). Similarly, fiber had a tendency for total protein ($P = 0.10$) and a tendency for days of supplementation ($P = 0.09$) indicating that total protein could be increased with longer time of supplementation.

Experiment 3b

Fiber solubility and top-dress level of supplementation did not affect sow BCS ($P = 0.18$) and BW (Table 6) during the pre-farrowing period and lactation ($P > 0.05$). Number of pigs born alive ($P = 0.23$), piglet birth weight ($P = 0.36$), stillborn pigs ($P = 0.49$), number of pigs born below

1 kg ($P = 0.63$), number of pigs weaned ($P = 0.21$), wean weight of piglets ($P = 0.85$), and non-viable pigs at wean (pigs weighing less than 3.6 kg, $P = 0.77$) did not differ between treatments. However, soluble fiber reduced the weaning-to-estrus interval irrespective of supplementation level (5.15 and 6.87 vs 7.33 days, for soluble fiber, insoluble fiber and control, respectively).

Glucose readings during farrowing were higher for sows consuming the pelleted fiber top-dress ($P = 0.0013$) supplement compared with the control treatment. Nevertheless, fiber treatments did not differ from each other (Table 7). Estimations of percentage of IgG in sow colostrum as measured using brix for this experiment were not statistically different ($P = 0.14$) (Table 8).

Composition of colostrum samples (Table 9) were similar to the results reported in experiment 1. Fat and casein were not increased with a longer time of fiber supplementation ($P > 0.05$). Total solids had a tendency to be influenced by soluble fiber provided at 0.45 kg ($P = 0.10$), and ash tended to be higher ($P = 0.06$) when insoluble fiber was provided at 0.45 kg. Moreover, lactose, did not changed due to fiber treatment, and day of supplementation had minimal influence ($P = 0.09$), and total protein results tended to increase ($P = 0.10$) with fiber supplementation.

Fiber supplementation did not ($P > 0.05$) improve sow constipation scores during the pre-farrowing period, or during post-farrowing (Table 10).

Discussion

The potential benefit of fiber or its inclusion level in gestation diets or during the pre-farrowing period it is not well known. Therefore, two studies were conducted to evaluate the effects of soluble (primarily sugar beet pulp) and insoluble fiber (primarily soyhulls) and determine the impact of level of supplementation during the pre-farrowing period. To our knowledge, this is the first study that applied a specifically designed pelleted fiber supplement to be provided to the

sows as addition (top-dress) to their common lactation diet during the pre-farrowing period. Most other investigations have evaluated complete diets high in fiber (Ramonet et al., 1999; Guillemet et al., 2006; Renteria-Flores et al., 2008a; Guillemet et al., 2010; Loisel et al., 2013; Tan et al., 2018).

Short-term top-dress fiber supplementation did not influence sow and litter performance. Since the top-dress fiber supplements were provided close to the farrowing date (2 ± 1 d), we suspect there was not enough time to significantly impact sow metabolism and subsequent performance. Even though our time of fiber supplementation was short, Krogh et al. (2015), supplemented fiber during the last 10 days of gestation and the first 5 days of lactation and their results indicated that fiber had no influence on sow body weights and piglet birth weights.

The longer duration of fiber supplementation in Exp. 2 (7 ± 1 d) seemed to start unravelling measurable effects compared to a shorter duration in Exp. 1. Sows typically lose weight during lactation due to the high nutrient and energy demand associated with milk production, and this has been accentuated in modern hyperprolific sows nursing larger litters (Eisenn et al., 2003; Rosero et al., 2016). A sow that is too skinny at the end of lactation will most likely not be bred within the expected time, compromising the next reproductive cycle (Thaker and Bilkei, 2005). Supplementation with soluble fiber seemed to reduce the weaning-to-estrus interval compared to the other treatments.

Sows tend to develop moderate to mild constipation around parturition (Tabeling et al., 2003). However, severe signs of constipation can be associated with disorders such as post-partum disgalactia, increased farrowing duration, and increased number of stillborn pigs (Hermansson et al., 1978; Martineau et al., 1992; Oliviero et al., 2010; Pearodwong et al., 2016). One of the benefits

of fiber inclusion in sow diets is relieving constipation that in turn may improve farrowing outcome.

Oliviero et al., (2009) reported that high fiber diets decreased constipation in sows during late gestation and early lactation. Similarly, Tan et al. (2015) reported sows with softer stool before farrowing and during the first five days of lactation when incorporating soluble fiber in their diets. In the current study a decrease in constipation was not observed during the pre-farrowing period, or after post-farrowing. This can be related to certain extent to the relatively low number of sows under evaluation for fecal consistency compared to other studies (Tabeling et al., 2003; Oliviero et al., 2009; Tan et al., 2015; Pearodwong et al., 2016; Shang et al., 2021), and the duration of fiber supplementation.

Glucose is the main source of energy in mammals, and during farrowing it is crucial to maintain glucose concentrations and prevent the sow from depleting energy availability. When glucose decreases, the sow fatigues and uterine contractions start to decrease, farrowing length increases and this in turn can increase the possibility of stillborn pigs (Christianson, 1992; Oliviero et al., 2010).

In the present study, fiber was effective at maintaining glucose levels in sows and newborn piglets compared to control fed sows during farrowing. Our method to evaluate glucose concentration using a glucose meter was non-invasive and it did not cause stress to the sows. Our findings are in agreement with other authors reporting a higher glucose concentration in sow blood either before farrowing, or immediately after farrowing with inclusion of fiber in their diets (Quesnel et al., 2009; Oliviero et al., 2009; Feyera et al., 2018; Feyera et al., 2019).

To our knowledge, there are no studies that have implemented this method of monitoring glucose during farrowing for both sow and piglet. But a similar study (Kemp et al., 1996) used a

glucose meter to determine glucose tolerance in gestating sows by taking samples from the tail of sows. And other investigations have used catheters (Serena et al., 2009; Feyera et al., 2019; Nielsen et al., 2021) or collected blood samples (Girard et al., 1995; Farmer et al., 1996; Pedersen et al., 2020) from sows directly which may be seen as the most common techniques for sow studies. However, it should be noted that while it can be used as a tool to obtain rapid results, the glucose meter measure whole blood, which contains other components such as proteins, thus it is difficult to quantify glucose alone (Tonyushkina and Nichols, 2009). This in turn may underestimate glucose values compared to a laboratory reference values (Stoot et al., 2014; Del Baldo et al., 2020).

Colostrum consumption by newborn piglets is essential to serve as a source of energy proteins, and immunoglobulins that are important for passive immunity (Le Dividich et al., 2005; Theil et al., 2014a). Energy reserves of piglet at birth can only keep them alive for a short duration, and adequate consumption of colostrum at birth is essential to prevent starvation, hypothermia and death (Milon et al., 1993; Quesnel, 2011; Decaluwé, et al., 2013).

In our studies, colostrum composition was not influenced by the fiber-rich top-dress supplement. In line with our findings, Loisel et al, (2013) found no evidence that a high fiber diet changed the composition of lactose in colostrum. On the other hand, they reported that the concentration of IgG and IgA in colostrum tended to decrease, whereas the fat content increased when sows were fed high fiber diets. In contrast, Theil et al. (2014b) found that sows produced less fat and protein in colostrum, but lactose concentrations increased when sows consumed a diet with pectin residue or sugar beet pulp during gestation.

Improvement of colostrum nutrients is a challenging task to achieve, as colostrum composition varies from sow to sow, and other factors play an important role such as genetics, age

parity of the sow, and immune status that should be considered (Farmer and Quesnel, 2009; Quesnel and Farmer, 2019).

Because the placenta of sows is epitheliochorial, it is not possible to transfer large molecules into the fetus such as proteins, including immunoglobulins but it can transfer small molecules such as glucose and amino acids (Bauer et al., 1998). Thus, the newborn pig relies only on colostrum which is rich in immunoglobulins that are the responsible to provide immune status to the pig (Rooke and Bland, 2002; Herpin et al., 2002).

Immunoglobulins in colostrum, especially IgG are pivotal for pigs because it is closely related to survivability and disease prevention (Klobasa and Werhahn, 1981; Theil et al., 2014a). In addition, IgA and IgM are important because they give a protective barrier in the intestine of the neonate (Milon et al., 1983; Bianchi et al., 1999).

Considering the great importance of making sure piglets consume colostrum, it is also important to determine if the sow is able to confer adequate protective immunity to the pig. The brix refractometer can be used as a practical tool to evaluate the IgG content of colostrum on-site and thus results can be obtained much faster than laboratory analysis. The brix refractometer has been used in other animal species including dairy cattle (Bielmann et al., 2010; Silva-del-Rio et al., 2017; Gamsjäger et al., 2020), small ruminants (goats, sheep) (Santiago et al., 2020; Kessler et al., 2021) and equines (Korusue et al., 2013). In general, the brix refractometer measures the percentage of sucrose in aqueous solutions (e.g fruits, wine), but when the aqueous solutions do not contain high levels of sucrose, it can be used as an approximate to measure the percentage of total solids (Quigley et al., 2013).

