

Effects of essential fatty acids and branched-chain amino acids in lactation diets on sow and litter performance

by

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AN ABSTRACT OF A DISSERTATION

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Abstract

This dissertation is comprised of 5 chapters consisting of a review of literature on branched-chain amino acids (BCAA) in lactation diets, a meta-regression analysis to evaluate the effects of BCAA on sow and litter growth performance, evaluation of the effects of essential fatty acids (EFA) in lactating sow diets on sow reproductive performance, colostrum and milk composition, and piglet survivability, supplementation of fat sources and pre-farrow EFA intake on lactating sow performance and EFA status, and the effects of increasing soybean meal in corn-based diets on growth performance of late finishing pigs. Chapter 1 presents a review of the literature on the effects of BCAA on sow mammary gland metabolism, colostrum and milk composition, and sow and litter performance. Chapter 2 describes a meta-regression analysis conducted to evaluate the effects of BCAA and their interactions in lactating sow diets to predict litter growth performance, sow bodyweight change, and sow feed intake. The results suggest that Ile, Leu, and Val play an important role in litter growth, sow bodyweight change, and sow feed intake during lactation; however, the influence of BCAA on these criteria is much smaller than that of other dietary components such as net energy, SID Lys, sow average daily feed intake, and crude protein. In Chapter 3, mixed-parity sows and their litters were used to evaluate the effects of EFA intake on sow reproductive performance, piglet growth and survivability, and colostrum and milk composition. Overall, sows consuming high EFA produced litters with heavier piglet weaning weights and greater litter average daily gain (ADG) when compared to litters from sows fed diets with low EFA. However, there was no impact of sow EFA intake on piglet survivability or subsequent sow reproductive performance. Chapter 4 describes a study evaluating the effects of supplemental fat sources and pre-farrow EFA intake on lactating sow and litter performance and EFA composition of colostrum, milk, and adipose tissue. The results suggest that providing

dietary fat sources with high concentrations of EFA can increase colostrum linoleic acid and α -linolenic acid concentrations that are maintained throughout lactation. However, the changes in colostrum and milk composition did not alter litter growth performance in this experiment.

Lastly, Chapter 5 presents three experiments that were conducted to determine the effects of increasing soybean meal levels in replacement of feed-grade amino acids in corn-based diets on growth performance of late finishing pigs raised in commercial facilities. The combined results of the three experiments suggest that inclusion at least 4 to 8% dietary SBM at the expense of feed-grade amino acids in corn-based diets with or without grain co-products can improve growth performance of late-finishing pigs.

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Dedication

This dissertation is dedicated to my parents, Douglas and Kimberly.

Preface

This dissertation is original work completed by the author, J. P. Holen. All chapters were formatted for publication according to the required standards of the Journal of Animal Science and Translational Animal Science.

Chapter 1 - A review of branched-chain amino acids in lactation diets on sow and litter growth performance

ABSTRACT

Branched-chain amino acids (BCAA) are three essential amino acids (AA) for lactating sows; however, the effects of dietary Leu, Val, and Ile on sow and litter performance within the literature is equivocal. The BCAA are structurally similar and share the first steps of their catabolism pathway where Leu, Val, and Ile are transaminated through BCAA aminotransferase and irreversibly decarboxylated by the branched-chain α -ketoacid dehydrogenase complex. Although these steps are shared among BCAA, Leu is recognized as the primary stimulator due to Leu's greater affinity towards the enzymes compared to Val and Ile. Since the late 1990's, sows are producing larger and heavier litters and generally consume diets with greater concentrations of Leu and crystalline AA, which may create imbalances among dietary BCAA. Research conducted with growing-finishing pigs confirms that high concentrations of Leu can impair BCAA utilization and growth performance. However, the effects of BCAA on lactating sow and litter performance are not as clearly understood. Within mammary tissue, BCAA uptake is greater than milk output of BCAA since Val, Ile, and Leu are catabolized to form non-essential AA, lactose, fatty acids, and other metabolites. Within the mammary gland, BCAA aminotransferase activity is much higher than within skeletal muscle, liver, or small intestine. Thus, competition among the BCAA, namely between Leu and Val, can significantly inhibit Val uptake within mammary tissue. Therefore, dietary modifications that mitigate BCAA competition may positively influence Val utilization for colostrum and milk synthesis. Little data exists on Ile and Leu requirements for modern lactating sows. Although Val requirements have been extensively researched in the last 25 years, an ideal Val:Lys has not been consistently

established across experiments. Some studies concluded that total Val concentrations above 120% of Lys optimized performance whereas others determined that increasing SID Val:Lys from 55 to 136% did not improve piglet growth performance. Although increasing dietary Val positively influences fat and protein composition of colostrum and milk, litter growth during lactation is not always positively affected. Given the competition among BCAA for utilization within mammary tissue, research evaluating the Leu and Ile requirement of modern lactating sows is warranted to fully understand the influence and interactions of BCAA on reproductive and litter growth performance.

Key words: branched-chain amino acids, lactation, litter performance, sow

INTRODUCTION

Structural similarities among the branched-chain amino acids (BCAA) necessary for lactating sow milk protein synthesis can create instances of antagonism and impaired utilization. Leucine, Ile, and Val share the first step of the catabolism pathway where branched-chain amino acid aminotransferase (BCTA) reversibly transaminates the BCAA to their respective α -keto acids. These α -keto acids may then be irreversibly decarboxylated through the branched-chain α -ketoacid dehydrogenase (BCKD) enzyme to produce ketogenic and glucogenic products for utilization in the TCA cycle.

High levels of Leu are commonly present in lactation diets that include corn and corn co-products (NRC, 2012) and thus, utilization and availability of the other BCAA may be impaired. In growing-finishing pigs, BCAA utilization and growth performance declined when diets contained increasing Leu:Lys ratios above 100% of the Leu requirement (Kwon et al., 2019). Furthermore, Cemin et al. (2019) confirmed that increasing Leu:Lys negatively affected growth performance of growing-finishing pigs due to imbalanced Val, Ile, and large neutral amino acids

(LNAA) such as Trp. However, supplemental feed-grade L-Val and L-Ile can mitigate unbalanced BCAA scenarios in diets with high levels of Leu such that growth performance of pigs may be maintained (Kerkaert et al., 2021). This practice has continued to be actively researched and applied for growing-finishing pigs, however, the relationship among BCAA on sow reproductive and litter growth performance is not clearly understood. Amino acid requirements for the lactating female must support milk production for litter growth. Furthermore, metabolism of BCAA within the sow's mammary gland for milk protein synthesis must be considered. The objective of this review is to summarize the current literature on BCAA metabolism on mammary development, colostrum and milk composition, and litter growth performance.

BRANCHED-CHAIN AMINO ACID METABOLISM

Metabolism of Ile, Leu, and Val begins after dietary consumption, absorption, and transport from the liver to skeletal muscle for degradation (Harper et al., 1984). These three BCAA share the first step of catabolism where BCTA reversibly transaminates Ile, Leu, and Val to the α -ketoacids α -keto- β -methylvalerate, α -ketoisocaproate, and α -ketoisovalerate, respectively. This catabolism step also forms glutamate that can be used for transformation to glutamine and alanine for protein synthesis. After transamination, the α -ketoacids are decarboxylated through the BCKD enzyme in the liver, which is an irreversible process. The final glucogenic and ketogenic products of these catabolism steps include succinyl-CoA and acetyl-CoA for utilization in the TCA cycle for energy production.

Each degradation step is shared among the BCAA and any of the three BCAA can stimulate the catabolism pathway described above. However, Leu is recognized as the primary stimulator of BCTA and BCKD due to Leu's greater affinity towards these enzymes compared to

Val and Ile (Harper et al., 1984). Leucine has also been recognized to stimulate protein synthesis through activation of the mTOR signaling pathway within skeletal muscle (Zhang et al., 2017) and for the detection of nutrient and hormone signals from the GI tract to the brain to regulate feed intake (Cota et al., 2006). Additionally, BCAA share brain transporters with other LNAA such as Trp, Thr, Phe, and Tyr (Pardridge, 1977). The ingestion of BCAA and subsequent catabolism creates competition among the BCAA and other LNAA at the blood-brain barrier that can influence transport of LNAA to the brain (Fernstrom, 2005). When a mixture of LNAA including the BCAA is consumed, the conversion of Trp for serotonin activity within the brain may be reduced, which could lead to instances of reduced feed intake (Fernstrom, 2013). Decreased feed intake responses may also be linked to nutrient sensing along the intestinal epithelium. Tian et al. (2019) observed that L-Leu, L-Ile, or a combination of BCAA each stimulated expression of the taste dimeric receptor type 1-member 1/3 (T1R1/T1R3) along the jejunum and increased secretion of cholecystinin (CCK), a hormone responsible for satiety, in an in vitro porcine model. Furthermore, as stated in a review conducted by Cemin et al. (2019), excess Leu can negatively influence growth performance of growing-finishing pigs if dietary Ile, Val, or LNAA such as Trp are not also considered. However, the relationship of BCAA and LNAA such as Trp on lactating sow performance is not well understood.

BRANCHED-CHAIN AMINO ACIDS AND SOW MAMMARY GLAND METABOLISM

There are three phases of rapid mammary gland development for the sow, two of which include the last third of gestation and lactation where nutritional strategies may be implemented to modify colostrum and milk composition (Farmer and Hurley, 2015). Each of the sow mammary glands are distinct with epithelial cells that line alveoli for colostrum and milk

synthesis. To satisfy the lactation requirements for milk protein synthesis, the sow mammary gland utilizes large amounts of free AA available in blood plasma (Rezaei et al., 2016). Within mammary tissue, BCAA uptake is much greater than BCAA output in milk. Valine, Ile, and Leu are catabolized to form non-essential amino acids such as glutamine and alanine, lactose, fatty acids, and other metabolites (Trottier et al., 1997; Li et al., 2009; Lei et al., 2012a). To support milk production under instances of insufficient nutrient or AA intake, the sow must mobilize adipose and skeletal muscle tissue (Jones and Stahly, 1999; Shennan and Peaker, 2000). Additionally, AA uptake from plasma may be upregulated to support milk protein synthesis, however, concentrations of Val and Ile within plasma continue to decrease as lactation progresses (Chen et al., 2018). As lactation progresses and sow body tissue mobilization occurs, concentrations of BCAA within skeletal muscle have been observed to decrease beyond levels initially established pre-partum (Clowes et al., 2005).

Uptake of AA from circulating blood by mammary epithelial cells is influenced by plasma AA concentrations, tissue flux, and AA metabolism for utilization (Rezaei et al., 2016). However, scenarios of AA deficiency or imbalances can alter efficiency and utilization within the mammary gland as necessary for milk production. In one of the first studies to evaluate AA uptake in the modern lactating sow, Trottier et al. (1997) determined that the uptake of AA, especially the BCAA, exceeded milk output of each AA and suggested that there may be biological requirements for mammary gland utilization. Transport of AA within epithelial cells dictate the intracellular availability and potential retention of AA for milk protein synthesis. In bovine mammary epithelial cells, exposure to increasing Leu can increase synthesis of non-essential AA such as alanine, aspartate, glutamate, glutamine, and asparagine (Lei et al., 2012b). Furthermore, competition among the BCAA, namely between Leu and Val, can significantly

inhibit uptake of Val within mammary tissue (Jackson et al. 2000). Thus, dietary modifications to account for competition among the BCAA may positively influence Val or other BCAA utilization by the mammary gland. In a study conducted by Che et al. (2019), providing diets with increasing Val:Lys from 57 to 85% in late gestation increased mammary epithelial cell proliferation and protein synthesis through stimulation of the mTOR pathway, regardless of identical dietary Ile:Lys and Leu:Lys for lactating sows.

Branched-chain amino acid aminotransferase activity within the lactating sow mammary gland is much higher than activity within skeletal muscle, liver, or the small intestine (2.36 vs. 0.66, 0.37, and 0.74 nmol/mg protein per minute, respectively) and 60% of the transaminated BCAA were decarboxylated (Li et al., 2009). Furthermore, glutaminase activity within the mammary gland was not detected. As a result, it is critical to recognize and consider the highly active BCAA catabolism steps within the sow mammary tissue that produce acetyl-CoA from Leu and Ile and succinyl-CoA from Ile and Val. These end-products can subsequently be used for fatty acid synthesis or formation of non-essential AA, such as glutamine, to be excreted in milk.

Changes in the sows' physiological state can also influence AA transport and utilization within the mammary gland. Evaluation of plasma AA pre- and post-partum confirm that most AA including Lys, Met, Thr, and the BCAA increased significantly when the sow transitions from pregnancy to lactation (Chen et al., 2018). However, plasma levels of free AA are not maintained throughout lactation to d 17. As the sow advances in days of lactation, she may mobilize protein tissue to maintain milk synthesis within mammary glands through peak lactation (NRC, 2012; Tokach et al., 2019). To limit mobilization of skeletal muscle and

optimize utilization of dietary AA intake for milk protein synthesis, competition, and catabolism among the BCAA within mammary tissue must be considered.

EFFECTS OF BRANCHED-CHAIN AMINO ACIDS ON SOW COLOSTRUM AND MILK COMPOSITION

Recently, studies have evaluated the influence of BCAA on colostrum composition, which may aid the interpretation of discrepancies among recent BCAA sow and litter growth performance research. Of the three BCAA, Val has been established as the most efficiently transported and utilized amino acid by the mammary gland (Manjarin et al., 2012). Additionally, Val is often recognized as a limiting amino acid for lactating sows (Kim et al., 2001; Soltwedel et al., 2006; Kim et al., 2009), confirming the importance of Val for milk synthesis. However, modifications in BCAA catabolism under varying dietary conditions with excess Leu or limited Ile may influence Val utilization for milk synthesis and subsequent litter growth.

Initial research conducted by Richert et al. (1997b) and Moser et al. (2000) evaluated the interactive effects of Val, Ile, Leu, and total BCAA on both litter growth performance and milk composition. Despite linear increases in dietary Val that improved litter weight gain, there were no reported effects of Val, Val \times Ile, or total BCAA concentrations on milk protein or lactose concentrations (Richert et al., 1997b; Table 1). Although there were no statistical effects of Val, increases of dietary Val from 0.72 to 1.42% appeared to linearly increase milk fat composition. Additionally, increased dietary Ile linearly increased milk protein and fat concentrations. These modifications to milk composition may have supported the author's observed advantage in litter gain during lactation. Moser et al. (2000) also observed linear improvements of increasing Val on litter growth performance. However, this advantage

was not supported by modifications to milk composition as the authors reported no influence of Val, Ile, Leu, or total BCAA on milk protein, fat, or lactose composition (Table 2).