The ability of the brix refractometer to estimate IgG content in sow colostrum has been validated by Hasan et al. (2016), by comparing brix readings for total solids with the concentration

of IgG determined with an ELISA kit which had a positive correlation ($r = 0.63$) between the brix readings and ELISA results. In addition, a positive correlation ($r = 0.66$) was found between the percentage of total solids and the brix readings. Further, Balzani et al. (2016), validated the use of the brix refractometer in sow colostrum by comparing the brix results with the concentration of IgG determined with radial immunodiffusion assay and found a positive correlation ($r = 0.56$) between the brix refractometer and IgG obtained with the radial immunodiffusion.

Despite our study did not compare IgG content in colostrum using laboratory methods, the brix readings were comparable with the results from Hazan et al. (2016) and of Balzani et al., (2016). According to the category scale recommended by Hasan et al. (2016) our brix readings would classify as “adequate” IgG content in sow colostrum in which an average brix reading of 25 to 29%, is suggested as such. Whereas a brix reading between 20 to 24% was considered as “borderline”, a reading below 20% was suggested as “poor” and a reading of 30% or more was considered as “very good”. However, these are suggested categories, therefore they should be carefully taken in consideration when obtaining results on-site as further research is required to actually determine if these ranges are in fact an adequate estimate. IgG concentration is highest during the first 3 hours during farrowing, with an average of 64 mg/ml according to Quesnel et al., (2015) and it starts to drop between 10-12 hours after onset of farrowing, and after 24 hours the drop can be greater than 70% (Devillers et al., 2011).

It has been found that newborn pigs that died have a lower concentration of IgG in serum compared to their surviving litter mates indicating low colostrum consumption which could also be related to energy status and hypothermia (Kielland et al., 2015). Since IgG content and piglet survivability are correlated, the earlier colostrum consumption by the pig, the better.

In conclusion, supplementation of a fiber rich top-dress supplement immediately prior to farrowing period was not a successful strategy to improve sow and litter performance during lactation. When fiber supplementation was implemented during the last week of gestation and the pre-farrowing period, it reduced the weaning-to-estrus interval, and little changes were made in colostrum composition. Furthermore, fiber was able to maintain a higher concentration of sow glucose during farrowing, indicating a better energy status to handle this demanding event. Constipation assessment in sows did not seem to improve by fiber solubility during the pre-farrowing period, and IgG estimation was not impacted.

We propose that a longer period of fiber supplementation may be necessary to determine the role of fiber during the pre-farrowing period on sow and litter performance. Further research is suggested to demonstrate the potential influence of fiber and type of fiber to improve the nutritional profile of colostrum and maintain energy availability during parturition.

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Table 1

Calculated and analyzed composition of insoluble and soluble top-dress pelleted fiber supplement for the pre-farrowing period

Item	No Top-dress ¹	Insoluble pellet		Soluble pellet	
	0	0.45kg	0.90kg	0.45kg	0.90kg
Composition, %					
TDF	11.30	35.31	35.31	34.21	34.21
Soluble Fiber	1.49	4.19	4.19	5.91	5.91
Insoluble Fiber	9.80	31.11	31.11	28.28	28.28
InSol:Sol Fiber	6.58	7.42	7.42	4.78	4.78
Estimated intake, g/d²					
TDF	205.80	365.27	525.45	360.30	515.52
Soluble Fiber	27.04	46.07	65.10	53.87	80.71
Insoluble Fiber	177.86	319.02	460.17	306.18	434.49
InSol:Sol Fiber	6.58	6.92	7.07	5.68	5.38
Analyzed composition, as is basis (w/w, %)					
NDF		33.58	34.82	31.62	32.30
ADF		18.36	18.43	17.34	17.62
TDF		39.72	40.11	39.15	39.62
Soluble TDF		0.23	0.27	1.20	1.51
Insoluble TDF		39.47	39.91	37.72	38.44
Crude protein		13.43	13.75	12.67	12.75
Moisture		11.22	11.28	10.99	10.99
Crude fat		3.90	3.83	3.81	3.76
Crude fiber		14.68	15.02	13.52	13.66
Ash		4.40	4.41	4.23	4.27

¹Estimated intake of fiber for the lactation diet when consumed at 2.72 kg/d.

²Estimated intake of fiber for the lactation diet plus the contribution from the top-dress.

Table 2. Ingredient composition of the top-dress pelleted fiber supplementsTop-dress supplement¹

Insoluble		Soluble	
Fiber ingredients	Inclusion %	Fiber ingredients	Inclusion %
Soybean hulls	30	Soybean hulls	20
Sugar beet pulp	0	Sugar beet pulp	15
Wheat middlings	49	Wheat middlings	42
Sorghum	10	Sorghum	12
Cereal fines	10	Cereal fines	10
Soy oil	0.95	Soy oil	0.95
Color Fe Oxide YEL	0.05	Color Fe Oxide RED	0.05

¹In experiment 1, top-dress was supplemented during the pre-farrowing period (2 ± 1 d.). In experiment 2, top-dress was supplemented in gestation (4 ± 1 d) and during the pre-farrowing period (3 ± 1 d).

Table 3

Effect of fiber solubility during the pre-farrowing period on sow and litter performance (Exp. 3a)

Item	Treatments ¹					SEM	P-values
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	11	16	14	22	19		
*BW at placement, kg ³	235.66	235.54	247.99	237.93	250.43	15.50	0.57
Number of pigs born per litter	12.70	13.39	14.27	12.90	13.30	1.77	0.42
Number of stillborn pigs per litter	1.33	1.28	1.53	1.47	2.11	0.50	0.76
Low-birth weight pigs (below 1 kg) ⁵	1.10	0.73	0.69	0.52	0.75	0.50	0.89
Piglet weight at birth, kg ⁴	1.55	1.54	1.66	1.68	1.58	0.13	0.35
Litter birth weight, kg	20.07	20.83	22.70	18.99	19.36	1.18	0.19
Number of pigs weaned per litter	9.27	10.67	10.45	9.90	10.30	0.52	0.44
*Piglet wean weight, kg ⁴	5.38	5.79	5.74	6.00	6.26	0.90	0.84
*Small wean pigs (below 3.6 kg) ⁵	1.10	1.63	2.83	0.30	0.44	0.51	0.20
*Litter wean weight, kg	54.05	66.88	70.00	65.70	72.00	2.95	0.61
*Sow BW at weaning, kg	201.69	187.47	207.80	198.98	208.94	29.00	0.82
Lactation length, d	26	25	25	24	25	0.80	0.57

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows for sow and litter performance at placement and at birth. The experiment was conducted from June-July 2021.

³ Sow BW was measured prior entering the farrowing room (113 ± 1 d).

⁴ Piglet weight at birth and weaning was measured for each individual pig, the results were analyzed by litter and presented as means of each treatment.

⁵Number of pigs per litter.

*A subset of 40 sows and their litters were weighed to obtain weaning weights. Values are reported as least square means.

Table 4

Estimation of IgG in sow colostrum using the brix refractometer (Exp. 3a)

Item	Treatments ¹					SEM
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹	
Sows, n ²	8	8	8	8	8	
Brix (%)	24.20	23.17	25.86	26.61	25.84	1.25
Min Brix (%) ³	21.64	20.62	23.31	24.06	23.29	
Max Brix (%) ³	26.75	25.73	28.42	29.17	28.40	

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

³Minimum and maximum brix readings per treatment.

No differences were detected in the estimation of IgG in sow colostrum (P = 0.30).

Table 5

Effect of fiber supplementation on colostrum composition in sows (Exp. 3a)

Item	Treatments ¹					SEM	Probability ^{3,4}
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	8	8	8	8	8		
Colostrum composition (%)							
Ash	0.70	0.72	0.67	0.62	0.60	0.03	DS***, FS‡, DS x FS**, DS x FS x TD (Insol)***
Casein	4.56	3.30	4.25	3.98	3.39	0.77	
Fat	5.08	5.57	5.91	5.25	5.22	0.95	
Lactose	2.63	2.62	2.72	2.91	3.10	0.20	DS‡, DS x FS‡
Total protein	15.49	14.53	16.77	17.31	16.55	0.92	DS‡, FS‡
Total solids	23.90	23.44	26.07	26.10	25.47	1.38	FS x TD (Sol+1)*

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.² Values represent least square means for n sows.³ Effect abbreviations: DS= Days of supplementation, FS= Fiber solubility, DSxFS= Interaction between days of supplementation and fiber solubility, DSxFSxTD= Interaction between days of supplementation, fiber solubility and top-dress level (0.45, 0.90 kg).⁴ Significance levels: ***P≤ 0.0001; **P≤ 0.01; *P≤ 0.05; ‡ 0.10> P >0.05.