Recently, a study conducted by Xu et al. (2017) reported significant improvements in litter weight gain as SID Val:Lys ratios increased from 63 to 123% and observed linear increases in concentrations of essential amino acids within both colostrum and milk. Sows within this study began consuming assigned lactation Val treatments on d 107 of gestation, resulting in potential changes in mammary gland amino acid utilization in the week leading up to farrowing. This might have altered colostrum amino acid composition and then maintained a similar amino acid composition in subsequent milk collected through the rest of the 28-d lactation period. Another study conducted by Che et al. (2019) evaluated the effects of supplementing Val from d 85 of gestation on protein synthesis of colostrum. In this study, gilts consumed diets with either 0.71% Val (0.57:1.00 Val:Lys) or 1.07% Val (0.87:1.00 Val:Lys). Gilts consuming diets with 1.07% Val produced colostrum with increased protein, fat, lactose, and non-fat solids. In a similar study evaluating effects of Val in late gestation, Che et al. (2020) observed linear increases in colostrum protein, fat, and non-fat solids as dietary Val increased from 0.63% to 0.93% total Val:Lys. The authors also observed linear improvements in piglet weaning weights and average daily gain. The consistently observed modifications to colostrum and milk fat and protein composition due to increasing dietary Val in late gestation with potential to carry over to lactation may explain some of the benefits in reported litter growth performance.

As the BCAA are decarboxylated by BCKA, the carbon skeletons are incorporated into the TCA cycle for energy production. Due to the role of BCAA in energy production and subsequent lipid metabolism of the mammary gland, a study was conducted to evaluate the effects of increasing total BCAA in high-fat (8.0%) lactation diets fed to sows from d 107 of

gestation through weaning (Ma et al., 2020). Diets contained similar ratios of Leu:Ile:Val at 2:1:1.5, but increased total BCAA concentrations from 2.85 to 3.24%. Increasing dietary Leu, Ile, and Val from 1.38 to 1.49, 0.62 to 0.68, and 0.85 to 1.07%, respectively, significantly increased fat concentration of colostrum but did not influence CP or lactose concentrations in colostrum or in milk collected on d 12 and 18 of lactation. Increased supplementation of BCAA to the high fat diets also increased total fatty acid content of colostrum. Additionally, litter weaning weights and litter ADG increased with increasing total dietary BCAA content, regardless of the same 2:1:1.5 ratios of Leu:Ile:Val. These results and those mentioned previously indicate that total BCAA can alter both the amino acid composition of colostrum and the fatty acid profile of colostrum in a manner that supports enhanced litter growth. Propionyl-CoA, the substrate produced by Val and Ile after the BCKD catabolism process, can increase circulating endogenous odd-chain fatty acids in mice (Bishop et al., 2020). Although the effects of BCAA on lipid metabolism in lactating sows has not yet been evaluated, colostrum fatty acid composition may be altered if Leu, Val, or Ile influence uptake of circulating fatty acids in mammary tissue. Therefore, it may be important to consider the interactions of energy and amino acid metabolism when evaluating the effects of any or all BCAA on sow reproductive and litter growth performance.

EFFECTS OF BRANCHED-CHAIN AMINO ACIDS ON SOW AND LITTER PERFORMANCE

Little research has been recently conducted to establish the BCAA requirements for modern, high producing females. Current requirement estimates from the NRC (2012), Brazilian Tables for Poultry and Swine (2017), PIC Nutrition Guidelines (2020), and Danish Nutrient Standards (2020) for BCAA are presented in Table 3. Branched-chain amino acid requirements

are variable among nutrition guideline sources, with SID AA:Lys ratios ranging from 0.64 to 0.85 for Val, 0.56 to 0.60 for Ile, and 1.02 to 1.15 for Leu (NRC, 2012; Rostagno et al., 2017; PIC, 2020; Tybirk et al., 2020). The variability among sources is likely a reflection of data availability at the time of publication and interpretation of the data available.

Relatively little data exists on the Ile and Leu requirement of modern lactating sows and literature on these requirements are not reported in the NRC (2012). In contrast, Val requirements of lactating sows have been extensively researched in the last 25 years, but conclusions across studies were equivocal. Initial evaluation of Val requirement studies evaluated total Val:Lys ratios were not consistent among litter growth characteristics with Richert et al. (1996; 1997a,b) and Moser et al. (2000) observing improvements in litter gain when diets contained 118%, 154%, or 128% Val:Lys, respectively (Table 4). In contrast, Carter et al. (2000) and Gaines et al. (2006) did not observe improvements of Val:Lys above 79%, 86%, or 70%.

Within the last few years, re-evaluation of Val:Lys ratios in lactation diets with modern high producing females also yielded inconsistent responses in sow reproductive performance and litter growth rates when dietary SID Val:Lys ratios ranged from 55% to 105% (Devi et al., 2015; Strathe et al., 2016; Xu et al., 2017; Greiner et al., 2019). Xu et al. (2017) observed linear improvements in litter ADG when increasing SID Val:Lys ratios from 74 to 133% across a small sample size of sows (n = 24 sows). In contrast, Strathe et al. (2016) and Greiner et al. (2019) did not report any influence of increasing SID Val:Lys from 55 to 105% on sow performance when evaluated over much larger sample sizes (n = 558 and 422 sows, respectively). Beyond dietary modifications, some of the reasons for these differences in response could reflect variations in parity, lactation length, litter size, feed allowance, or start date of dietary treatment intake across

studies. Within these experiments, lactation length ranged from 17 to 28 days and pigs weaned per litter ranged from 9.4 to 13.6. Although litter size could influence the observed responses, changes in feed allowance may have also influenced the reported litter performance criteria. In contrast to the study conducted by Xu et al. (2017) where sows were allowed ad libitum access to feed immediately post-farrow, maximum feed intake for sows was limited to 5.5 kg/d (Greiner et al., 2019) or 7.4 kg/d (Strathe et al., 2016) during lactation. Additionally, sows within the Strathe et al. (2016) study did not begin consumption of assigned dietary treatments until 2-d post-farrow, whereas sows within the other studies began consumption of diets approximately 7-d or 3-d pre-farrow (Xu et al., 2017 and Greiner et al., 2019; respectively). In combination, these factors may explain the discrepancies in reported litter growth performance among the evaluated Val:Lys ratios.

Although limited literature is available, some researchers have directly evaluated the effects of Ile and total BCAA in addition to increasing Val on sow performance (Richert et al., 1997b; Moser et al., 2000). Within these studies, Ile:Lys ratios ranged from 49 to 135%, Leu:Lys ranged from 133 to 209% and Val:Lys ratios ranged from 70 to 154%. Both studies observed significant advantages of increasing dietary Val on litter growth performance, but no influence of total BCAA or Leu. However, Richert et al. (1997b) did observe a linear improvement in litter weight gain as Ile:Lys increased from 49 to 121%, indicating that Ile alone, regardless of Val, may influence litter growth. In contrast, the trial conducted by Moser et al. (2000) did not observe any influence of dietary Ile on sow or litter performance, regardless of Val, Leu, or total BCAA composition of the diet.

In summary, some studies that evaluated Val:Lys requirement for lactating sows concluded that total Val concentrations above 120% of Lys optimized litter weaning weights and

average daily gain (Richert et al., 1996; 1997a,b; Moser et al., 2000; Xu et al., 2017). In contrast, others determined that increasing SID Val:Lys ratios from 55 to 136% did not improve piglet growth performance (Carter et al., 2000; Gaines et al., 2006; Devi et al., 2015; Craig et al., 2016; Strathe et al., 2016; Greiner et al., 2019). Within some these studies, it is important to note that dietary BCAA content, namely Leu:Lys ratios, were not controlled across the treatments evaluated (Moser et al., 2000; Gaines et al., 2006; Craig et al., 2016). However, variation among Leu:Lys ratios do not appear to resolve the discrepancy between studies that observed positive effects of increasing Val:Lys and those that did not observe evidence for differences among increasing Val.

Since the late 1990's, sows are producing much larger and heavier litters and generally consume diets with greater concentrations of Leu and crystalline amino acids, which may create imbalances among the dietary BCAA. Uptake of BCAA by the mammary gland exceeds output of Ile, Leu, and Val in milk which indicates potential retention in mammary tissue for synthesis of non-essential amino acids, protein, lactose, and/or fatty acids. Given the well-established relationship among BCAA and LNAA metabolism pathways, one may hypothesize that Ile, Leu, total BCAA or LNAA such as Trp or Thr may have influenced the observed inconsistent responses among Val:Lys and Ile:Lys in published studies.

CONCLUSION

In review of the available literature, sow and litter growth responses to dietary BCAA and LNAA such as Trp are equivocal. Within the mammary gland of lactating females, catabolism of the BCAA is highly active. The positive influence of Val on fat and protein composition of colostrum and milk has been consistently observed, however, this does not always support enhanced litter growth during lactation. Furthermore, competition among Val,

Ile, and Leu for utilization and formation of non-essential AA and fatty acid synthesis within the mammary tissue must be considered when interpreting the influence of dietary BCAA on performance of the lactating sow.

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Table 1.1. Effects of Val and Ile on milk composition, adapted from Richert et al. (1997b)¹

Val, %	0.72			1.07			1.42
Ile, %	0.50	0.85	1.20	0.50	0.85	1.20	0.50
Total BCAA, %	2.57	2.92	3.27	2.92	3.27	3.62	3.27
Diet composition ²							
SID Lys, %	0.92	0.91	0.92	0.90	0.92	0.93	0.94
Ile:Lys	0.53	0.87	1.28	0.52	0.96	1.26	0.51
Leu:Lys	1.49	1.49	1.48	1.49	1.48	1.46	1.45
Val:Lys	0.77	0.80	0.77	1.17	1.15	1.15	1.48
Milk composition, %							
Crude protein ³	5.16	5.31	5.61	4.94	5.39	5.33	5.30
Crude fat ⁴	5.76	6.00	6.67	5.87	6.38	6.66	6.89
Lactose ⁵	4.47	4.48	4.24	4.5	4.29	4.45	4.23

¹A total of 16 sows/treatment were milked between d 14 and 16 of lactation.

²Analyzed chemical composition of dietary treatments.

³Ile linear, $P = 0.005$.

⁴Ile linear, $P = 0.002$.

⁵ $P > 0.05$.

Table 1.2. Effects of Ile, Leu, and Val on milk composition, adapted from Moser et al. (2000)¹

	Val, %	0.80				1.20			
		0.68		1.08		0.68		1.08	
	Ile, %								
	Leu, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97
Total BCAA, %		3.05	3.45	3.45	3.85	3.25	3.85	3.85	4.25
Diet composition ²									
SID Lys, %		0.93	0.90	0.91	0.89	0.88	0.87	0.93	0.87
Ile:Lys		0.73	0.78	1.09	1.16	0.74	0.78	1.13	1.14
Leu:Lys		1.60	1.96	1.65	2.01	1.60	2.01	1.60	2.01
Val:Lys		0.86	0.93	0.86	0.91	1.23	1.31	1.18	1.22
Milk composition, %									
Crude protein ³		4.60	4.58	4.49	4.55	4.55	4.47	4.47	4.51
Crude fat ³		5.12	5.40	5.31	5.21	4.95	5.23	5.37	5.43
Lactose ³		5.82	5.75	5.87	5.87	5.89	5.89	5.83	5.87

¹A total of 16 sows/treatment were milked between d 14 and 16 of lactation.

²Analyzed chemical composition of dietary treatments.

³Val, Ile, Leu, and all interactions, $P > 0.05$.

Table 1.3. Branched-chain amino acid requirement estimates for lactating sows.

Item	NRC (2012)	Brazil (2017) ¹	PIC (2020) ²	Danish Nutrient Standards (2020) ³
SID ⁴				
Lys, %	0.72 – 0.87	1.04 – 1.10	1.05	1.00
Val:Lys	0.85	0.83	0.64	0.69 – 0.74
Ile:Lys	0.56	0.60	0.56	0.56 – 0.60
Leu:Lys	1.11 – 1.15	1.15	1.14	1.02 – 1.08
SID intake, g/d				
Lys	42.2 – 52.6	64.5 – 68.9	50.0 – 62.0	---
Val	35.9 – 44.9	53.5 – 57.2	32.0 – 39.7	---
Ile	23.4 – 29.4	38.7 – 41.4	28.0 – 34.7	---
Leu	47.1 – 60.3	74.2 – 79.2	57.0 – 70.7	---

¹ Brazilian Tables for Poultry and Swine (2017).

² PIC Nutrition guidelines (2020).

³ Danish nutrient standards (2020).

⁴ SID = standardized ileal digestible.

Table 1.4. Summarized effects of increasing Val:Lys in lactation diets on litter performance.