Table 6

Effect of fiber solubility during the pre-farrowing period on sow and litter performance (Exp. 3b)

Item	Treatments ¹					SEM	P-values
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	18	18	16	16	17		
BCS at placement	3.61	3.78	4.00	3.56	3.35	0.19	0.18
*BW at placement, kg ³	160.86	203.94	181.54	191.96	184.81	58.77	0.83
Number of pigs born per litter	14.33	12.94	14.31	12.13	14.65	0.89	0.23
*Piglet weight at birth, kg ⁴	1.42	1.57	1.44	1.53	1.45	0.14	0.36
Number of stillborn pigs per litter	1.50	1.00	1.63	1.50	1.18	0.28	0.49
*Low-birth weight pigs (below 1 kg) ⁵	0.58	0.40	0.50	0.83	0.46	0.20	0.63
*Litter birth weight, kg	19.89	19.45	21.99	18.89	21.13	4.68	0.71
Number of pigs weaned per litter	10.25	10.63	11.75	10.13	11.88	0.66	0.21
*Piglet wean weight, kg ⁴	6.59	5.94	6.94	6.60	5.88	0.90	0.32
*Small weaned pigs (below 3.6 kg) ⁵	0.00	0.57	0.17	0.33	0.20	0.17	0.77
*Litter wean weight, kg	74.25	65.68	80.91	73.07	67.80	12.99	0.42
*Sow BW at weaning, kg	202.73	162.88	216.25	175.96	187.90	39.06	0.25
Lactation length, d	22.83	21.38	23.19	22.43	21.58	0.53	0.08
Weaning-to-estrus-interval	7.33 ^a	7.57 ^a	6.21 ^a	5.00 ^b	5.30 ^b	0.72	0.02

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.² Values represent least square means for n sows for sow and litter performance at placement and at birth. The experiment was conducted from July-August 2021.³ Sow BW was measured prior entering the farrowing room (112 ± 1 d).

Table 6. (Continued).

⁴Piglet weight at birth and weaning was measured for each individual pig, the results were analyzed by litter and presented as means of each treatment.

⁵Number of pigs per litter.

*A subset of 40 sows and their litters were weighed to obtain birth and weaning weights. Values are reported as least square means.

Table 7

Glucose estimation during farrowing measured using a hand-held glucose meter (Exp. 3b)

Item	Treatments ¹					SEM
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹	
Sows, n ²	3	3	3	2	3	
Pigs per treatment, n ²	17	22	17	10	16	
Glucose concentration (mg/dL)	41.53 ^b	61.90 ^{ba}	68.06 ^a	52.40 ^{ba}	68.31 ^a	6.57
Min glucose concentration (mg/dL) ³	34.11	47.51	51.68	36.03	55.37	
Max glucose concentration (mg/dL) ³	48.94	76.31	84.44	68.77	81.26	

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

³Minimum and maximum mean values of glucose readings per treatment.

Significant differences found for fiber supplementation vs control P= 0.001.

Fiber treatments were not different from each other P= 0.59.

Level of top-dress supplement was not different P= 0.24.

Table 8.

Estimation of IgG in sow colostrum using the brix refractometer (Exp. 3b)

Item	Treatments ¹					SEM
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹	
Sows, n ²	6	6	6	6	6	
Brix (%)	23.07	23.80	23.75	27.53	24.40	1.27
Min Brix (%) ³	25.70	21.17	21.12	24.90	21.77	
Max Brix (%) ³	26.75	26.43	26.38	30.16	27.03	

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

³Minimum and maximum brix readings per treatment.

No statistical differences were detected in estimation of IgG in sow colostrum P= 0.14.

Table 9

Effect of fiber supplementation on colostrum composition in sows (Exp. 3b)

Item	Treatments ¹					SEM	Probability ^{3,4}
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	6	6	6	6	6		
Colostrum composition (%)							
Ash	0.75	0.82	0.75	0.76	0.77	0.04	DS***, FS‡, DS x FS**, DS x FS x TD‡ (Insol+1)
Casein	5.20	4.35	4.05	4.58	4.40	0.83	
Fat	5.28	3.86	6.18	5.60	4.79	1.02	
Lactose	2.52	2.72	2.49	2.40	2.73	0.22	DS‡
Total protein	14.66	14.16	14.68	16.46	15.46	0.99	DS‡, FS*, FS x TD‡
Total solids	23.20	21.55	24.10	25.22	23.75	1.48	FS x TD(Sol+1)*

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

³ Effect abbreviations: DS= Days of supplementation, FS= Fiber solubility, DSxFS= Interaction between days of supplementation and fiber solubility, DSxFSxTD= Interaction between days of supplementation, fiber solubility and top-dress level (0.45, 0.90 kg).

⁴ Significance levels: ***P ≤ 0.0001; **P ≤ 0.01; *P ≤ 0.05; ‡ 0.10 > P > 0.05.

Table 10
Effect of fiber solubility on sow constipation score

Item	Treatments ¹					SEM	P-value
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	9	9	9	9	9		
Score (7-day eval)	0.96	1.13	0.84	1.25	1.04	0.17	0.35
<u>Period</u>							
Pre-farrowing ³	0.97	1.15	0.93	1.26	1.22	0.09	0.32
Post-farrowing ⁴	0.95	1.11	0.75	1.23	0.87	0.11	0.58

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

³Pre-farrow= days -3, -2, -1, 0.

⁴Post-farrow= days 1, 2, 3.

Score scale: 0= dry feces, 1= dry to normal, 2=normal and soft, 3= normal and wet (still formed but not firmed), 4= wet feces (not formed and liquid).

CHAPTER V:

Impact of amount and solubility of dietary fiber fed during late gestation and during the pre-farrowing period on sow and litter performance in lactation

ABSTRACT: This study evaluated the impact of level and solubility of dietary fiber on sow and litter performance when fed during late gestation and during the pre-farrowing period. Sows (n=241) were assigned by BCS to a 2×2 factorial arrangement plus a control treatment (regular gestation diet, 12% TDF, regular lactation diet; 11.30% TDF) with the following factors: 1) High soluble dietary fiber (SDF; 9.63 %) and insoluble dietary fiber (IDF; 30.73 %); low soluble dietary fiber levels (SDF; 4.18 %) and insoluble dietary fiber levels (IDF 25.25 %) and 2) Supplementation level of a fiber top-dress added to the gestation feed, and posteriorly to lactation feed (0.45 vs 0.90 kg). The top-dress supplements were formulated to meet target fiber levels using sugar beet pulp and soyhulls. Sows began their dietary treatments at 99 days of gestation and when they were transferred into the farrowing house at approximately 112 (\pm 1 d) days of gestation, experimental treatments were continued from placement until parturition. Blood samples were collected to evaluate the concentration of glucose and serum chemistry on sows during late gestation in 3 time points: before the first feed (time 0), 2 hours after the first meal, and 4 hours after the first meal. Farrowing process was monitored with video equipment as a pilot study to evaluate fetal expulsion length, and piglet vitality index (PVI). Piglet vitality index followed a 4-point scale consisting of 0= no movement, no breathing, 1= no movement, but pig is attempting to breathe, 2= moving, attempting to breathe, and/or coughing, and 3= good movement, pig is breathing and able to stand within 1 minute or less after born. Fiber solubility and top-dress level had no effects on sow BW during the pre-farrowing period ($P= 0.32$) and lactation ($P> 0.05$). Weaning-to-estrus interval was higher for insoluble fiber at 0.45 kg ($P= 0.0003$) and control compared to the other treatments (6.59^a and 6.51^a days vs 5^b, and 4.99^{ba} days for insoluble fiber at 0.90 kg, and soluble fiber, respectively). Number of pigs born per litter ($P= 0.39$), and piglet birth weight ($P= 0.96$), did not differ between treatments. However, number of stillborn pigs ($P= 0.03$) was reduced by insoluble

fiber at 0.45 kg (1.04^b stillborn pigs), whereas insoluble fiber at 0.90 kg increased the number of stillborn pigs compared to control and soluble fiber treatments (1.82^a vs 1.52^{ba}, 1.58^{ba} stillborn pigs, respectively). Similarly, insoluble fiber at 0.45 kg, increased the number of low-birth weight pigs (P= 0.0085) weighing less than 1 kg (1.31^a vs 0.50^b, 0.33^b, 0.40^b, and 0.47^b for control, insoluble fiber at 0.90 kg, and soluble fiber at 0.45 kg and 0.90 kg, respectively). Number of pigs at wean (P= 0.87) and wean weight of piglets was not different between treatments (P= 0.34) but, control and insoluble fiber increased (P< 0.001) the number of small weaned pigs (less than 3.6 kg BW) when it was offered at 0.45 kg. In contrast, insoluble fiber at 0.90 kg decreased the number of small weaned pigs compared to the other treatments (3.27^a and 3.31^a vs 0.53^c, 1.00^{bc}, and 2.00^{ab} for insoluble fiber at 0.45 kg, control, insoluble fiber at 0.90 kg, soluble fiber at 0.45 kg, and soluble fiber at 0.90 kg, respectively). Glucose concentrations were not different between dietary treatments and were not influenced by sampling period. For serum chemistry analysis, GGT was significantly reduced by fiber (P= 0.03), and it changed overtime (P= 0.02). Magnesium had a tendency (P= 0.09) to increase, and it was influenced by sampling period (P= 0.004). BUN and triglycerides were not affected by dietary treatments (P> 0.05), but their profile changed overtime (P< 0.05). Preliminary analysis of PVI and fetal expulsion during farrowing did not indicate to be affected by fiber supplementation.

Results indicate that supplementation of fiber during late gestation and during the pre-farrowing period does not affect BW of sows and piglets during lactation. However, insoluble fiber and control had higher weaning-to-estrus interval in sows compared to soluble fiber regardless of the allowance and insoluble fiber when offered at 0.45 kg. Moreover, insoluble fiber at 0.45 kg was able to reduce the number of stillborn pigs, it increased the number of low-birth piglet weight and at number of non-viable pigs at weaning. Insoluble fiber at 0.90 kg increases the number of

stillborn pigs, but also reduces the number of non-viable pigs at weaning. Soluble fiber did not elicit negative effects on sow performance and for piglet weights at birth, and it also reduces the number of non-viable pigs at weaning compared to control. Fetal expulsion length, or PVI does not seem to be affected by fiber, though a larger scale study is needed to confirm this criterion.

Collectively, these data suggests that supplementation of soluble fiber may be a practical nutritional strategy for sows during late gestation and during the pre-farrowing period. Whereas insoluble fiber may need further evaluation to consider if at lower levels of inclusion, the observance of stillborn pigs, low-birth and non-viable pigs at weaning are consistent.

Key words: fiber solubility, pre-farrowing, late gestation, sows

Introduction

The last third of the pregnancy of sows is characterized by an increase in uterine, mammary, fetal growth, and nutrient demand from both the sow and the fetus (Dourmand et al., 1996; Miller et al., 2000). However, during the last 15 days of gestation the physical and metabolic changes occurs exponentially (Mahan et al., 2009; Theil, 2015).

Fiber has been implemented in gestation diets for sows to control their body weight during pregnancy and to improve satiety and welfare (Matte et al., 1994; Girard et al., 1995), but the benefits of fiber go further than controlling body weight. It has been suggested that fiber can contribute to 30% of maintenance energy for sows (Varel and Yen, 1997) through the fermentation process that yields SCFA, resulting in reduced glucose peaks (Daou and Zhang, 2012). In the process of parturition, fiber has been associated with reduction of stillborn pigs which can be explained by a potential decrease in farrowing duration (Feyera et al., 2017) and may possibly

improve piglet vitality at birth. In addition, an increase in lactation feed intake has been observed when sows receive high fiber in the diets during gestation (Sun et al., 2014) which is closely related to the increase in litter weaning weights (Che et al., 2011). However, the effects observed depend highly on the type of fiber implemented (soluble vs insoluble) and could potentially depend on the time of supplementation.

Therefore, the objective of this study is to evaluate the impact of fiber solubility (soluble vs insoluble) and level of supplementation during late gestation and during the pre-farrowing period on sow and litter performance during lactation.

Materials and methods

The present study was conducted at a 2,600-sow commercial farm owned by the Hanor Family of Companies located in Mooreland, Oklahoma. Protocols for animal use were approved and monitored by licensed veterinarians.

The experiment consisted of a 2×2 factorial treatment arrangement plus a control treatment. Factors included: 1) Supplementation of a fiber supplement (Table 1) added in addition to the gestation and lactation feed as a top-dress at 2 levels (0.45 kg, 0.90 kg); and 2) Fiber solubility of the top-dress using a high soluble dietary fiber formulation (soluble and insoluble dietary fiber levels of 9.63 % and 30.73 %, respectively, and total dietary fiber (TDF) of 34.92 %) and high insoluble dietary formulation (soluble and insoluble dietary fiber levels of 4.18 % and 25.25 %, respectively, and total dietary fiber (TDF) of 34.91 %).

The top-dress was formulated to achieve a targeted daily allowance of 414 g/d and 573 g/d of TDF using primarily soyhulls as the insoluble fiber, and 414 g/d and 573 g/d of TDF using primarily sugar beet pulp as the soluble fiber source (Table 1). The top-dress was manufactured

by the feed mill owned and operated by the company (Table 2) and was pelleted to avoid sorting by the sow. Pens of the sows receiving the top-dress in gestation were color coded for visual confirmation and proper treatment assignments.

The top-dress was provided to sows between placement and farrowing using an automated feeding system (Howema, Big Dutchman, Vechta Germany) on top of the normal lactation feed allotment. After farrowing the sows received a standard lactation diet and were allowed to eat ad libitum and had free water access by installed water nipples. Sows assigned to the control treatment did not receive any supplement and were fed the standard lactation diet.

Sows ($n= 241$) entered the farrowing house (112 ± 1 d) in groups of 24 to 30 sows per group. Within each group sows were randomly assigned to one of the 5 experimental treatments (control, insoluble top-dress provided at 0.45 kg and 0.90 kg, and soluble top-dress provided at 0.45 kg and 0.90 kg). The experimental design was considered as a generalized linear mixed model and was balanced by body condition score at placement in gestation. Supplementation of the top-dress was initiated at day 99 ± 1 d of gestation. Gestation boxes were adjusted accordingly to body condition score and feeders were color coded for visual identification. The top-dress was provided at targeted levels manually once per day, and when the sows were transferred to the farrowing house (112 ± 1 d) the top-dress treatment continued to be provided using an automated feeding system previously described.

After farrowing, number and weight of pigs born alive, number of stillborn pigs, and mummies, were recorded. Cross-fostering was done for at least 24 hours after farrowing, to allow colostrum consumption. Handling and processing of the litters was performed according to standard farm practices under the supervision of licensed veterinarians. Farrowing was not induced, and piglets did not receive milk replacers or creep feed during the experiments. Mortality

of pigs was recorded during lactation. Pigs were weaned following the farm production schedule (at 21 ± 1 d). Number of sows, pigs weaned, weight of weaned pigs and number of non-viable pigs (less than 3.6 kg) were also recorded (subset of sows $n= 73$). Estrus detection and artificial insemination were performed following the standard operating procedures of the farm. Sow events were recorded including sows that died, were euthanized, culled, aborted, and sows used as nurse sows. These sows were excluded from the statistical analysis ($n= 32$) which corresponds to control treatment ($n= 7$), insoluble fiber at 0.45 kg ($n= 8$), insoluble fiber at 0.90 kg ($n= 6$), soluble fiber at 0.45 kg ($n= 5$), and soluble fiber at 0.90 kg ($n= 6$).

Serum chemistry and Glucose monitoring during late gestation

Blood samples were collected from 15 sows at 110 days of gestation to evaluate the effect of fiber during late gestation on serum chemistry. The treatments that were chosen for this measurement are control and the 0.91kg fiber top-dress. Blood samples were collected for 3 sampling periods: time 0, 2 and 4 (0 = before the first feed, 2 = 2 hours after the first feed, and 4 = 4 hours after the first feed). Blood samples were collected from the jugular vein while the sows were held by nose restraint snare. After collection, blood samples were centrifuged at 1,000 g for 12 minutes at room temperature to obtain serum which was frozen at -80 C° . Subsequently, samples were submitted to Antech Diagnostic Laboratory (Cary, NC) for analysis of serum chemistry using artificial intelligence software program. At the same points, glucose concentrations were determined in whole blood using a hand-held glucose meter (Precision Xtra, Abbott, CA, USA).

Farrowing monitoring through video equipment

Fetal expulsion length and piglet vitality index were evaluated using video equipment. Cameras (n= 15, 3 observations per treatment) were placed in one of the farrowing rooms the day sows were transferred from gestation to the farrowing house.

Piglet vitality index followed a scale adapted from Baxter et al. (2008). The vitality index scale consisted of the following: 0 = no movement, and no breathing (equivalent to a stillborn pig), 1 = no movement, but pig is attempting to breathe, 2 = moving, attempting to breathe, and/or coughing, and 3 = good movement, pig is breathing and able to stand within 1 min or less. For the piglets with index 1 and 2, measurement of the minutes these piglets took to stand on their own was included and the measurement started after the 1-minute evaluation for the piglet vitality index was completed.

Statistical analysis

Sow and litter performance were analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). The model included fixed effects of control, fiber source (insoluble, soluble) and level of supplementation (0.45, or 0.90 kg) during gestation, and the pre-farrowing period, and their interactions. Group of sows entering the farrowing house (8 groups of 24 to 30 sows per group), were considered as a random effect. Number of pigs born alive, number of stillborn pigs, piglet birth weight, number of low-birth weight (pigs weighing below 1 kg), number of weaned pigs, wean piglet weight and number of non-viable pigs at weaning (pigs weighing below 3.6 kg), were analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC).

Serum chemistry and glucose monitoring using a hand-held glucose meter was analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). The model included fixed effects of

control and fiber source (insoluble soluble) and level of supplementation (0, vs 0.90 kg) during gestation, sampling time, and their interactions.

Fetal expulsion length and piglet vitality index was treated as a pilot study due to the low number of sows per treatment (n= 3 sows per treatment) and analyzed with Proc Glimmix of SAS (9.4 SAS Inst. Inc., Cary, NC). The model included the birth interval between pigs (when possible), movement detection (within 1 minute and after 1 minute), fiber solubility, amount of top-dress (0.45 kg, and 0.90 kg) and control treatment. To detect if there was any relationship between movement detection and piglet vitality index, a MANOVA partial correlation matrix was calculated.