Study	Range of SID Val:Lys, %	Improved litter gain?	Optimal Val:Lys
Richert et al., 1996	70 to 119	Yes	119%
Richert et al., 1997a	75 to 118	Yes	118%
Richert et al., 1997b	70, 112, and 154	Yes	154%
Moser et al., 2000	78 or 128	Yes	128%
Carter et al., 2000	79 to 136	No	79%
Gaines et al., 2006 (Exp. 1)	86 to 121	No	86%
Gaines et al., 2006 (Exp. 2)	70 to 131	No	70%
Devi et al., 2015	81 or 86	No	81%
Craig et al., 2016	77 to 118	No	77%
Strathe et al., 2016	66 to 105	No	66%
Xu et al., 2017	74 to 133	Yes	113%
Greiner et al., 2019	55 to 102	No	55%

Chapter 2 - A meta-regression analysis to evaluate the influence of branched-chain amino acids in lactation diets on sow and litter growth performance

ABSTRACT

The branched-chain amino acids (BCAA) Ile, Leu, and Val are three dietary essential amino acids for lactating sows; however, effects of dietary BCAA on sow and litter growth performance in the literature are equivocal. Thus, a meta-regression analysis was conducted to evaluate the effects of BCAA and their interactions in lactating sow diets to predict litter growth performance, sow bodyweight change, and sow feed intake. Thirty-four publications that represented 43 trials from 1997 to 2020 were used to develop a database that contained 167 observations. Diets for each trial were reformulated using NRC (2012) nutrient loading values in an Excel-based spreadsheet. Amino acids were expressed on a standardized ileal digestible (SID) basis. Regression model equations were developed with the MIXED procedure of SAS (Version 9.4, SAS Institute, Cary, NC) and utilized the inverse of reported squared SEM with the WEIGHT statement to account for heterogeneous errors across studies. Predictor variables were assessed with a step-wise manual forward selection for model inclusion. Additionally, statistically significant ($P < 0.05$) predictor variables were required to provide an improvement of at least 2 Bayesian information criterion units to be included in the final model. Significant predictor variables within three optimum equations developed for litter ADG included the count of weaned pigs per litter, NE, SID Lys, CP, sow ADFI, Val:Lys, Ile:Lys, and Leu:Val. For sow BW change, significant predictor variables within two developed models included litter size at 24 h, sow ADFI, Leu:Lys, and Ile+Val:Leu. The optimum equation for sow ADFI included

Leu:Trp, SID Lys, NE, CP, and Leu:Lys as significant predictor variables. Overall, the prediction equations suggest that BCAA play an important role in litter growth, sow BW change, and feed intake during lactation; however, the influence of BCAA on these criteria is much smaller than that of other dietary components such as NE, SID Lys, sow ADFI, and CP.

Key words: branched-chain amino acids, lactation, litter performance, sows

INTRODUCTION

The branched-chain amino acids (BCAA) Ile, Leu, and Val are three dietary essential amino acids necessary for both skeletal and milk protein synthesis of lactating sows. Structural similarities among the BCAA can create instances of antagonisms within their catabolic pathway, which can impair their utilization. Leucine is the primary enzymatic stimulator of branched-chain amino acid aminotransferase and branched-chain α -ketoacid dehydrogenase, where the BCAA are reversibly converted to their appropriate α -keto acids and then irreversibly decarboxylated (Harper et al., 1984). Under dietary conditions of high Leu, catabolism is increased and utilization of the other BCAA, Ile and Val, are especially impaired.

Since the late 1990's, sows are producing much larger and heavier litters and generally are fed diets with greater concentrations of crystalline amino acids which unintentionally increases Leu and may create imbalances among the dietary BCAA. Typical lactation diets that include corn and corn co-products often contain high levels of Leu, which may decrease the utilization and availability of Ile and Val. Kwon et al. (2019) observed reduced growth performance and decreased BCAA utilization when growing pigs were fed diets with Leu:Lys increasing from 100% to 300% of the Leu:Lys requirement. Additionally, a meta-regression analysis conducted by Cemin et al. (2019) to evaluate BCAA effects on growing-finishing pig

performance established that increasing Leu:Lys negatively influences performance due to insufficient levels of the other BCAA and large neutral amino acids (LNAA) such as Trp. However, incorporation of feed-grade amino acids such as L-Val and L-Ile may mitigate scenarios where growth performance may otherwise be negatively affected by excess Leu (Kerkaert et al., 2021). Although this practice has been actively researched and implemented for growing-finishing swine, the relationship of all three BCAA on sow reproductive and litter growth performance has not been established. Therefore, the objective of this regression analysis was to summarize studies evaluating the effects of BCAA in lactation diets and develop a statistical model to predict the influence of the interrelationships of BCAA on sow and litter growth performance.

MATERIALS AND METHODS

Database

A literature search was conducted through the Kansas State University Libraries, utilizing the Academic Search Premier, CAB Direct, and Web of Science search engines to evaluate the impact of BCAA in lactating sow diets on sow and litter growth performance. Key search terms included sow AND lactation AND one of the following terms: branched-chain amino acids, amino acids, isoleucine, leucine, tryptophan, or valine. Initially, data that directly evaluated BCAA in sow lactation diets were used. The database was then expanded to incorporate studies that indirectly manipulated BCAA ratios in diet formulation by adding the following search terms: canola meal, corn gluten meal, crude protein, dried distillers grains with solubles, soybean meal, or tryptophan. All data selected for inclusion in the database were peer-reviewed publications from 1990 to 2021 that reported enough detail to accurately reformulate diet nutrient composition.

All response criteria from each trial were recorded in a spreadsheet template. Commonly reported data included parity, count of sows, lactation length, average daily feed intake (ADFI), bodyweight (BW) change, backfat change, start litter size, wean litter size, litter weight at start, litter weight at weaning, litter gain, piglet gain, litter average daily gain, piglet average daily gain, and weaning to estrus interval.

The final database contained data from 34 papers incorporating 43 trials published from 1997 to 2020 to total 167 observations. Diets for each experimental treatment within trial were reformulated in an excel-based formulator primarily using the NRC (2012) nutrient loading values for ingredients to standardize ingredient nutrient concentrations. For ingredients that were not reported in the NRC (2012), CVB (2016), Stein (2021) feed ingredient database, or analyzed ingredient composition reported within study were utilized for nutrient loading values. These ingredients were as follows: sugar, linseed meal, and rapeseed meal (CVB, 2016); millmix and sorghum DDGS (Stein, 2021); high protein canola meal (Liu et al., 2018) and sugar product (Huber et al. 2015; 2016; Zhang et al., 2019; 2020).

Amino acid concentrations were expressed on an SID basis. The predictor variables evaluated in the statistical model to predict litter ADG and sow BW change included sow ADFI, parity, lactation length, start litter size, wean litter size, crude protein (CP), net energy (NE), Lys, Ile:Lys, Leu:Lys, Met:Lys, Met+Cys:Lys, Thr:Lys, Trp:Lys, Val:Lys, total BCAA:Lys, Ile:Leu, Val:Leu, Leu:Ile, Val:Ile, Leu:Val, Ile:Val, (Ile+Val):Leu, Ile:Trp, Leu:Trp, Val:Trp, total BCAA:Trp, Lys intake, Ile intake, Leu intake, Met intake, Thr intake, Trp intake, Val intake, and total BCAA intake. The predictor variables evaluated in the statistical model to predict sow ADFI included the predictor variables stated above except for daily amino acid intakes.

Statistical Analysis

Regression equations were developed with the MIXED procedure of SAS (Version 9.4, SAS Institute, Cary, NC). The method of maximum likelihood was used to evaluate potential predictor variables through single variable equations. Study was utilized as a random effect and statistical significance for inclusion of variables in the model was determined at $P < 0.05$. The inverse of reported squared SEM was utilized with the WEIGHT statement to account for heterogeneous errors across studies (St. Pierre, 2001). Additionally, for instances where litter ADG was not directly reported but could be calculated with total litter gain and lactation length, SEM of the litter ADG was estimated for inclusion in the statistical model. For these studies ($n = 17$), a simple linear regression equation was developed from studies within the final database that reported both the litter ADG SEM and the respective litter wean weight SEM within study.

To begin model building, the single-variable model with the lowest Bayesian information criterion (BIC) was selected, and then additional predictive variables were assessed through a step-wise manual forward selection for model inclusion. To be included in the model, significant ($P < 0.05$) predictor variables must have provided at least a 2-point reduction in BIC (Kass and Raftery, 1995). Additionally, in scenarios where daily amino acid intakes were statistically significant, main effects of sow daily feed intake and the respective amino acid predictor variables were tested together in the model. If both predictive variables were statistically significant, they remained in the model prior to subsequent assessment of daily amino acid intake predictive factors. When the model with the lowest BIC was obtained, the method of maximal likelihood was utilized to obtain parameter estimates and to evaluate model histogram residuals for evidence of data normality. Evaluation of the plots of model studentized residuals and of

predicted compared to actual values suggested that model assumptions of data normality were met for all litter ADG, sow BW change, and sow ADFI models.

RESULTS AND DISCUSSION

A summary of publications in the final database for predicting the influence of BCAA on lactating sow performance is presented in Table 1. In the final database, studies ranged from 18 to 714 sows, 49 to 135% Ile:Lys, 99 to 216% Leu:Lys, 55 to 154% Val:Lys, and 13 to 26% Trp:Lys.

The models developed for litter ADG, sow BW change, and sow lactation feed intake do not consider effects of sow parity. As is common in many research experiments, studies within our database controlled for parity differences among treatments during allotment at initiation of the trials. Therefore, we were unable to investigate effects of BCAA in lactation diets on litter and sow performance by parity.

Litter Average Daily Gain

When evaluating single predictive variables for litter ADG, count of pigs weaned per litter yielded the lowest BIC value (-156.2; $P < 0.001$) and was selected as the first predictor variable in the model. Other variables were evaluated in addition to pigs weaned per litter and subsequently added to the model. The stepwise inclusion of dietary NE ($P < 0.001$, BIC = -174.3) and sow ADFI (linear and quadratic terms, $P < 0.001$, BIC = -196.2) improved BIC for all models. However, further stepwise inclusion of SID Lys and dietary CP concentration yielded identical BIC ($P < 0.001$; BIC = -218.8). Therefore, the stepwise inclusion tests for significant predictor variables in addition to both SID Lys and CP were evaluated separately. For Model 1, after inclusion of SID Lys, the stepwise inclusions of Val:Lys ($P < 0.001$, BIC = -227.8) and Ile:Lys ($P = 0.014$, BIC = -230.1) improved the BIC of the model. For Models 2 and 3, after

inclusion of CP concentration, the stepwise inclusion of SID Lys ($P < 0.001$, BIC = -227.7), and either Val:Lys ($P = 0.006$, BIC = -231.6) or Leu:Val ($P = 0.007$, BIC = -231.4) improved BIC of the models. The inclusion of other variables did not further improve BIC for any of the three models.

To further evaluate the direct relationship of BCAA on litter growth performance, stepwise tests of only the predictive factors directly assessing any of the BCAA ratios in relation to Lys or the other BCAA were evaluated. The following BCAA were statistically significant predictive factors of litter ADG: Val:Lys ($P = 0.001$); Val:Leu ($P < 0.001$); Leu:Val ($P < 0.001$); and Ile+Val:Leu ($P < 0.001$). However, tests for the stepwise inclusion of any additional BCAA ratios did not improve the model ($P > 0.05$). These single predictive factors suggest that regardless of other dietary or sow performance criteria, the BCAA Val, Leu, and Ile are critical components of litter growth performance.

The final litter ADG models (Table 2) suggest that increasing NE and ADFI for sows positively impacts litter growth. Although the quadratic response to ADFI indicates diminishing returns, these predictive factors in all three of the established models agree with the well-accepted dogma that sow feed intake positively influences milk production and subsequent litter growth. Additionally, sow energy intake is essential for meeting the sow's maintenance and milk production requirements. However, modern sows do not consume enough dietary energy to meet these demands and will preferentially utilize body stores to support milk production and energy output for litter growth (Tokach et al., 2019). Therefore, it is not surprising that the models predict a significantly positive impact of increasing NE to increase sow daily energy intake on litter gain.

The models also suggest that increasing dietary CP positively impacts litter gain. Crude protein represents both essential AA and nitrogen for non-essential AA synthesis and milk protein output to support litter growth. Increasing dietary CP can improve litter performance during lactation (Strathe et al., 2017). The positive effect of CP in the developed models may be an indication of imbalanced AA or inadequate essential or non-essential AA in some of the studies within the database.

Within our final database, some studies utilized experimental diets deficient in Lys to estimate amino acid:Lys ratios. As a result, despite utilizing study as a random effect in the experimental model, SID Lys was still a strong positive predictive factor of litter ADG in all three of the established models. This positive coefficient aligns with the recently published literature for modern lactating sows. Previously, evaluation of Lys requirements for lactating gilts and sows indicated a positive influence of increasing Lys intake on litter growth and on minimizing sow bodyweight loss (Gourley et al., 2017; Greiner et al., 2020). Additionally, litter growth rate can serve as a predictive variable for the sow's Lys requirement (Pettigrew et al., 1993; Boyd et al., 2000; Tokach et al., 2019; Greiner et al., 2020).

The prediction equation for litter ADG established in Model 1 also indicated a positive influence of increasing Ile:Lys and Val:Lys on litter growth. Within the database, SID Ile:Lys averaged 71%, but ranged from 49 to 135%, and SID Val:Lys ranged from 55 to 154%. Previously, Richert et al. (1997b) observed an overall improvement among litter weight gain when sows consumed diets with increasing Ile:Lys ratios from 50 to 120%. Although Moser et al. (2000) did not observe a statistical difference of increasing Ile:Lys from 68 to 108% on litter weight gain, a numerical advantage of 1 kg per litter was observed as dietary Ile was increased. Again, we are not aware of any other studies that have been recently conducted to directly

determine the Ile requirement for the lactating sow. However, these responses support our models' small but significant influence of increasing Ile:Lys on litter gain. Additionally, our model suggests that increasing Val:Lys improves litter growth.

In contrast to the growing-finishing pig models established by Cemin et al. (2019), dietary Leu:Lys was not a significant predictive factor for litter ADG. However, similar to Cemin et al. (2019), the relationship among the BCAA appears to be important. Specifically, the ratio of Leu:Val had a significantly negative influence on predicted litter ADG. Multiple studies have attempted to distinguish an appropriate Val requirement for lactating females, but initial studies did not control SID Leu:Lys across the Val treatments evaluated. As a result, Leu:Val ratios ranged from 113 to 207% (Richert et al., 1996; 1997a; Carter et al., 2000; Gaines et al., 2006; Devi et al., 2015). Recent evaluation of Val:Lys for modern sow lactation diets contained Leu:Val ratios that ranged from 95 to 209% (Strathe et al., 2016; Craig et al., 2016; Xu et al., 2017; Greiner et al., 2019). This wide range in Leu:Val ratios across studies may explain some of the conflicting responses observed, whereas control of Leu:Lys could limit competition among BCAA metabolism and the subsequently negative influence of increasing Leu:Val ratios on litter gain. Thus, the models suggest that the ratio of Leu:Val or other BCAA should be considered in diet formulation; however, additional research is necessary to clarify the appropriate ratios of BCAA as modifications to Leu within the diet occur.