Least square means were reported and compared using multiple comparison test Tukey-Kramer and for the control treatment Dunnett's test was used to identify meaningful comparisons. Differences of $P \leq 0.05$ were considered significant. Tendencies were considered when $0.05 < P \leq 0.10$.

Results

Fiber solubility and level of supplementation of the top-dress did not affect sow body weight at placement in the farrowing rooms ($P = 0.32$), or at weaning ($P = 0.86$) (Table 3). Weaning-to-estrus interval ($P < 0.001$) was reduced by soluble fiber regardless of the level of supplementation and by insoluble fiber at 0.90 kg (4.77, 5.22, and 5 days, respectively) compared to the other treatments (6.51 days for control, and 6.59 days for insoluble fiber at 0.45 kg).

Number of pigs born per litter ($P = 0.39$) and piglet weight at birth ($P = 0.96$) were not affected by fiber solubility or level of supplementation. Number of stillborn pigs ($P = 0.03$) decreased for sows supplemented with insoluble fiber at 0.45 kg (1.04^b) compared with sows fed

insoluble fiber at 0.90 kg (1.82^a), whereas for control and soluble fiber at 0.45 and 0.90 kg were not different (1.52^{ab}, 1.52^{ab}, and 1.65^{ab}, respectively). However, insoluble fiber fed at 0.45 kg ($P=0.008$) increased the number of low-birth-weight piglets (1.31^a) compared with soluble fiber fed at 0.45 kg and 0.90 kg, insoluble fiber at 0.90 kg, and control (0.47^b, 0.40^b, 0.33^b and 0.50^b, respectively)

Number of pigs weaned per litter ($P=0.87$) and piglet weight at weaning ($P=0.34$) did not differ between treatments. But insoluble fiber at 0.45 kg increased ($P<0.001$) the number of non-viable pigs at weaning, whereas soluble fiber at 0.45 kg, had the lowest number of non-viable pigs at weaning (3.27^a vs 1.00^{bc}, respectively).

No differences were detected in glucose concentrations for sows measured in gestation at 110 days of gestation ($P=0.94$) and glucose concentrations did not differ when measured overtime ($P=0.96$) (Table 4).

Serum chemistry analytes (Table 5) were generally within expected range and did not differ between treatments with the exception of gamma-glutamyl-transferase (GGT) which was reduced by fiber regardless of the source ($P=0.003$) and on each sampling period ($P=0.02$) fiber treatments had lower values compared to control treatment. Magnesium resulted in a tendency ($P=0.09$) to increase by fiber supplementation and values of fiber increased with each sampling period relative to control ($P=0.004$). Blood urea nitrogen (BUN) fluctuated overtime ($P=0.001$) beginning with lower values for the first sampling period (6.13, 7.80, 5.80 mg/dL for control, insoluble, and soluble fiber at 0.90 kg, respectively) but remained constant during the sampling period 2 and 3 (6.5, 8.3, and 6.2 mg/dL in average for control, insoluble, soluble fiber at 0.90 kg), however no effect was detected for fiber relative or control ($P=0.58$). Triglycerides increased with each

sampling period for all treatments ($P < 0.05$) but were not affected by fiber composition or supplementation level compared to control treatment ($P = 0.56$).

For the fetal expulsion length, and piglet vitality index, 3 sows were removed due to sudden death during farrowing, severe complications during farrowing and loss of connection of video recording during farrowing. Therefore, observations for 12 sows were completed and presented here. The pilot evaluation for fetal expulsion length, and piglet vitality index did not reveal an effect of fiber influencing these variables compared to control (Table 6). Results from partial correlations (Table 7) suggested a negative relationship between the birth interval and piglet vitality index. Thus, at longer birth intervals (Figure 1), the piglet had a low vitality index, and it may manifest with the use of insoluble fiber (Figure 2) as it yielded more piglets with piglet vitality index of 1 (Figure 3).

Discussion

The period of late gestation or approximately the last 15 days of gestation are crucial for both the sow and the product of conception. The sow needs to be in optimal body condition, with a positive energy status to be able to support the exponential growth of the fetus, uterus and mammary gland, prepare for the onset of parturition, and produce colostrum and milk.

This current experiment focused on late gestation and the pre-farrowing period in providing the sow with fiber as a supplement provided in addition to the regular diet to improve performance during lactation but also to help the sow ease the parturition process, potentially reducing the risk of stillborn pigs.

Fiber supplementation lasted 18 ± 1 days on average. This is a longer period of supplementation compared to the studies described in chapter 4. Fiber solubility and level of

supplementation did not influence body weight of sows at placement in the farrowing rooms, and at weaning.

Weaning-to-estrus interval was positively affected by the soluble fiber irrespective of the level of supplementation, and by insoluble fiber when supplemented at 0.90 kg. Farmer et al. (1996), fed sows with high fiber during gestation and evaluated lactation performance, their findings reported a tendency to reduce the weaning-to-estrus interval for sows fed high fiber compared to their control sows. However, other investigations (Matte et al., 1994; Gourdine et al., 2004; Veum et al., 2009; Huang et al., 2020) where high fiber diets were provided to sows during gestation, reported that weaning-to-estrus interval did not change with fiber in gestation diets relative to the control treatments.

Although the physiological mechanism of how fiber may improve the weaning-to-estrus interval is unknown, it is well established that sows with a high body tissue mobilization during lactation results in low fat reserves at weaning which can delay mating of the sow after weaning (Thaker and Bilkei, 2005; Wientjes et al., 2013; Rosero et al., 2016) and it is closely related to low lactation voluntary intake (Eissen et al., 2003; Schenkel et al., 2010).

Fiber solubility and level of supplementation did not affect piglet birth weight or weaning weight. Insoluble fiber supplemented at 0.45 kg reduced the number of stillborn pigs per litter but increased the number of low-birth weight pigs (pigs weighing less than 1 kg) and increased the number of non-viable pigs at weaning (pigs weighing less than 3.6 kg). In contrast, insoluble fiber supplemented at 0.90 kg produced the highest number of stillborn pigs, but sows fed this treatment were able to produce quality litters at weaning by having the lowest number of non-viable pigs at weaning. Soluble fiber irrespective of the level of supplementation did not influence the number

of stillborn pigs or piglet weight at birth but had a lower number of non-viable pigs at weaning compared to the control treatment.

Improvements in litter performance when fiber is included in sow diets have been demonstrated previously (Che et al., 2011; Feyera et al., 2017). Our results suggests that fiber can improve the quality of litters at weaning, but the effects are linked to the type of fiber, and level of inclusion. It may take more than one reproductive cycle to begin observing consistent effects of fiber in sow and litter performance (Veum et al., 2009).

A normal farrowing is a process that typically takes between 4 to 6 hours (van Rens and van der Lende, 2004; van Dijk et al., 2005) for fetal expulsion, while an estimated time of 4 hours is expected for placenta expulsion (van Rens and van der Lende, 2004). There are several factors that influence farrowing duration such as environment (crate vs pen, Oliviero et al., 2008), age of parity, body condition of the sow, and feed intake during gestation. In addition, sows during late gestation can develop mild to severe constipation (Oliviero et al., 2010). Fiber seems to improve constipation scores, freeing the birth canal allowing for a faster farrowing (Oliviero et al., 2009; Tan et al., 2015).

Our study monitored parturition in sows, and we analyzed this as a pilot study only due to the low number of experimental units. We observed that fiber did not seem to reduce the fetal expulsion phase and it did not seem to improve piglet vitality at birth. Results from partial correlations are in agreement with other studies (Oliviero et al., 2010; Oliviero et al., 2013; Oliveira et al., 2020) where at prolonged farrowing or longer birth intervals between piglets, their chances of survival are reduced. Curiously, insoluble fiber had lower piglet vitality index, which may explain the increased number of low-birth weight pigs and number of stillborn pigs observed. However, these initial estimates should be considered very carefully, in light of the low number of

observations. Results of this pilot evaluation suggest feasibility and probability of success (Leon et al., 2011; Lee et al., 2014; Sim, 2019) of implementing fiber supplementation in a larger-scale scenario.

Farrowing duration is highly associated with stillborn rate and this in turn can be related to the concentration of glucose from the sow at parturition (Langendijk and Plush, 2019). Glucose is an energy source used for uterine contractions in addition to hormonal factors associated with parturition (Kaiser et al., 2018; Peltoniemi et al., 2020), and its availability is essential to prevent the sow from depleting energy reserves during farrowing (Oliveira et al., 2020; Nielsen et al., 2021).

Fiber has successfully demonstrated the ability to maintain a steady glucose concentration in gestating sows (Yde et al., 2011). But when the onset of farrowing is close, fiber has not been effective maintaining glucose status probably due to the high demand of glucose by the fetus and the decrease in insulin sensitivity that is developed in late gestation (Père and Etienne, 2000). In our study, glucose concentrations measure using a hand-held glucose meter did not change over time at 112 days of gestation, and the results from the serum chemistry analysis were consistent with the glucose meter results indicating that fiber was not able to maintain steady glucose concentrations as it did not differ from the control sows. Our findings are in agreement with Loisel et al. (2013), reporting no differences in plasma glucose at day 112 of gestation when sows received a high fiber and low fiber diet (23.4 % and 13.3 % TDF) from day 91 of gestation until farrowing. Quesnel et al. (2009), showed glucose fluctuations overtime on sows fed a control and high fiber diet (2.8 % and 11 % crude fiber) from day 26 of gestation until farrowing. The sows were sampled from day 109 of gestation until farrowing but were not influenced by fiber. Similarly, Hansen et al., (2012) did not show significant changes in glucose during the transition

period when sows were sampled from day 108-112 of gestation for sows fed a standard and three high fiber diets (17.1 %, 32.3%, 36.7% and 40% dietary fiber, respectively) from mating until day 108 of gestation.

Results from the serum chemistry analysis were within expected ranges (Verheyen et al., 2007) and most of the analytes were not statistically different except for GGT and a trend to increase magnesium. While there was a time of sampling effect for BUN and triglycerides, they were not influenced by fiber supplementation. GGT is used as an indicator of liver disease and it is usually evaluated together with ALT (Leonard et al., 1984; Lee et al., 2004). This may indicate that fiber, independent of the source used in this experiment, contributes to the optimum functioning of the liver during the transition of gestation to farrowing. The liver is the central organ for many metabolic functions and one of them includes milk and colostrum synthesis (Theil, 2015). The neonate piglet utilizes colostrum fat as their energy source post-partum (Metzler-Zebeli, 2021), as it contains lipids (Nuntapaitoon, 2022) and milk fat provide essential fatty acids to the suckling piglet (Burrin et al., 1992; Reshef et al., 2003; König et al., 2012).

In conclusion, fiber solubility and level of supplementation did not influence sow body weight at placement in farrowing and at the end of lactation. However, soluble fiber regardless of the level of supplementation together with insoluble fiber at 0.90 kg, decreased the weaning-to-estrus interval of sows compared to sows receiving the control and insoluble fiber at 0.45 kg treatments.

Insoluble fiber provided at 0.45 kg decreased the number of stillborn pigs, but also increased the number of low-birth weight pigs. Whereas insoluble fiber provided at 0.90 kg, increased the number of stillborn pigs, but decreased the number of non-viable pigs at weaning compared to the rest of the treatments.

Soluble fiber irrespective of the level of supplementation did not cause negative effects on piglet performance during lactation and had a reduced number of non-viable pigs at weaning compared to control and insoluble fiber at 0.45 kg. This suggests that insoluble fiber when provided at 0.90 kg and soluble fiber (regardless of the level provided) have the potential to improve litter weight uniformity at weaning, and to improve the weaning-to-estrus interval.

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Table 1

Calculated and analyzed composition of insoluble and soluble top-dress pelleted supplement for gestation and the pre-farrowing period

Item	No Top-dress ¹	Insoluble pellet		Soluble pellet	
	0	0.45kg	0.90kg	0.45kg	0.90kg
Gestation					
Composition, %					
TDF	12.00	34.91	34.91	34.92	34.92
Soluble Fiber	1.07	4.18	4.18	9.63	9.63
Insoluble Fiber	7.93	30.73	30.73	25.25	25.25
InSol:Sol Fiber	7.41	7.35	7.35	2.62	2.62
Estimated intake, g/d²					
TDF	272.23	430.64	589.06	430.66	589.09
Soluble Fiber	24.27	43.25	62.22	67.96	111.64
Insoluble Fiber	179.90	319.34	458.77	294.44	408.98
InSol:Sol Fiber	7.41	7.38	7.37	4.33	3.66
Pre-farrowing					
Composition, %					
TDF	11.3	34.91	34.91	34.92	34.92
Soluble Fiber	1.49	4.18	4.18	9.63	9.63
Insoluble Fiber	9.80	30.73	30.73	25.25	25.25
InSol:Sol Fiber	6.58	7.35	7.35	2.62	2.62
Estimated intake, g/d³					
TDF	256.35	414.76	573.18	414.78	573.21
Soluble Fiber	33.80	52.78	71.75	77.49	121.17
Insoluble Fiber	222.32	361.76	501.20	336.86	451.41
InSol:Sol Fiber	6.58	6.85	6.99	4.35	3.73
Analyzed composition, as is basis					
NDF, %		32.18	32.40	28.15	28.41
ADF, %		17.23	17.43	15.09	14.95
TDF, %		38.88	38.76	35.54	34.98
Soluble TDF, %		0.27	0.20	2.10	2.52
Insoluble TDF, %		38.65	38.55	33.32	32.17
Crude protein, %		12.54	12.97	12.58	12.67
Moisture, %		12.32	12.15	11.46	11.45
Crude fat, %		3.89	3.92	4.03	3.88
Crude fiber, %		14.04	13.72	11.50	10.76
Ash, %		3.89	3.84	4.93	4.92

Table 1. (Continued).

¹Estimated intake of fiber for the gestation diet when consumed at 2.27 kg, and estimated intake of fiber for the lactation diet when consumed at 2.72 kg/d.

²Estimated intake of fiber for the gestation diet plus the contribution from the top-dress.

³Estimated intake of fiber for the lactation diet plus the contribution from the top-dress.

Table 2

Formulation of insoluble and soluble top-dress

Top-dress product¹			
Insoluble		Soluble	
Fiber ingredients	Inclusion %	Fiber ingredients	Inclusion %
Soybean hulls	32	Soybean hulls	0
Sugar beet pulp	0	Sugar beet pulp	45
Wheat middlings	44	Wheat middlings	38
Corn	23	Corn	16
Color-yellow	0.05	Color-yellow	0.05
Soy oil	0.95	Soy oil	0.95

¹Top-dress supplement was manually fed during late gestation (15 ± 1 d). At the transfer to lactation facility, treatments were continued until farrowing (3 ± 1 d).

Table 3

Effect of fiber solubility during late gestation and the pre-farrowing period on sow and litter performance

Item	Treatments ¹					SEM	P-values
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹		
Sows, n ²	50	49	49	47	46		
BCS at day 90 of gestation	3.62	3.55	3.57	3.49	3.63	0.11	0.91
*BW at placement, kg ³	248.76	265.36	275.54	264.36	258.54	20.09	0.32
Number of pigs born per litter	14.54	13.42	13.29	13.26	13.70	0.53	0.39
*Piglet weight at birth, kg ⁴	1.82	1.63	1.67	1.72	1.70	0.41	0.96
Number of stillborn pigs per litter	1.52 ^{ba}	1.04 ^b	1.82 ^a	1.51 ^{ba}	1.65 ^{ba}	0.18	0.03
*Low-birth weight pigs (below 1 kg) ⁵	0.50 ^b	1.31 ^a	0.33 ^b	0.47 ^b	0.40 ^b	0.19	0.008
Litter weight at birth, kg ⁴	25.87	24.73	21.29	23.17	23.37	5.91	0.81
Number of pigs weaned per litter	10.78	11.02	10.46	11.15	10.98	0.48	0.87
*Piglet wean weight, kg ⁴	4.50	5.80	5.09	4.85	5.03	0.96	0.34
*Small weaned pigs (below 3.5 kg) ⁵	3.31 ^a	3.27 ^a	0.53 ^c	1.00 ^{bc}	2.00 ^{ab}	0.36	<0.001
*Litter weight at wean, kg ⁴	47.40	64.40	52.22	55.95	54.17	11.13	0.22
*Sow BW at weaning, kg	221.43	229.33	233.10	227.03	219.71	21.63	0.86
Lactation length, d	22.34	21.91	21.88	22.81	22.31	0.30	0.17
Weaning-to-estrus-interval, days ⁶	6.51 ^a	6.59 ^a	5.00 ^b	4.77 ^b	5.22 ^{ba}	0.37	0.003

¹Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.²Values represent least square means for n sows for sow and litter performance at placement and at birth. The experiment was conducted from July-September 2021.³Sow BW was measured prior entering the farrowing room (112 ± 1 d).

Table 3. (Continued).

⁴ Piglet weight at birth and weaning was measured for each individual pig, the results were analyzed by litter and presented as means of each treatment.

⁵Number of piglets per litter.

*A subset of 73 sows and their litters were weighed to obtain birth and litter weights. Values are reported as least square means.

Table 4

Glucose estimation during farrowing measured using a hand-held glucose meter

Item	Treatments ¹			SEM
	Control	Insol + 0.90 kg ¹	Sol + 0.90 kg ¹	
Sows, n ²	3	3	3	
Mean glucose concentration (mg/dL)	69.25	66.93	66.93	5.88
Glucose concentration at 0 hours (mg/dL)	63.76	65.00	63.22	11.00
Glucose concentration at 2 hours (mg/dL)	69.80	66.00	63.38	6.67
Glucose concentration at 4 hours (mg/dL)	74.20	69.80	74.20	6.00

¹ Insol + 0.90= Insoluble fiber w/0.90 kg; Sol + 0.90= Soluble fiber w/0.90 kg.