Sow Bodyweight Change

When evaluating single predictive variables for sow BW change, the starting count of pigs per litter, defined as the count of pigs per litter after cross-fostering, had the lowest BIC value (629.8; $P < 0.001$) and was selected as the first predictor variable in the model. The step-wise inclusion of sow ADFI ($P < 0.001$, BIC = 535.7), and either Leu:Lys ($P < 0.001$, BIC =

532.3) or Ile+Val:Leu ($P < 0.001$, BIC = 533.2) improved the model BIC. However, the addition of other predictor variables did not further improve the BIC of either model. Therefore, the final models selected included start count of pigs per litter, sow ADFI, and either Leu:Lys or Ile+Val:Leu (Table 2).

The equations for sow BW change suggest that litter size after cross-fostering influences predicted degree of sow BW change. This is not surprising, as sows with large litters will have greater demand to increase milk output to support growth of the litter throughout lactation. Increased sow ADFI, as indicated in the model, will minimize sow BW change that may occur if daily intake of nutrients does not support milk production. Additionally, the models suggest a positive influence of increasing Leu:Lys on minimizing sow BW change. Leucine can directly stimulate protein synthesis through activation of the mTOR signaling pathway and has been observed to increase skeletal muscle protein synthesis in neonatal pigs under conditions with excess dietary Leu (Escobar et al., 2006; Torrazza et al., 2010). Thus, the lactating sow may also preferentially utilize Leu for maternal body protein deposition when dietary Leu is not limiting. The negative coefficient for Ile+Val:Leu in predicting sow BW change (Table 2) indicates that increasing concentrations of Ile and Val relative to Leu can negatively impact sow BW change during lactation. This response may suggest that additional dietary Val and Ile could enable AA utilization for improved milk production, rather than protein deposition.

Sow Average Daily Feed Intake

When evaluating single predictive variables for sow ADFI, the ratio of Leu:Trp had the lowest BIC value (262.7; $P < 0.001$) and was selected as the first predictor variable in the model. Other variables were then evaluated and subsequently added to the model. The step-wise inclusion of NE ($P < 0.001$, BIC = 214.2), CP ($P < 0.001$, BIC = 202.3), Leu:Lys ($P < 0.001$,

BIC = 193.4), and SID Lys ($P < 0.001$, BIC = 189.9) improved the model BIC. The addition of other predictor variables did not further improve the model BIC. Therefore, the final model included Leu:Trp, NE, CP, Leu:Lys, and SID Lys (Table 2).

The first predictive factor, Leu:Trp indicates that increasing Leu:Trp ratios negatively affect sow feed intake. Tryptophan, one of the LNAA, shares brain transporters with other LNAA, including Leu, Val, and Ile (Pardridge et al., 1977). Increased concentrations in blood of any one LNAA increases competition at the blood-brain barrier for uptake capacity of the other LNAA. One may speculate that high levels of Leu in lactation diets may negatively influence availability and transport of Trp to the brain, as demonstrated by Fernstrom (2013). Thus, we cannot dismiss the positive influence of dietary Trp, when considering the variation in composition of dietary BCAA and other LNAA such as Thr, Tyr, and Phe on sow feed intake. Although few studies have been conducted to evaluate these responses in lactating sows, Trotter and Easter (1995) confirmed that reducing Trp:BCAA ratios reduced feed intake. Our model also suggests that increasing Leu:Lys will positively influence sow feed intake as long as Trp is adequate to maintain a lower Leu:Trp ratio.

Although no research has been conducted to evaluate the relationship between BCAA and sow feed intake specifically, other research in young pigs suggests that ADFI is reduced when diets contain excess Leu, imbalanced BCAA, or over-supplementation of BCAA (Gloaguen et al., 2011; 2012; Millet et al., 2015; Meyer et al., 2017; Kwon et al., 2019; Tian et al., 2019). In contrast to the effects of Leu on growing-finishing pig feed intake, increasing Leu:Lys and subsequently reducing Leu:Trp will improve sow feed intake during lactation, according to the developed model. However, this positive response among lactating sows has yet

to be evaluated. Overall, our models suggest that Leu:Lys positively influences sow ADFI and minimizes sow BW change during lactation.

To display the practical application of the sow and litter performance prediction models, example diets based on corn and soybean meal (SBM), corn and DDGS, and wheat and barley were formulated (Table 3). Although modifications to BCAA can marginally influence the predicted litter performance, the addition of dietary fat and subsequently increased NE was predicted to increase litter ADG by 0.05 kg/d and decrease sow ADFI without drastically impacting sow BW change. The inclusion of 20% DDGS and the subsequent increase in Leu:Lys, Ile:Lys, and Val:Lys resulted in predicted litter performance similar to that of a common corn and SBM-based diet, but sow BW loss and ADFI were both predicted to be less for the DDGS-based diet than for the corn/SBM diet. Application of the developed models for litter ADG to wheat and barley-based diet, which naturally contain lower NE and Leu:Lys, suggests that litter ADG would be approximately 0.10 kg/d less than that of common corn/SBM diets, despite the model's predicted greater sow ADFI for the wheat and barley-based diet. However, the combination of reduced Leu:Lys and higher Ile+Val:Leu ratios in a wheat and barley-based diet can counterbalance the detrimental effects of reduced NE on predicted litter performance. Additionally, although greater sow ADFI may occur with the wheat and barley-based diet, this effect may not correlate directly to litter performance if dietary NE is not adjusted to be similar to that of a corn-SBM diet. Validation of these sow and litter growth performance models among differing diet types is needed.

CONCLUSIONS

In review of the available literature, sow and litter growth responses to dietary BCAA and LNAA, such as Trp, are equivocal. Our predicted litter ADG model suggests that Leu, Ile,

and Val impact litter growth, but the effects of BCAA are much smaller than the effects of dietary NE, Lys, and CP. Furthermore, the developed models suggest that increasing Leu:Lys and reducing Ile+Val:Leu ratios can positively influence sow BW change during lactation. Although interactions among BCAA within the mammary gland occur, the sow may also preferentially utilize Leu for whole body protein synthesis. In contrast to research among nursery and growing-finishing pigs, our model suggests that reduced Leu:Trp and increased Leu:Lys positively influence sow feed intake during lactation. However, validation of these predicted litter growth and sow performance responses through dietary modifications of the BCAA and Trp is necessary.

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Table 2.1. Summary of publications considered in the meta-regression analysis to predict the influence of branched-chain amino acids on lactating sow performance¹

Publication	Trials	Sows	Average pigs weaned/litter	Average ADFI, kg	SID Lys, % ²	Range of SID Ile:Lys	Range of SID Leu:Lys	Range of SID Val:Lys	Range of SID Trp:Lys
Richert et al (1996)	1	203	10.2	6.2	0.79	73	145	70-119	23
Libal et al. (1997)	1	115	8.4	6.1	0.67	57	151	68	15-22
Richert et al. (1997a)	2	202	9.9	4.5	0.77 or 1.14	74-78	119-124	75-118	24
Richert et al (1997b)	1	185	10.8	6.1	0.80	49-135	133-134	70-154	23
Touchette et al. (1998a)	1	247	9.8	4.5	0.78-0.80	65-81	151-173	74-89	18-23
Touchette et al. (1998b)	1	116	10.0	4.0	1.03	78	154	85-96	24
Johnston et al. (1999)	2	267	9.7	5.3	0.69-0.70	65 or 83	163 or 187	76 or 92	18 or 23
Carter et al. (2000)	1	231	10.2	5.8	0.76	70	161	79-136	21
Moser et al. (2000)	1	306	10.6	5.9	0.78	70-121	158-209	78-128	22
Southern et al. (2000)	1	79	10.3	5.5	0.92-0.94	78-84	159-169	85-94	23
Gaines et al. (2006)	2	468	10.0	6.4	0.75-0.79	73-77	144-165	70-131	22
Song et al. (2010)	1	307	9.8	6.6	0.84-0.90	63-81	169-210	76-95	15-23
Devi et al (2015)	1	18	11.7	5.5	0.93	74	152	81-86	21
Greiner et al. (2015)	3	522	10.2	6.2	1.02-1.09	62-77	132-203	68-88	17-21
Huber et al. (2015)	1	38	10.1	5.7	0.72-0.73	73-81	135-175	111-112	24-25
Sotak-Peper et al. (2015)	1	134	11.9	6.0	0.93-0.94	77-84	161-202	84-94	22-23
Craig et al. (2016)	2	109	12.8	7.6	1.14 or 1.30	57-67	107-125	72-119	20-22
Fan et al. (2016)	2	225	10.5	6.1	0.86	69	172	80	18-33
Huber et al. (2016)	1	23	9.7	5.1	0.72-0.73	74 or 81	135 or 175	110 or 112	24
Strathe et al. (2016)	1	558	13.4	6.2	0.99-1.00	54-56	99-102	66-105	18-19
Choi et al. (2017)	1	60	9.9	5.0	0.94-0.99	63-64	132-135	89-90	23
Greiner et al. (2017)	1	284	11.9	5.2	0.95	56	165	69	14-19
Velayudhan et al. (2017)	1	45	10.5	7.4	0.87	57-79	130-166	71-87	20-23
Xu et al. (2017)	1	32	9.8	4.3	0.83	64	142	74-133	17
Greiner et al. (2018)	2	714	10.3	5.5	1.02-1.09	57-78	123-155	63-84	17-23
Liu et al. (2018)	1	180	10.3	4.6	0.83-0.90	60-74	137-158	77-81	16-22
Gao et al. (2019)	1	60	9.8	3.6	1.23	65	130-153	72-102	19
Greiner et al. (2019)	1	422	11.7	5.2	0.97	65	114	55-102	19
Hojgaard et al. (2019)	1	520	13.0	6.7	0.87-0.88	54-80	99-141	65-89	22-26
Shang et al. (2019)	1	45	10.2	5.1	0.81-0.82	76-81	158-173	113-116	23
Zhang et al. (2019)	1	54	9.8	5.2	0.89-0.90	57-79	113-163	85-87	19-23

Gourley et al. (2020)	1	131	12.9	5.5	1.05	60-76	130-152	85	20-23
Ma et al. (2020)	1	48	10.0	5.7	0.71-0.72	68-84	155-216	80-103	18
Zhang et al. (2020)	2	24	10.7	6.2	0.89-0.90	58 or 79	113 or 161	85 or 87	19 or 23

¹Reported standardized ileal digestible (SID) amino acid ranges represent diet composition utilizing NRC (2012) or CVB Feed Table (2016) nutrient loading values.

²Standardized ileal digestible Lys ranged within some studies after diet reformulation and conversion of total Lys to SID Lys.

Table 2.2. Regression equations to predict sow and litter growth performance¹

Variable ²	Equation ³	BIC ⁴
Litter ADG, kg		
Model 1	= -4.8199 + (0.1967 × pigs weaned per litter) + (0.000568 × net energy, kcal/kg) + (0.8119 × ADFI, kg) - (0.06202 × ADFI × ADFI) + (1.0735 × SID Lys, %) + (0.0012 × Val:Lys) + (0.000963 × Ile:Lys)	- 230. 1
Model 2	= -5.1198 + (0.2002 × pigs weaned per litter) + (0.000679 × net energy, kcal/kg) + (0.8065 × ADFI, kg) - (0.06097 × ADFI × ADFI) + (0.01763 × Crude protein, %) + (0.805 × SID Lys, %) + (0.000902 × Val:Lys)	- 231. 6
Model 3	= -4.8731 + (0.1988 × pigs weaned per litter) + (0.000676 × net energy, kcal/kg) + (0.7882 × ADFI, kg) - (0.05954 × ADFI × ADFI) + (0.0214 × Crude protein, %) + (0.7224 × SID Lys, %) - (0.00048 × Leu:Val)	- 231. 4
Sow BW change, kg		
Model 1 ⁵	= -43.5295 - (0.1748 × start litter size) + (5.5202 × ADFI, kg) + (0.03143 × Leu:Lys)	532. 3
Model 2 ⁵	= -33.3003 - (0.5108 × start litter size) + (5.6935 × ADFI, kg) - (0.02421 × Ile+Val:Leu)	533. 2
Sow ADFI, kg	= 13.7105 - (0.00187 × Leu:Trp) - (0.00315 × net energy, kcal/kg) - (0.1047 × Crude protein, %) + (0.006263 × Leu:Lys) + (2.4641 × SID Lys, %)	189. 9

¹Model adjusted for heterogenous errors using the inverse of squared SEM.

²ADG = average daily gain. ADFI = average daily feed intake. BW = bodyweight.

³Amino acid ratios expressed on standardized ileal digestible (SID) basis.

⁴Bayesian information criterion.

⁵Start litter size = count of piglets placed per litter at 24 h postpartum (after cross-foster).

Table 2.3. Practical scenarios for prediction of sow and litter performance based on common lactation diet types¹

Ingredient, %	Corn/SBM/			
	Corn/SBM	Added Fat	Corn/SBM/DDGS	SBM/Barley/Wheat
Corn	64.85	62.70	47.30	---
Soybean meal	27.83	27.98	25.38	24.46
Barley	---	---	---	48.22
DDGS	---	---	20.00	---
Wheat	---	---	---	20.00
Choice white grease	3.00	5.00	3.00	3.00
Monocalcium phosphate	1.70	1.70	1.70	1.70
Limestone	1.25	1.25	1.25	1.25
Sodium chloride	0.50	0.50	0.50	0.50
Vitamin/mineral premix	0.40	0.40	0.40	0.40
L-Lys HCl	0.25	0.25	0.25	0.25
DL-Met	0.07	0.07	0.07	0.07
L-Thr	0.12	0.12	0.12	0.12
L-Trp	0.03	0.03	0.03	0.03
Calculated analysis, %				
Crude protein, %	19.0	18.9	22.0	20.4
Net energy, kcal/kg	2,544	2,633	2,497	2,358
SID Lys, %	1.05	1.05	1.05	1.05
SID Ile:Lys	65	64	72	66
SID Leu:Lys	136	135	166	116
SID Val:Lys	71	70	81	74
SID Trp:Lys	21	21	22	24
SID Leu:Val	192	192	206	157
SID Ile+Val:Leu	99	100	92	120
SID Leu:Trp	641	636	758	484
Litter ADG, kg ^{2,3}				
Model 1 ⁴	2.68	2.73	2.67	2.57
Model 2 ⁵	2.67	2.73	2.70	2.57
Model 3 ⁶	2.66	2.72	2.69	2.59
Sow BW change, kg ^{2,7}				
Model 1 ⁸	-9.90	-9.94	-8.95	-10.52
Model 2 ⁹	-9.40	-9.41	-9.21	-9.90
Sow ADFI, kg ¹⁰	5.94	5.68	5.75	6.56

¹Diets formulated with the NRC (2012) nutrient loading values to meet or exceed nutrient requirements.