² Values represent least square means for n sows.

Fiber treatments were not different from each other P= 0.94.

No influence of glucose concentration overtime P= 0.96.

Table 5

Effects of fiber solubility during late gestation in sow serum chemistry

Item ²	Treatments ¹			SEM	P-value
	Control	Insol + 0.90 kg ¹	Sol + 0.90 kg ¹		
Sows, n ³	5	5	5		
Total Protein (g/dL)	6.09	6.09	6.01	0.13	0.90
Albumin (g/dL)	3.24	3.26	3.15	0.11	0.78
Globulin (g/dL)	2.84	2.83	2.86	0.12	0.98
A/G Ratio	1.14	1.16	1.11	0.07	0.91
AST (SGOT) (IU/L)	21.39	19.53	21.60	3.61	0.90
ALT (SGPT) (IU/L)	26.65	30.47	34.85	2.66	0.13
Alk Phosphatase (IU/L)	231.09	122.47	313.93	69.57	0.19
GGT (IU/L)	44.02 ^a	39.20 ^{ba}	32.20 ^b	1.90	0.003
BUN (mg/dL)	6.38	8.13	6.07	1.03	0.34
Creatinine (mg/dL)	2.58	2.55	2.27	0.16	0.33
BUN/CREAT Ratio	2.54	3.20	2.73	0.44	0.58
Phosphorus (mg/dL)	6.29	6.31	6.30	0.19	0.99
Glucose (mg/dL)	74.17	69.13	77.40	3.92	0.35
Calcium (mg/dL)	9.50	9.23	9.44	0.13	0.32
Magnesium (mEq/dL)	1.65	1.81	1.85	0.06	0.09
Sodium (mEq/dL)	141.77	141.07	141.20	0.95	0.86
Potassium (mEq/dL)	5.46	5.44	5.33	0.20	0.88
NA/K Ratio	26.05	26.13	26.73	0.91	0.85
Chloride (mEq/dL)	103.54	102.27	101.40	0.87	0.26
Cholesterol (mg/dL)	63.15	60.67	70.20	5.03	0.41
Triglyceride (mg/dL)	63.74	71.46	77.93	9.16	0.56
Amylase (IU/L)	1192.88	1307.47	873.00	150	0.15
PrecisionPSL (IU/L)	7.20	7.00	7.20	0.57	0.96
CPK (IU/L)	989.28	776.33	1502.93	385.46	0.42

¹Insol + 0.90= Insoluble fiber w/ 0.90kg; Sol + 0.90= Soluble fiber w/0.90 kg.²A/G= albumin/globulin ratio; AST= aspartate aminotransferase; ALT= alanine aminotransferase; GGT= gamma-glutamyl transferase; BUN= blood urea nitrogen; BUN/CREAT= blood urea nitrogen/creatinine ratio; Precision PSL= precision pancreas-specific-lipase; CPK= creatine phosphokinase³ Values represent least square means for n sows and includes all sampling periods

*GGT, time of sampling effect (P= 0.02)

*BUN, time of sampling effect (P= 0.001)

*Triglyceride, time of sampling effect (P= 0.01)

Table 6

Exploratory analysis of fiber effect on fetal expulsion length and piglet vitality index

Item	Treatments ¹					SE
	Control	Insol + 0.45 kg ¹	Insol + 0.90 kg ¹	Sol + 0.45 kg ¹	Sol + 0.90 kg ¹	
Sows, n ²	3	3	3	2	1	
Individual pigs ³	35	43	44	16	13	
Fetal expulsion, hrs.	3.86	5.43	8.29	5.82	11.01	2.42
PVI ⁴	2.32	2.03	2.11	2.36	1.92	0.27

¹ Insoluble fiber w/ 0.45kg; Insoluble fiber w/ 0.90kg; Soluble fiber w/ 0.45kg; Soluble fiber w/0.90 kg.

²Values represent least square means for n sows.

³Number of individual pigs recorded during birth per treatment.

⁴Piglet vitality index: 0= no movement, no breathing; 1= no movement but pig is attempting to breathe; 2= moving, attempting to breathe, coughing; 3= good movement, pig is breathing and able to stand within 1 minute or less.

Table 7

Partial correlation matrix coefficients of movement detection, born alive, PVI, birth interval, and fetal expulsion

	Move detect s¹	BA²	PVI³	B_interv⁴	Fetal_ex (hrs)⁵
Move detect s	1.00	0.16	-0.08	-0.02	0.07
		0.06	0.34	0.83	0.39
BA	0.16	1.00	0.15	-0.07	0.04
	0.06		0.07	0.39	0.63
PVI	-0.08	0.15	1.00	-0.24	-0.53
	0.34	0.07		0.00	<.0001
B_interv	-0.02	-0.07	-0.24	1.00	0.40
	0.83	0.39	0.00		<.0001
Fetal_ex (hrs)⁵	0.07	0.04	-0.53	0.40	1.00
	0.39	0.63	<.0001	<.0001	

¹Movement detection (seconds).

²Born alive.

³Piglet vitality index: 0= no movement, no breathing; 1= no movement but pig is attempting to breathe; 2= moving, attempting to breathe, coughing; 3= good movement, pig is breathing and able to stand within 1 minute or less.

⁴Birth interval.

⁵Fetal expulsion (hrs).

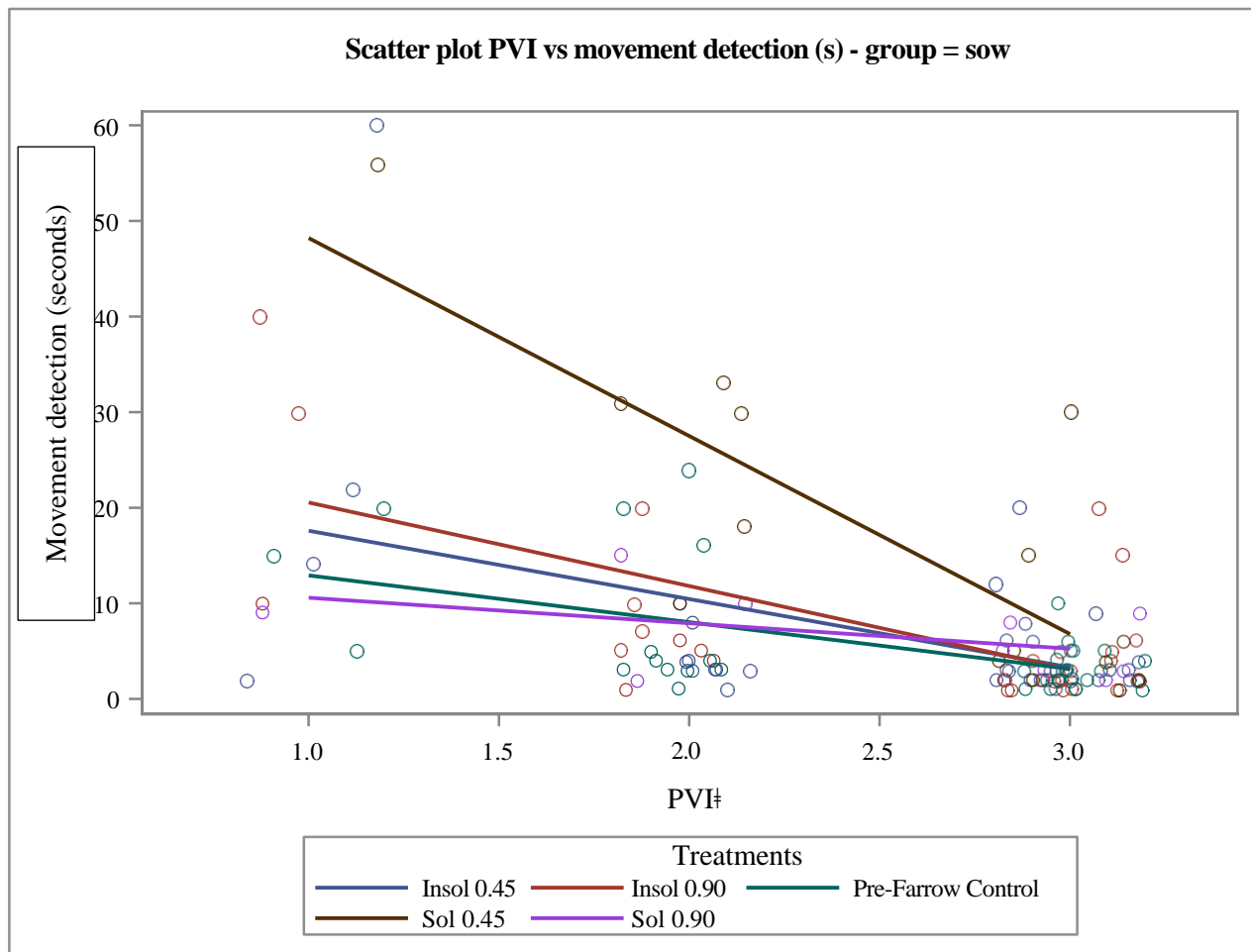


Figure 1. Scatter plot by sow of piglet vitality index vs movement detection (seconds)
 *Insoluble fiber w/ 0.45 kg; Insoluble fiber w/ 0.90 kg; Pre-farrow control; Soluble fiber w/ 0.45 kg; Soluble fiber w/ 0.90 kg
 #Piglet vitality index: 0= no movement, no breathing; 1= no movement but pig is attempting to breathe; 2= moving, attempting to breathe, coughing; 3= good movement, pig is breathing and able to stand within 1 minute or less

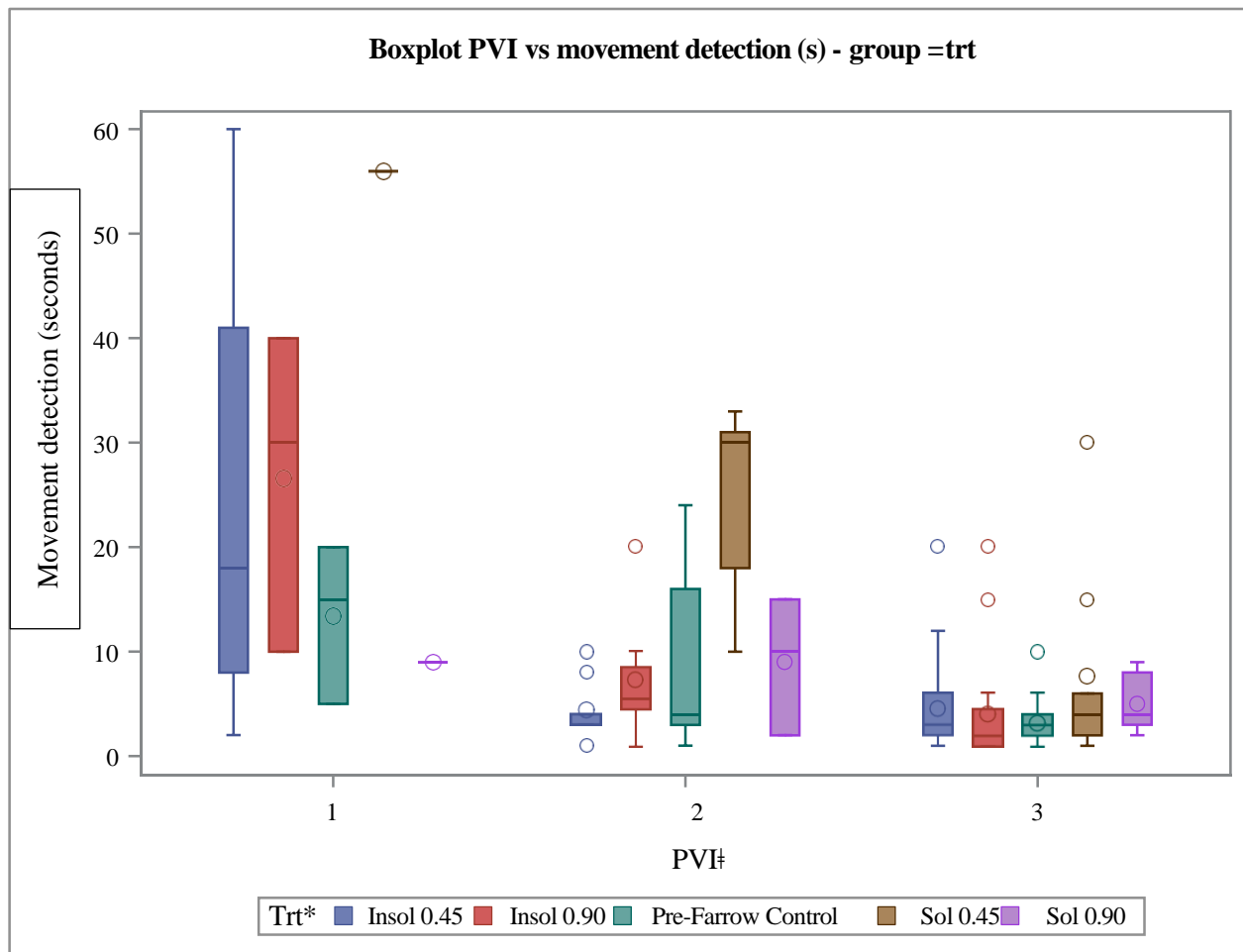


Figure 2. Boxplot plot of piglet vitality index vs movement detection (seconds) by treatment
 *Insoluble fiber w/ 0.45 kg; Insoluble fiber w/ 0.90 kg; Pre-farrow control; Soluble fiber w/ 0.45 kg; Soluble fiber w/ 0.90 kg
 ‡Piglet vitality index: 0= no movement, no breathing; 1= no movement but pig is attempting to breathe; 2= moving, attempting to breathe, coughing; 3= good movement, pig is breathing and able to stand within 1 minute or less

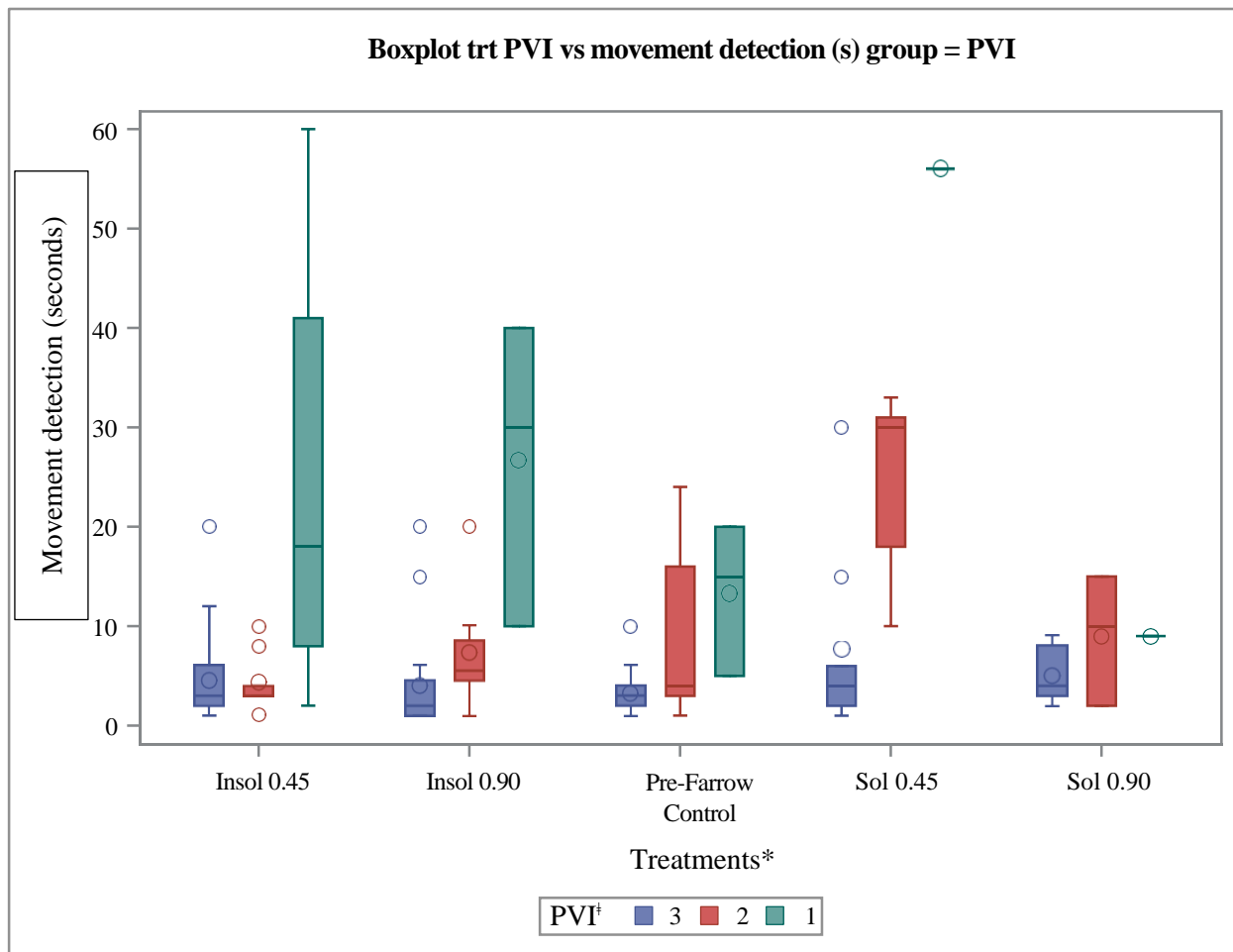


Figure 3. Boxplot plot of treatment piglet vitality index vs movement detection (seconds)
 *Insoluble fiber w/ 0.45 kg; Insoluble fiber w/ 0.90 kg; Pre-farrow control; Soluble fiber w/ 0.45 kg; Soluble fiber w/ 0.90 kg
 ‡Piglet vitality index: 0= no movement, no breathing; 1= no movement but pig is attempting to breathe; 2= moving, attempting to breathe, coughing; 3= good movement, pig is breathing and able to stand within 1 minute or less