²Assumed 5.7 kg average daily feed intake.

³Assumed 11 pigs weaned per litter.

⁴Litter ADG, kg = $-4.8199 + (0.1967 \times \text{pigs weaned per litter}) + (0.000568 \times \text{net energy, kcal/kg}) + (0.8119 \times \text{ADFI, kg}) - (0.06202 \times \text{ADFI} \times \text{ADFI}) + (1.0735 \times \text{SID Lys, \%}) + (0.0012 \times \text{Val:Lys}) + (0.000963 \times \text{Ile:Lys})$.

⁵Litter ADG, kg = $-5.1198 + (0.2002 \times \text{pigs weaned per litter}) + (0.000679 \times \text{net energy, kcal/kg}) + (0.8065 \times \text{ADFI, kg}) - (0.06097 \times \text{ADFI} \times \text{ADFI}) + (0.01763 \times \text{Crude protein, \%}) + (0.805 \times \text{SID Lys, \%}) + (0.000902 \times \text{Val:Lys})$.

⁶Litter ADG, kg = $-4.8731 + (0.1988 \times \text{pigs weaned per litter}) + (0.000676 \times \text{net energy, kcal/kg}) + (0.7882 \times \text{ADFI, kg}) - (0.05954 \times \text{ADFI} \times \text{ADFI}) + (0.0214 \times \text{Crude protein, \%}) + (0.7224 \times \text{SID Lys, \%}) - (0.00048 \times \text{Leu:Val})$.

⁷Assumed start litter size of 12 pigs.

⁸Sow BW change, kg = $-43.5295 - (0.1748 \times \text{start litter size}) + (5.5202 \times \text{ADFI, kg}) + (0.03143 \times \text{Leu:Lys})$.

⁹Sow BW change, kg = $-33.3003 - (0.5108 \times \text{start litter size}) + (5.6935 \times \text{ADFI, kg}) - (0.02421 \times \text{Ile+Val:Leu})$.

¹⁰Sow ADFI, kg = $13.7105 - (0.00187 \times \text{Leu:Trp}) - (0.00315 \times \text{net energy, kcal/kg}) - (0.1047 \times \text{Crude protein, \%}) + (0.006263 \times \text{Leu:Lys}) + (2.4641 \times \text{SID Lys, \%})$.

Chapter 3 - Evaluation of essential fatty acids in lactating sow diets on sow reproductive performance, colostrum and milk composition, and piglet survivability

ABSTRACT

Mixed parity sows (n=3,451; PIC, Hendersonville, TN) and their litters were used to evaluate the effects of essential fatty acid (EFA) intake on sow reproductive performance, piglet growth and survivability, and colostrum and milk composition. At approximately d 112 of gestation, sows were randomly assigned within parity groups to 1 of 4 corn-soybean meal-wheat-based lactation diets that contained 0.5 (Control) or 3% choice white grease (CWG), 3% soybean oil (SO), or a combination of 3% soybean oil and 2% choice white grease (Combination). Thus, sows were provided diets with low EFA (linoleic acid [LA] and α -linolenic acid [ALA]) in diets with CWG or high EFA in diets that included soybean oil. Sows received their assigned EFA treatments until weaning and were then fed a common gestation and lactation diet in the subsequent reproductive cycle. Average daily feed intake during the lactation period increased ($P < 0.05$) for sows fed the Combination and CWG diets compared to sows fed the Control or SO diet. However, daily LA and ALA intakes of sows fed the Combination and SO diets were still greater ($P < 0.05$) than those of sows fed 0.5 or 3% CWG. Overall, sows consuming high EFA from the Combination or SO diets produced litters with heavier ($P < 0.05$) piglet weaning weights and greater ($P < 0.05$) litter ADG when compared to litters from sows fed diets with CWG that provided low EFA. Despite advantages in growth performance, there was no impact of sow EFA intake on piglet survivability ($P > 0.10$). Additionally, lactation diet EFA composition did not influence sow colostrum or milk dry matter, crude protein, or crude fat

content ($P > 0.10$). However, LA and ALA content in colostrum and milk increased ($P < 0.05$) in response to elevated dietary EFA from SO. There was no evidence for differences ($P > 0.10$) in subsequent sow reproductive or litter performance due to previous lactation EFA intake. In conclusion, increased LA and ALA intake provided by soybean oil during lactation increased overall litter growth and pig weaning weights, reduced sow ADFI, but did not affect piglet survivability or subsequent performance of sows.

Key words: α -linolenic acid, essential fatty acids, lactation, linoleic acid, piglet survivability, sow

INTRODUCTION

Nutrient requirements for the modern lactating sow must be met to support milk production and nutrient output for the growth and development of larger and heavier litters. However, sows often do not consume enough feed during lactation to meet nutrient intake requirement estimates (Tokach et al., 2019). Utilization of supplemental fat sources are an effective and widely accepted strategy to increase energy density of sow lactation diets that can also provide essential fatty acids (EFA) such as linoleic acid (LA) and alpha-linolenic acid (ALA) that cannot be synthesized by the sow. Essential fatty acids support neonatal brain, vision, and immune system development and function (Kaur et al., 2014). The two parental EFA (LA and ALA) may be elongated to form other polyunsaturated fatty acids (PUFA) such as arachidonic acid (ARA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) that serve as precursors for prostaglandins that regulate inflammatory responses (Ricciotti and FitzGerald, 2011) and reproductive function (Roszkos et al., 2020). The NRC (2012) currently

suggests 6.0 g/d LA intake for sows, but specific requirements for ALA intake for the prolific sow are not currently available.

Previously, researchers have observed alterations in milk fat or fatty acid composition as a reflection of dietary fatty acid composition when supplemented in mid- to late-gestation (Lauridsen et al., 2004; Jin et al., 2017). However, the influence of supplemental fat source and EFA content on colostrum and milk composition provided shortly prior to farrowing are not fully understood. The primary route of EFA excretion is through the sow's milk and thus, changes in EFA intake even shortly prior to farrowing could influence colostrum and milk EFA composition and potentially impact litter growth performance and survivability.

Rosero et al. (2015) concluded that sows remaining in a negative EFA balance may enter a state of deficiency that impairs subsequent reproductive function and later suggested that dietary EFA intake should exceed 125 g/d LA and 10 g/d ALA to maximize reproductive performance (Rosero et al., 2016a). Additionally, Australian Pork Ltd (van Wettere, 2018) observed a reduction in piglets born dead when sows were fed diets containing 120 g/d LA compared to 70 g/d of LA beginning at entry to the farrowing room. However, the influence of elevated LA and ALA intake in sow lactation diets on litter growth and survivability responses has not been extensively evaluated. Therefore, the objective of this study was to determine the influence of fat source providing low and high EFA intake on sow performance, litter growth and survivability, colostrum and milk composition, and subsequent reproductive performance.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This experiment was conducted at commercial sow research facility in Utah (Smithfield Foods Inc., Milford, Utah) between August 2020 and July 2021.

Animals, Housing, and Treatments

A total of 3,451 mixed-parity sows (parity = 4.8 ± 1.8 ; initial BW = 250.3 ± 26.6 kg; PIC, Hendersonville, TN) were used in this experiment. On approximately d 112 of gestation, sows were blocked by parity within farrowing room and randomly assigned to 1 of 4 dietary treatments. Lactation diets were pelleted corn-soybean meal-wheat-based and included supplemental fat as either 0.5 (Control) or 3% (CWG) choice white grease, 3% soybean oil (SO), or a combination of 3% soybean oil and 2% choice white grease (Combination). For the Control treatment, 0.5% added fat was included for pelleting purposes. Thus, sows were provided diets with low and high EFA and were projected to have daily EFA intakes as follows: Control: 89 g/d LA and 5 g/d ALA; CWG: 109 g/d LA and 6 g/d ALA; SO: 189 g/d LA and 19 g/d ALA; and Combination: 205 g/d LA and 20 g/d ALA (assumed 6.3 kg ADFI). All diets were formulated to meet or exceed NRC (2012) requirement estimates with a constant SID Lys:ME ratio for all diets at 3.22 g/Mcal with SID Lys increasing from 1.07 to 1.14% (Table 1) as dietary fat increased. Prior to farrowing, sows were provided 1.8 kg/d of their assigned lactation treatment and then allowed *ad libitum* access after parturition. Throughout the lactation period, individual sow feed intake was monitored by recording daily feed additions and weighing remaining feed at weaning. Primiparous sows were not utilized in this study.

During feed manufacturing, soybean oil was added to the mixer for incorporation into SO and Combination treatments and choice white grease was sprayed on pellets after mixing of complete diets. All diets were manufactured in pelleted form for the duration of the experimental period and the average percentage of pellet fines for each treatment were as follows: Control, 11.2%; CWG, 13.1%; SO, 18.3%; and Combination, 21.5%.

At entry to the farrowing rooms and at weaning, sow bodyweight (BW) and backfat depth were recorded. Backfat measures were completed with ExaGo (BioTronics Inc., Ames, IA, USA) at the last rib position approximately 6 to 8 cm from the midline. Each farrowing stall (2.39 × 1.70 m) contained a nipple waterer and feeder for the sow.

Litter size was standardized through cross-fostering of pigs within treatment within 24 h of parturition. Count of pigs born alive, stillborn, and mummified and litter weights of pigs born alive were recorded for each sow. Additionally, all stillborn and mummified pigs were weighed and recorded within litter. Litters were weighed again at 24 h after cross-fostering and one day prior to weaning to determine litter growth performance. All instances and reasons for piglet mortalities were recorded. Total pigs born was calculated as the sum of pigs born alive, stillborn, and mummified. Survivability from birth to 24 h was calculated as: [(Pigs born alive – count of mortality within 24 h)/Pigs born alive]. Survivability from 24 h to weaning was calculated as: (count of pigs at weaning/count of pigs alive at 24 h).

Within 3 h of the onset of parturition, colostrum was collected from a subset of 40 sows (n = 10 sows/treatment) by hand stripping all functional teats, with an attempt to collect equal volumes from all teats for one representative sample. One day prior to weaning, milk samples were also collected as previously described. To initiate milk letdown at weaning, 10 IU of oxytocin was administered via intramuscular injection. All samples were immediately frozen and stored at -20°C until analysis.

At weaning, sows were moved to individual gestation stalls and checked daily for signs of estrus. Wean to first service interval and the percentage of sows bred by d 7 and 12 were recorded on the 2,938 sows that remained after culling. Farrowing rate and subsequent farrowing performance including total born, born alive, stillborn, and mummified were also evaluated.

During the subsequent performance period, all sows consumed a common gestation and lactation diet that contained 0.5% CWG.

Chemical Analysis

Diet samples were collected once weekly, pooled by month (n = 6 per treatment), and stored at -20 °C before submission to commercial laboratories for proximate and fatty acid profile analysis (Midwest Labs, Omaha, NE; and University of Missouri, ESCL, Columbia, MO, respectively; Table 2). Standard procedures (AOAC International, 2006) were followed for analysis of moisture (method 934.15), crude protein (method 990.03), ether extract (method 2003.05), ash (method 942.05), and fatty acid profiles (method 996.06). Analysis of crude fiber was completed according to the AOCS (2017) approved procedure (method Ba 6a-05).

Additionally, colostrum and milk samples were sent to a commercial laboratory for analysis of moisture (method 934.01), crude protein (method 990.03), ether extract (method 920.39), and fatty acid profiles (method 996.06; University of Missouri ESCL, Columbia, MO).

Statistical Analysis

Data were analyzed using the GLIMMIX procedure in SAS (Version 9.4, SAS Institute, Inc., Cary, NC) and considered sow (litter) as the experimental unit. The statistical model considered fixed effects of dietary treatment and random effects of farrowing room. The following response criteria were fitted with a Poisson distribution in the statistical model: parity, functional teats, and litter size at farrowing, start, and weaning. The percentage of pigs born alive, stillborn, and mummified, survival of pigs from birth to 24 h and from 24 h to wean, percentage of sows bred by d 7 and d 12, and farrowing rate were fitted by a binomial distribution in the statistical model. All other response criteria were fit using a normal distribution. At the initial allotment, a total of 4,036 sows were enrolled, however, any sow that

did not complete a full lactation period was removed from the final dataset prior to analysis (n = 344 sows; Table 3). Reasons for early lactation removal included sow prolapses, early weaning, and mortalities. Additionally, nurse sows and sows with mixed litters after cross-fostering were removed from the final dataset (n = 241 sows). Therefore, the final dataset contained data collected from 3,451 sows (Table 4). Data are reported as least square means and considered statistically significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

RESULTS AND DISCUSSION

Sow Performance and Litter Survivability

As expected, average parity, days of pre-farrow lactation diet consumption, lactation length, and count of functional teats per sow were similar across experimental treatments ($P > 0.10$; Table 5). Although there was no evidence for differences among sow BW when sows entered the farrowing rooms at d 112 of gestation or at weaning ($P > 0.10$), sows that consumed the Combination diet with 5% added fat tended ($P = 0.090$) to lose less BW during the lactation period compared to sows consuming diets with either 0.5 or 3% CWG, with sows fed SO intermediate. Although variation in the effects of increasing supplemental lipids among studies exists, a review by Rosero et al. (2016a) suggests that increased daily calorie intake of lipid-fed sows reduced sow BW loss by 1.0 kg during lactation, which aligns with the results observed in the present study.

There was no evidence of difference ($P > 0.10$) in sow backfat thickness at entry to the farrowing room among experimental treatments. Additionally, sows fed the Combination fat diet exhibited less backfat depth at weaning compared to all other treatments ($P = 0.046$). As stated in the NRC (2012), maternal protein and lipids are mobilized to provide a source of energy when maintenance energy and milk production requirements are not supported by dietary energy intake

alone. However, the overall change in backfat depth of sows from d 112 of gestation to weaning was similar across dietary treatments ($P > 0.10$).

Controlled feed offerings prior to farrowing resulted in similar pre-farrow ADFI across dietary treatments ($P > 0.10$). Overall, lactation daily feed intake was greater when sows were fed the Combination and CWG diets compared to sows consuming the Control and SO diets ($P < 0.001$). These findings contrast others that have observed a reduction in lactation ADFI as dietary energy density increases (Shurson and Irvin, 1992; Park et al., 2008; Xue et al., 2012).

Despite reduced feed intake, sows provided diets with 3% SO still consumed greater ($P < 0.001$) daily intakes of LA and ALA than sows fed the control and 3% CWG diets. Currently, the NRC (2012) indicates that lactating sows should consume at least 6 g/d of LA, but recommendations for ALA intake are not stated. From a review conducted by Rosero et al. (2016a), it is suggested that sows consume at least 125 g/d of LA and 10 g/d of ALA to mitigate negative EFA balance during lactation and maximize reproductive efficiency. Daily LA and ALA intakes of sows within the current study for the SO and Combination dietary treatments exceeded the recommended LA and ALA intakes from Rosero et al. (2016a), whereas diets containing CWG at 0.5% or 3% did not.

The count of pigs born per litter and percentage of mummified pigs were not influenced ($P > 0.10$) by dietary treatments provided approximately 5-d prior to farrowing. However, the percentage of pigs born alive decreased when sows were provided diets with high EFA and added fat at 5% when compared to sows provided low EFA and 0.5% added fat within the Control treatment, with sows provided dietary fat at 3% as either CWG or SO intermediate ($P < 0.05$). This response was supported by the greater percentage of stillborn pigs per litter among sows provided the Combination treatment compared to the Control, with sows provided CWG

and SO intermediate ($P < 0.005$). Although feed intake was similar across treatments prior to farrowing, sows consumed 5.8 to 6.2 Mcal/d ME when provided diets with added fat. However, it was not expected that dietary treatments provided to sows approximately 5-d pre-farrow would influence stillborn rate.

Overall, there was no influence ($P > 0.10$) of sow lactation treatments on piglet survivability from birth to 24 h or from 24 h to weaning. Available literature regarding the influence of supplemental fat and dietary n-3 and n-6 PUFA content on litter survivability are variable. In contrast to the current study, pre-weaning survivability of piglets improved when sows were provided supplemental fat sources with elevated n-6 and n-3 PUFA provided by soybean oil or with increased n-3 PUFA alone provided through fish oils (Rooke et al., 2001; Quiniou et al., 2008; Farmer et al., 2010; Jin et al., 2017; Lavery et al., 2019). Others, however, were not able to detect any influence of fat source or EFA content on piglet survivability (Mateo et al., 2009; Rosero et al., 2012a). Furthermore, effects of n-3 PUFA through utilization of fish oils that provide high concentrations of DHA and EPA in gestation and lactation diets has been evaluated, but with inconsistent responses on litter survivability (Tanghe and Smet, 2013; Roszkos et al., 2020). This variation is likely due to differences among oil sources, inclusion rates, timing of pre-farrow supplementation, and basal population mortality rates across studies. Furthermore, consideration of type 2 errors due to insufficient treatment replication to evaluate litter survivability differences across studies may be warranted. In the present study, 850 to 874 replications per treatment should have been sufficient to support evaluation of true litter survivability differences if present.

The larger litter size of modern sows increases the potential for oxidative stress, especially in late gestation and lactation (Berchieri-Ronchi et al., 2011; Liu et al., 2018). Dietary

oils that stimulate production of anti-inflammatory compounds and reduce oxidative stress can positively influence both sow performance and litter survival (Ward et al., 2020). Plant oil sources provide rich amounts of the parental n-3 and n-6 fatty acids that serve as precursors for conversion to long-chain PUFA. Alpha-linolenic acid can be converted to DHA and EPA, which are present in high concentrations within fish oils, and LA can be converted to ARA. These long chain PUFA can be provided through direct dietary consumption or from *de novo* synthesis from the parental ALA or LA. However, conversion efficiency may be limited, as desaturase enzymes are shared among the EFA (Lauridsen and Danielsen, 2004). Although conversion efficiency may be limited between LA and ALA, long-chain PUFA incorporated into cell membranes can influence gastrointestinal health and function and inflammatory immune response (Calder, 2003; Farmer et al., 2010; Leonard et al., 2011; Calder, 2013; Peng et al., 2019; Lauridsen, 2020). In the present study, n-6:n-3 ratios among experimental treatments were not considered in diet formulation, however, n-6:n-3 ratios ranged from 18:1, 17:1, 7:1, and 7:1 across the Control, CWG, SO, and Combination treatments, respectively.

Litter Growth Performance

There was no evidence for difference ($P > 0.10$) in litter or average piglet weights at birth or 24 h after birth (Table 6). However, sows fed diets with high EFA provided in the Combination and SO diets produced litters with greater ($P < 0.05$) total litter gain and litter ADG during lactation. This response supported heavier litter weaning weights for sows with high LA and ALA daily intake when compared to litters from sows provided low EFA in diets containing CWG at 0.5 or 3%. These litter growth responses mirrored heavier piglet weaning weights and piglet ADG ($P < 0.001$) for litters from sows fed the Combination and SO diets when compared to litters from sows fed diets with low EFA provided through CWG.

To support milk production for improved growth of larger litter sizes, elevated lactation feed intake, mobilization of sow body reserves, or both must occur (Strathe et al., 2017). In the present study, sows provided CWG and Combination fat diets had greater ADFI than sows provided SO or 0.5% supplemental fat in the Control diet. However, litter ADG between SO and Combination treatments were similar despite differences in sow ADFI and EFA intake. It is possible that the influence of increased ME in the Combination treatment supported enhanced litter growth (Park et al., 2008); however, the positive impacts of added fat on litter growth are not always observed (Rosero et al., 2012a). Therefore, we speculate that the elevated LA and ALA intake provided to sows with the SO and Combination treatments is the reason for their greater litter performance.

Essential fatty acids are primarily secreted in milk of the lactating sow to support litter growth and development (Innis, 2007; Odle et al., 2014). In review of the literature, many studies did not observe an influence of increased n-3 and/or n-6 PUFA provided to sows in late gestation through lactation on litter gain (Fritsche et al., 1993; Lauridsen and Jensen, 2007; Leonard et al., 2011; Smits et al., 2011; Rosero et al., 2016b; Lavery et al., 2019; McDermott et al., 2020). Others that supplemented fish oils rich in n-3 PUFA or soybean oil rich in both n-3 and n-6 PUFA did detect an improvement in litter growth during lactation (Lauridsen and Danielsen, 2004; Mateo et al., 2009; Luo et al., 2013; Jin et al., 2017). It is difficult to clearly distinguish the cause for discrepancy across studies in this area. However, the lack of responses in some studies could be due to low inclusion levels of oil sources, comparison of oil sources with similar PUFA profiles, or limited treatment replication within experiments.

Colostrum and Milk Composition

Supplemental fat source and EFA composition did not influence ($P > 0.10$) crude protein, or crude fat content in colostrum or milk at weaning (Tables 7 and 8). Previously, researchers have observed greater colostrum and milk fat output when lactating sows consumed diets with increased energy density provided by supplemental lipids (Tilton et al., 1999; Park et al., 2008; Farmer and Quesnel, 2009; Krogh et al., 2012; Rosero et al., 2015; Peng et al., 2019). Furthermore, others have suggested that milk fat content may contribute to improved litter growth performance and pre-weaning litter survivability (Pettigrew, 1981; Bontempo and Jiang, 2015; Jin et al., 2017). However, similar to the current study, others did not distinguish an impact of supplemental fat in lactation diets on milk fat concentrations (Lauridsen and Danielson, 2004; Llaurodo-Calero et al., 2021).

The similarity in milk fat content among treatments in the present study would argue that improved litter growth may not be due to macronutrient composition of colostrum and milk alone, but rather EFA composition or increased milk production. Regardless of similarities within colostrum fat content in the current study, colostrum LA (C18:2n-6) and ALA (C18:3n-3) increased ($P < 0.05$) in response to the increased EFA composition of diets that contained soybean oil. Additionally, sows provided SO prior to farrowing produced colostrum with a greater proportion of EPA (C20:5n-3) compared to sows provided diets with low EFA ($P < 0.005$). However, EFA intake did not influence the proportion of DHA within colostrum ($P > 0.05$).

As observed in the present study, fatty acid composition of milk is highly influenced by dietary fatty acid composition (Tilton et al., 1999; Lauridsen and Danielsen, 2004). Additionally, modifications to dietary EFA composition or alteration of sow EFA intake prior to parturition

can impact colostrum LA and ALA (Yao et al., 2012; Decaluwe et al., 2014). Therefore, it was not surprising that the modifications in colostrum EFA composition were also observed in later lactation where sow milk at weaning contained increased ($P < 0.001$) concentrations of LA and ALA when supplemental fat was provided by soybean oil rather than choice white grease. Sows provided low EFA with the Control or CWG diets produced milk with greater palmitoleic acid (16:1n-9) compared to sows provided high EFA through SO or Combination treatments ($P < 0.001$). Furthermore, sows provided high EFA also produced milk with a greater proportion of EPA (C20:5n-3; $P < 0.001$), but the proportion of DHA (22:6n-3) was not influenced by dietary EFA intake ($P > 0.05$).

Subsequent Reproductive Performance

There was no evidence for differences in wean-to-estrus interval, percentage of sows bred by d 7, percentage of sows bred by d 12, or farrowing rate among treatments ($P > 0.10$; Table 9). Additionally, there was no influence of lactation diet fat source and EFA intake on subsequent farrowing performance ($P > 0.10$).

Reproductive performance of sows can be directly influenced by PUFA incorporation into oocyte cell membranes, ovarian follicle and embryonic development, cell signaling for pregnancy recognition and maintenance, eicosanoid production, and modulation of prostaglandin expression patterns (Weems et al., 2006; Wathes et al., 2007; Thatcher et al., 2010). In lactating cattle, implementation of nutritional strategies that increase EFA intake has been observed to improve fertility (Santos et al., 2008; Thatcher et al., 2011). For the lactating sow, follicle development begins during lactation (Soede et al., 2011). Furthermore, the greatest likelihood for sows to enter a negative EFA scenario is during the lactation period when daily EFA intake is limiting and tissue mobilization is required for milk EFA secretion, especially as sows advance

in parity (Rosero et al., 2015; Rosero et al. 2016a). Thus, dietary modifications to EFA in the lactation period could influence subsequent reproductive performance.

Previously, Smits et al. (2011) observed an increase in subsequent litter size when sows were supplemented fish oil providing n-3 FA during the previous lactation period. Additionally, a dose-response study was completed by Rosero et al. (2016b) to evaluate increasing dietary LA and ALA through blends of canola, corn, and flaxseed oils on subsequent performance of sows. The authors observed reductions in wean-to-estrus intervals and improved farrowing rates for parity 3 to 5 sows, suggesting a positive impact of additional dietary EFA to mature sows. In the present study, average parity of the herd was 4.8. Therefore, utilizing the EFA intake recommendations from the retrospective analysis of Rosero et al. (2016b), we were surprised to observe no evidence for differences in subsequent reproductive performance of sows in this older herd. However, this observed response did align with another study that evaluated the comparison of salmon or soybean oil inclusion that provided varying n-3 and n-6 FA profiles in lactation diets where subsequent reproductive performance of sows was not influenced (McDermott et al., 2020).

Additional research may be warranted to understand the mechanisms by which n-3 and n-6 FA influence sow reproductive performance to understand the discrepancies among studies. Furthermore, it is important to consider the likelihood of exacerbated parental EFA deficiency under conditions of extreme heat stress that may occur when lactating sows exhibit reduced feed intake and increased tissue mobilization to support milk EFA secretion (Rosero et al., 2016a; Boyd et al., 2019). In the present study, sows lactated between August 2020 and February 2021. As a result, only a small proportion of sows mated in late summer and early fall may have

experienced symptoms of heat stress that could have otherwise affected subsequent reproductive performance.

CONCLUSIONS

In summary, sows that consumed diets with high EFA sourced from soybean oil produced litters with greater lactation ADG and heavier weaning weights when compared to sows with lower LA and ALA intakes. Supplemental lipids and EFA composition did not influence colostrum and milk macronutrient composition, but LA and ALA were elevated in colostrum and milk of sows provided diets with high EFA. Although litter survivability was not influenced in the first 24 h post-partum or from 24 h to weaning, the modifications to colostrum and milk composition in partnership with elevated sow EFA intakes during lactation supported improved litter performance. Additionally, we did not observe an impact of lactation LA and ALA intake on subsequent sow reproductive or farrowing performance. Despite the advanced herd age evaluated in the present study, sows may not have entered an EFA-deficient state, so improvements in subsequent reproductive performance may not have been realizable. Nonetheless, it is important to consider the positive effect of colostrum and milk LA and ALA transfer that supported improved litter growth performance.

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Table 3.1. Diet composition (as-fed basis)¹

Item	Control	CWG	SO	Combination
Ingredient, %				
Corn	42.69	37.87	37.67	33.98
Soybean meal (47% CP)	27.45	29.50	29.85	31.50
Wheat, soft white	25.00	25.00	25.00	25.00
Choice white grease	0.50	3.00	---	2.00
Soybean oil	---	---	3.00	3.00
Calcium carbonate	1.10	1.10	1.10	1.10
Monocalcium phosphate (21% P)	1.15	1.25	1.25	1.30
Salt	0.50	0.55	0.55	0.55
Liquid Lys 50%	0.38	0.36	0.36	0.34
Liquid Met 88%	0.05	0.05	0.05	0.05
L-Thr	0.07	0.07	0.07	0.07
Choline chloride 60%	0.05	0.05	0.05	0.05
Trace mineral premix ²	0.12	0.12	0.12	0.12
Vitamin premix ³	0.06	0.06	0.06	0.06
Miscellaneous ⁴	0.88	1.02	0.87	0.88
Total	100.00	100.00	100.00	100.00
Calculated analysis				
SID AA, %				
Lys	1.03	1.07	1.07	1.10
Ile:Lys	68	71	72	74
Met:Lys	29	30	30	30
Met and Cys:Lys	56	57	57	58
Thr:Lys	66	68	69	70
Trp:Lys	20	21	21	22
Val:Lys	77	80	81	83
ME, kcal/kg	3,197	3,296	3,327	3,413
SID Lys:ME, g/Mcal	3.22	3.22	3.22	3.22
CP, %	19.2	19.8	19.9	20.4
Crude fat, %	2.58	4.92	4.91	6.79
Ca, %	0.70	0.73	0.73	0.74
Available P, %	0.41	0.43	0.43	0.44
Linoleic acid, %	1.29	1.38	2.79	2.87
α -Linolenic acid, %	0.07	0.08	0.38	0.39

¹Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

²Guaranteed analysis of premix: 12.00% Zn; 12.00% Fe; 4.00% Mn; 1.60% Cu; 0.032% I; 0.024% Se.

³Provided per kg of premix: 16,664,903 IU vitamin A; 2,333,333 IU vitamin D3; 166,667 IU vitamin E; 52.9 mg vitamin B12; 6,333 mg menadione; 13,333 mg riboflavin; 50,000 mg pantothenic acid; 4,000 mg thiamine; 60,000 mg niacin; 8,000 mg vitamin B6; 6,000 mg folic acid; 866.7 mg biotin; 267 mg chromium.

⁴Includes laxative product, flow agent, and dye coloring for treatment identification.

Table 3.2. Chemical analysis of diets (as-fed basis)^{1,2}

Item, %	Control	CWG	SO	Combination
DM	87.28	87.26	87.88	87.77
CP	19.6	19.8	20.0	20.6
Crude fat	2.53	4.76	4.84	6.52
Acid detergent fiber	3.09	3.11	3.00	3.14
Ash	5.42	5.59	5.57	5.65
Linoleic acid ³	1.25	1.54	2.64	2.88
α -Linolenic acid ³	0.09	0.12	0.35	0.39

¹Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). Diet samples were collected once weekly and pooled by month prior to analysis. Values represent the average analyzed composition from 6 samples collected between August 2020 to February 2021.

²Proximate analysis was completed by Midwest Laboratories (Omaha, NE).

³Fatty acid profile analysis was completed by the University of Missouri Experiment Station Chemical Laboratories (Columbia, MO).

Table 3.3. Reasons for sow removal and mortality^{1,2}

Reason	Control	CWG	SO	Combination
Early weaned sows ³	34	25	25	29
Prolapse				
Vaginal/uterine	13	17	15	14
Rectal	3	7	4	10
Uncategorized	6	2	3	2
Sow mortality				
Euthanized ⁴	15	7	7	9
Sudden death	24	16	18	27
Unknown	3	3	4	2
Total	98	77	76	93

¹Sows were removed from the final dataset due to incompleteness of full lactation period.

²Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

³Reasons for early wean include small litter size, inability to milk/low functional teats, illness.

⁴Reasons for euthanasia include difficulty farrowing, retained pigs, lameness, injured, and downer sows.

Table 3.4. Parity distribution of sows within experimental treatments¹

Parity	Control	CWG	SO	Combination	Total
2	96	86	90	90	362
3	80	118	108	93	399
4	214	205	201	207	827
5	200	192	188	192	772
6	128	131	125	121	505
7	46	40	64	78	228
8	51	60	56	56	223
9	35	33	42	25	135
Total	850	865	874	862	3,451

¹Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

Table 3.5. Effects of dietary fat source and essential fatty acid intake on lactating sow performance¹

Trait	Control	CWG	SO	Combination	SEM	<i>P</i> =
Sows, n	850	865	874	862	---	---
Parity	4.7	4.7	4.7	4.7	0.11	0.858
Pre-farrow days	4.6	4.6	4.6	4.6	0.12	0.528
Lactation length, d	24.1	24.1	24.0	24.1	0.11	0.733
Functional teats	14.9	14.9	14.9	14.9	0.13	0.999
Sow BW, kg						
d 112 gestation	248.6	249.7	249.0	249.1	1.29	0.832
Wean	242.9	243.9	244.5	244.8	1.41	0.478
Change	-5.7 ^b	-5.7 ^b	-4.5 ^{ab}	-4.1 ^a	0.83	0.090
Sow backfat, mm						
d 112 gestation	12.2	12.3	12.3	12.0	0.13	0.219
Wean	12.1 ^a	12.1 ^a	12.0 ^a	11.7 ^b	0.12	0.046
Change	-0.20	-0.17	-0.25	-0.22	0.085	0.857
Sow ADFI, kg						
Pre-farrow	1.81	1.81	1.81	1.81	0.001	0.546
Lactation	6.64 ^b	6.83 ^a	6.57 ^b	6.88 ^a	0.039	< 0.001
Lactation EFA intake, g/d						
Linoleic acid ²	83.0 ^d	105.1 ^c	173.6 ^b	198.4 ^a	0.83	< 0.001
α-linolenic acid ²	6.0 ^d	8.2 ^c	23.0 ^b	26.9 ^a	0.10	< 0.001
Total EFA ²	88.9 ^d	112.6 ^c	196.6 ^b	225.3 ^a	0.93	< 0.001
Farrowing performance						
Total pigs born, n	15.6	15.5	15.7	15.8	0.14	0.481
Pigs born alive, %	88.4 ^a	88.3 ^{ab}	87.9 ^{ab}	87.4 ^b	0.34	0.033
Stillborn, %	8.9 ^b	9.4 ^{ab}	9.4 ^{ab}	10.2 ^a	0.30	0.003
Mummy, %	2.6	2.3	2.7	2.4	0.15	0.276
Litter survivability, %						
Birth to 24 h ³	89.9	89.1	89.3	89.6	0.33	0.167
24 h to wean ⁴	89.7	90.0	90.0	89.6	0.33	0.751

^{a-d}Means within row with different superscripts differ (*P* < 0.05).

¹A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

²Calculated using analyzed LA and ALA values and overall lactation ADFI.

³Survival from birth to 24 h = [(Pigs born alive - count of mortality within 24 h)/Pigs born alive].

⁴Survival from 24 h to wean = count of pigs at weaning/count of pigs alive at 24 h.

Table 3.6. Effects of dietary fat source and essential fatty acid intake on litter performance¹

Trait	Control	CWG	SO	Combination	SEM	<i>P</i> =
Sows, n	850	865	874	862	---	---
Litter size, n						
Start ²	12.5	12.5	12.4	12.4	0.12	0.996
Wean	11.2	11.2	11.2	11.2	0.11	0.995
Litter weight, kg						
Total born	20.4	20.3	20.3	20.5	0.17	0.677
Born alive	18.7	18.5	18.5	18.5	0.16	0.881
Start ²	17.7	17.7	17.7	17.6	0.13	0.528
Wean	75.5 ^b	76.5 ^{ab}	77.1 ^a	77.3 ^a	0.62	0.028
Litter gain, kg ³	57.8 ^b	58.7 ^{ab}	59.4 ^a	59.7 ^a	0.56	0.006
Litter ADG, kg ⁴	2.46 ^b	2.51 ^{ab}	2.54 ^a	2.55 ^a	0.020	0.003
Piglet bodyweight, kg						
Total born	1.34	1.33	1.33	1.33	0.009	0.606
Born alive	1.38	1.37	1.37	1.37	0.009	0.689
Start ²	1.42	1.42	1.43	1.42	0.008	0.620
Wean	6.72 ^b	6.79 ^b	6.88 ^a	6.90 ^a	0.045	< 0.001
Piglet ADG, kg ⁵	0.218 ^c	0.222 ^b	0.225 ^a	0.227 ^a	0.0016	< 0.001

^{a-c}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

²Start litter size represents litter size within 24 h of farrowing after cross-fostering within treatment.

³Litter gain = litter weight at wean - litter weight at start.

⁴Litter ADG = litter gain \div lactation length.

⁵Piglet ADG = Litter ADG \div count of pigs at wean.

Table 3.7. Effects of dietary fat source and essential fatty acid intake on colostrum composition¹

Trait	Control	CWG	SO	Combination	SEM	<i>P</i> =
Crude protein, %	16.8	16.6	17.1	18.2	0.95	0.584
Crude fat, %	4.2	4.4	4.5	3.9	0.46	0.697
Fatty acid profile, % ²						
14:0	1.35	1.28	1.22	1.29	0.065	0.590
16:0	21.74	21.19	20.93	20.80	0.373	0.287
16:1n-9	2.90	3.03	2.63	2.55	0.183	0.227
18:0	5.43	5.35	5.21	5.07	0.234	0.704
18:1n-9	33.00 ^a	33.08 ^a	31.18 ^a	28.78 ^b	0.836	< 0.001
18:2n-6	23.06 ^b	23.29 ^b	26.04 ^{ab}	28.45 ^a	1.176	0.003
18:3n-3	1.02 ^b	1.13 ^b	1.69 ^a	1.91 ^a	0.143	< 0.001
20:4n-6	1.13	1.10	1.19	1.13	0.057	0.720
20:5n-3	0.056 ^c	0.068 ^{bc}	0.080 ^a	0.077 ^{ab}	0.005	0.004
22:6n-3	0.047	0.049	0.045	0.049	0.003	0.678
Other ³	8.01	8.18	7.64	7.68	0.193	0.140

^{ab}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). A subset of 10 sows per treatment were randomly selected for analysis of colostrum composition.

²Represented as a percentage of total colostrum fat.

³Contains 2% or less of the following: 14:1, 15:0, 17:0, 17:1, 18:1 t , 18:2 t , 18:3n-6, 20:0, 20:2, 21:0, 22:0, 23:0, 24:0, and unidentifiable fatty acids.

Table 3.8. Effects of dietary fat source and essential fatty acid intake on milk composition¹

Trait	Control	CWG	SO	Combination	SEM	<i>P</i> =
Crude protein, %	6.2	5.9	5.9	6.0	0.21	0.670
Crude fat, %	6.2	6.2	6.4	6.7	0.37	0.693
Fatty acids, % ²						
14:0	4.28 ^a	4.11 ^a	3.48 ^b	3.69 ^b	0.137	< 0.001
16:0	38.64 ^a	35.17 ^b	33.71 ^b	33.86 ^b	0.712	< 0.001
16:1n-9	12.57 ^a	12.00 ^b	9.99 ^c	9.41 ^c	0.400	< 0.001
18:0	3.80	3.87	3.46	3.71	0.142	0.108
18:1n-9	20.90 ^b	23.22 ^a	19.46 ^b	20.73 ^b	0.515	< 0.001
18:2n-6	12.68 ^b	14.00 ^b	21.51 ^a	19.82 ^a	0.615	< 0.001
18:3n-3	0.94 ^b	1.11 ^b	2.80 ^a	2.59 ^a	0.129	< 0.001
20:4n-6	0.36	0.37	0.34	0.30	0.021	0.078
20:5n-3	0.025 ^b	0.030 ^b	0.050 ^a	0.047 ^a	0.003	< 0.001
22:6n-3	0.010	0.011	0.011	0.010	< 0.001	0.316
Other ³	3.78 ^b	4.42 ^a	3.47 ^c	3.79 ^b	0.103	< 0.001

^{ab}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). A subset of 10 sows per treatment were randomly selected for analysis of milk composition at weaning.

²Represented as a percentage of total milk fat.

³Contains 2% or less of the following: 14:1, 15:0, 17:0, 17:1, 18:1 t , 18:2 t , 18:3n-6, 20:0, 20:2, 21:0, 22:0, 23:0, 24:0, and unidentifiable fatty acids.

Table 3.9. Effects of dietary fat source and essential fatty acid intake on subsequent reproductive performance of sows¹

Trait	Control	CWG	SO	Combination	SEM	<i>P</i> =
Wean to estrus interval, d	4.7	4.5	4.6	4.7	0.14	0.790
Bred by d 7, %	94.8	95.9	95.1	95.5	0.81	0.749
Bred by d 12, %	95.6	96.4	95.8	96.0	0.74	0.838
Farrowing rate, %	87.9	87.2	88.9	86.8	1.25	0.564
Farrowing performance						
Subsequent litters, n	648	637	655	637	---	---
Total born, n	14.6	14.6	14.4	14.4	0.15	0.563
Born alive, %	91.2 ^b	92.3 ^a	91.9 ^{ab}	91.3 ^{ab}	0.42	0.012
Stillborn, %	6.6 ^a	5.8 ^b	6.3 ^{ab}	7.1 ^a	0.35	0.001
Mummy, %	2.1 ^a	1.9 ^{ab}	1.7 ^{ab}	1.5 ^b	0.16	0.024

^{ab}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

Chapter 4 - Evaluation of supplemental fat sources and pre-farrow essential fatty acid intake on lactating sow performance and essential fatty acid composition of colostrum, milk, and adipose tissue

ABSTRACT

A total of 91 sows (Line 241, DNA Genetics) were used to evaluate the effects of supplemental fat sources and essential fatty acid intake on lactating sow farrowing performance, litter growth performance, and essential fatty acid composition of colostrum, milk, and adipose tissue. At approximately d 107 of gestation, sows were blocked by body weight and parity, then allotted to 1 of 5 experimental treatments as part of a $2 \times 2 + 1$ factorial arrangement. Experimental diets were corn-soybean meal-based with a control diet that contained no added fat, or diets with 3% added fat as either beef tallow or soybean oil, with consumption of the added fat diets starting on d 107 or 112 of gestation. Thus, sows were provided low essential fatty acids (EFA; as linoleic and α -linolenic acid) without supplemental fat or with beef tallow or high EFA with soybean oil. Sows were provided approximately 2.8 kg/d of their assigned lactation diet pre-farrow and then provided ad libitum access after parturition. Sows consuming diets with beef tallow had greater lactation ADFI (fat source, $P = 0.030$), but lower daily linoleic acid (LA) and α -linolenic acid (ALA) intake than sows that consumed diets with soybean oil (fat source, $P < 0.001$). Supplemental fat sources providing either low or high EFAs did not influence litter growth performance (fat source, $P > 0.05$). Sows fed the beef tallow diet did not influence LA composition of colostrum; however, lactation diets with high EFA provided by

soybean oil on d 107 of gestation increased colostrum LA composition compared to providing diets on d 112 of gestation (fat source \times time, $P = 0.084$; time, $P < 0.001$). Additionally, regardless of pre-farrow timing, ALA composition of colostrum increased when sows consumed diets with soybean oil compared to beef tallow (fat source, $P < 0.001$). Both LA and ALA concentrations of milk at weaning were greater for sows that consumed diets with soybean oil compared to beef tallow (fat source, $P < 0.001$). Furthermore, concentrations of LA and ALA within adipose tissue were higher at weaning when sows consumed diets with high EFA compared to low EFA (fat source, $P < 0.05$). These responses suggest that providing dietary fat sources with high concentrations of EFA can increase backfat, colostrum, and milk LA and ALA. However, in this experiment, changes in colostrum and milk composition did not alter litter growth performance.

Key words: colostrum, essential fatty acids, lactation, milk composition, sow

INTRODUCTION

Sows often do not consume enough feed during lactation to meet nutrient requirements and must mobilize body tissue reserves to maintain milk production and nutrient output to support litter growth (Strathe et al., 2017; Tokach et al., 2019). Inclusion of supplemental fat sources in lactation diets provides an opportunity to increase energy density and daily energy intake of sows to support rapid-growing litters. Dietary lipids also provide essential fatty acids (EFA) including linoleic acid (LA) and α -linolenic acid (ALA) that cannot be synthesized by the sow, although the amount provided is fat source dependent. Essential fatty acids support brain, vision, and immune system development and function of the neonatal pig (Innis, 2007; Kaur et al., 2014). Linoleic acid and ALA serve as precursors for conversion to long-chain

polyunsaturated fatty acids (LC-PUFA) such as arachidonic acid (ARA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). These polyunsaturated fatty acids are structurally important for phospholipid bilayers of cell membranes, eicosanoid synthesis for immune function and inflammatory response, and reproductive function (Kurklak and Stephenson, 1999; Calder, 2003; Ricotti and FitzGerald, 2011; Roszkos et al., 2020). Current diet recommendations for the lactating sow are 6.0 g/d LA, but no requirements for ALA is specified for optimal sow and litter performance (NRC, 2012). However, recent literature evaluating parental EFA requirements suggests that dietary intake should exceed 125 g/d of LA and 10 g/d of ALA to maximize reproductive performance of the lactating sow (Rosero et al., 2016a).

The lactating sow secretes significant amounts of EFA in colostrum and milk to support litter growth and therefore, insufficient LA and ALA intake during lactation can generate a state of deficiency that impairs subsequent reproductive function, especially as sows advance in parity and EFA reserves may become depleted (Rosero et al., 2015; Rosero et al., 2016a). Additionally, EFA composition of colostrum and milk is largely accepted to reflect that of dietary fat sources utilized in mid- to late- gestation (Lauridsen and Danielsen, 2004; Farmer and Quesnel, 2009; Yao et al., 2012; Decaluwe et al., 2014). Although colostrogenesis is believed to begin 7 to 10 days pre-farrow (Theil, 2014), the effects of providing supplemental fat with varying EFA composition shortly prior to farrowing is not clearly established. Therefore, transition of sows to consume high EFA shortly prior to farrowing may still influence colostrum and milk composition to support litter growth. The first objective of this trial was to evaluate the impact of lactation diets containing no supplemental fat (low EFA), beef tallow (low EFA), or soybean oil (high EFA) on EFA intake and colostrum, milk, and adipose tissue fatty acid composition. The second objective of this experiment was to evaluate the timing of feeding low or high EFA diets

prior to farrowing (approximately d 107 or 112 of gestation) on colostrum and milk EFA composition.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This trial was conducted at the Kansas State University Swine Teaching and Research Center (Manhattan, KS, USA). All diets were manufactured at the Kansas State University Poultry Unit (Manhattan, KS, USA).

Animals, Housing, and Treatments

A total of 91 sows (Line 241, DNA Genetics) were used across four batch farrowing groups from January to August 2020. On d 107 of gestation, sows were weighed and moved into the farrowing house. Sows were blocked by entry body weight and parity, then allotted to 1 of 5 experimental treatments as part of a $2 \times 2 + 1$ factorial arrangement. Experimental diets were corn-soybean meal-based and contained either no supplemental fat, 3% beef tallow or 3% soybean oil to provide low EFA in diets without supplemental fat or with beef tallow, or high EFA provided through soybean oil. Sows were assigned to begin consumption of experimental diets at either d 107 or d 112 of gestation. Sows were provided a common gestation diet until initiation of lactation dietary treatments. Additionally, sows assigned to the diet without supplemental fat (control) began consumption of the lactation diet at d 112 of gestation. All diets were formulated to meet or exceed NRC (2012) requirement estimates and contained 1.1% SID Lys (Table 1). From d 107 of gestation until farrowing, sows were offered approximately 2.8 kg/d of their respective dietary treatment distributed by an electronic feeding system (Gestal Solo Feeders, Jyga Technologies, Quebec City, Quebec, Canada). After farrowing, sows were then

allowed ad libitum access to feed. Sow feed intake was monitored by daily record keeping of feed additions and weighing remaining feed every 7 d until weaning.

Sow bodyweight and backfat depth at the P2 position were recorded at d 107 of gestation, after parturition, and at weaning (Renco Lean Meter, S.E.C. Repro Inc., Golden Valley, MN). Litters of pigs were cross-fostered within treatments within 48 h of parturition in an attempt to standardize litter size. Counts of pigs born alive, stillborn, and mummified were recorded for each sow. Piglets were individually ear notched within 24 h of parturition and weighed after completion of cross-fostering at 48 h postpartum and at weaning to evaluate litter growth performance. All instances and reasons for piglet mortalities were recorded. After weaning, sows were moved to individual gestation stalls and checked daily for signs of estrus to determine wean to first service interval.

Colostrum was collected from a subset of 50 sows (n = 10 per treatment) by hand stripping all functional teats, with an attempt to collect equal amounts from all teats for one representative sample within 12 h of the onset of parturition. Milk samples were also collected as previously described one day prior to weaning. To initiate milk letdown at weaning, 10 IU of oxytocin was administered via IM injection. All samples were immediately frozen and stored at -20°C until analysis.

Adipose tissue samples were collected at the P2 position from a sub-set of sows (n = 49) at d 107 of gestation and at weaning. For the d 107 samples, the site location was determined by following the curvature of the last rib to the vertebral column and moving 1.27 cm towards the posterior of the animal and 1.27 cm lateral from midline. For samples collected at weaning, the site was moved in a straight line 2.54 cm towards the posterior of the animal from the previous biopsy site. For all biopsies, the hair from the site was clipped and then cleaned with 95%

betadine followed by 70% ethanol. Next, 0.5-1 mL of 2% Lidocaine HCl with (1%) epinephrine was administered subcutaneously at the biopsy site and 10 min of wait time was followed to minimize pain associated with the biopsy procedure. After analgesia, a sterile 13-gauge \times 5.08 cm long sterile piercing needle was utilized to penetrate through the skin. A 14-gauge \times 5 cm long QuickCoreBiopsy Instrument (Cook Medical, Bloomington, IN) was then inserted through the punctured skin and oriented nearly parallel to the skin to obtain lean-free adipose biopsies. After collection of adipose tissue, the biopsy site was cleaned with dilute betadine (5 parts water:1 part betadine) and direct digital pressure was applied to achieve hemostasis. Samples were placed in labeled cryotubes and then placed on ice until they could be stored at -80°C for further processing and analysis.

Chemical Analysis

Diet samples were collected within each farrowing and pooled by treatment ($n = 4$ samples per treatment) before storage at -20°C and submission to commercial laboratories for proximate and fatty acid profile analysis (University of Missouri, ESCL, Columbia, MO, respectively; Table 2). Standard procedures (AOAC International, 2006) were followed for analysis of moisture (method 934.15), crude protein (method 990.03), ash (method 942.05), and fatty acid profiles (method 996.06). Analysis of ether extract (method 2003.05) was completed at Midwest Labs (Omaha, NE).

Colostrum and milk samples were sent to a commercial laboratory for analysis of ether extract (method 920.39) and complete fatty acid profiles of colostrum, milk, and adipose tissue were analyzed by gas chromatography coupled to a flame ionization detector at the Kansas Lipidomics Research Center (Kansas State University, Manhattan, KS).

Statistical Analysis

Data were analyzed using the GLIMMIX procedure in SAS (v. 9.4, SAS Institute, Inc., Cary, NC) and considered sow (litter) as the experimental unit. The statistical model considered fixed effects of fat source, pre-farrow start date, and random effects of block within farrowing group. The following data responses were fitted by a binomial distribution in the statistical model: percentage of pigs born alive, stillborn, mummified, survival of pigs from birth to d 2 and from d 2 to wean, and sow wean-to-estrus interval. The following response criteria were fitted with a Poisson distribution in the statistical model: count of total pigs born, pigs born alive, and litter size after cross-fostering and at weaning. All other response criteria were fit using a normal distribution. All data are reported as least square means and considered statistically significant at $P \leq 0.05$ and marginally significant at $0.05 \leq P \leq 0.10$.

RESULTS AND DISCUSSION

Sow Performance

As expected, average parity, lactation length, initial bodyweight (BW), and backfat depth of sows at d 107 of gestation in this study were similar across experimental treatments ($P > 0.10$; Table 3). Additionally, lactation BW change was not influenced by provision of dietary treatments pre-farrow or fat source ($P > 0.10$) and therefore, sow BW within 24 h of parturition and at weaning were similar across treatments ($P > 0.10$). As a result, Supplemental fat sources in lactation diets increase energy density and can increase caloric intake of sows to minimize circumstances where BW loss may occur. In a review by Rosero et al. (2016a), increased energy intake of lactating sows was summarized to reduce sow BW loss during lactation. However, in the present study, the addition of dietary fat did not appear to reduce BW or backfat change for sows provided either beef tallow or soybean oil when compared to sows provided the control diet

with lower energy density. Furthermore, two of the four sow groups as part of this study farrowed during the summer months and were likely exposed to high ambient temperatures. Given the reduced heat increment of dietary fat associated with digestion and metabolism, these environmental conditions should have provided an opportunity to reduce BW and increase backfat depth changes from parturition to weaning. However, previous evaluation of supplemental fat sources and levels during lactation yielded similar responses where sow BW and backfat change were not affected despite exposure to heat stress (Rosero et al., 2012a;b).

Sows provided diets with beef tallow had greater lactation ADFI than sows provided diets with soybean oil (fat source, $P < 0.05$). In a similar study that evaluated supplemental fat sources and EFA intake of lactating sows, ADFI was also observed to decrease when diets contained soybean oil compared to choice white grease (Holen et al., 2022). Typically, lactation ADFI of sows is reduced when energy density of the diet increases (Shurson and Irvin, 1992; Park et al., 2008; Xue et al., 2012). However, we did not observe any evidence for difference in sow ADFI between diets including supplemental fat and the control diet with lower dietary energy ($P > 0.10$).

Despite the differences in lactation feed intake, daily intake of LA and ALA was greater for sows that consumed diets with high EFA supplied by soybean oil compared to low dietary EFA supplied by beef tallow (fat source, $P < 0.001$) or diets without supplemental fat ($P < 0.05$). The NRC (2012) states that sows in lactation should consume at least 6 g/d of LA, but no ALA estimate is provided. However, it has been suggested that sows consume at least 125 g/d of LA and 10 g/d of ALA to prevent potential negative EFA balance during lactation, when significant amounts of LA and ALA are secreted in milk, and improve subsequent reproductive performance (Rosero et al., 2016a). In the present study, daily LA and ALA intake for sows provided soybean

oil exceeded these recommendations, whereas intakes of LA and ALA for sows provided diets with beef tallow or without supplemental fat did not meet these recommendations. Although sows provided high EFA secreted greater LA and ALA in milk when compared to sows provided low EFA (fat source, $P < 0.001$) throughout lactation, daily retention of the EFA were still greater (fat source, $P < 0.001$). Regardless of daily LA and ALA intake, however, sows in the present study did not exhibit negative EFA balances.

Sows that consumed lactation diets with soybean oil tended to produce larger litter sizes compared to sows that consumed diets with supplemental beef tallow diet (fat source, $P = 0.068$). In the present study, dietary treatments were applied to sows at either d 107 or d 112 of gestation and, therefore, the differences observed are likely a result of biological variation within the small sample size of sows, rather than true fat source or pre-farrow treatment influences. Furthermore, sows that began consumption of diets with low EFA supplied by beef tallow on d 107 produced fewer stillborn pigs and had an increased percentage of piglets born alive compared to sows with low EFA beginning on d 112 or soybean oil on d 107, whereas the other treatments were intermediate (fat source \times time, $P < 0.001$). As stated in a review completed by Tanghe and De Smet (2013), published studies that have evaluated the effects of PUFA in maternal diets on sow reproductive performance did not yield any influence on stillbirths. As a result, the reduction in stillbirths may need further investigation before a direct association of lower EFA intake or provision of lactation diets on d 107 compared to d 112 of gestation is distinguished. There was no evidence for differences among treatments in the percentage of mummified pigs produced per litter ($P > 0.10$).

Wean-to-estrus interval increased by 0.3 d when sows began consumption of diets with soybean oil on d 112 of gestation compared to d 107, but for sows assigned to the beef tallow

diet, wean-to-estrus intervals decreased by 0.3 d when supplementation started on d 112 compared to d 107 (fat source \times time, $P = 0.061$, fat source, $P = 0.024$). Essential fatty acids can directly influence sow reproductive performance through PUFA incorporation in oocytes, production of eicosanoids, cell signaling for pregnancy retention, and prostaglandin metabolism (Weems et al., 2006; Wathes et al., 2007; Thatcher et al., 2010). By mitigating scenarios of EFA deficiency during lactation, subsequent reproductive performance of sows has been observed to improve (Smits et al., 2011; Rosero et al., 2016a;b). In the present study, we did not evaluate subsequent farrowing performance of sows. However, we did not expect to observe poorer wean-to-estrus intervals for sows provided high EFA. It is possible that the numerical increase in BW loss and backfat change for sows with high LA and ALA intake compared to sows that were provided diets with beef tallow influenced this observation. Nonetheless, average wean-to-estrus interval was 4.6 d or less for all treatments. Additionally, further treatment replication is likely necessary to validate this response.

Piglet Survivability and Growth Performance

Litter size at 48 h of age and at weaning were not different among treatments ($P > 0.10$; Table 4). This reflects the reduced piglet survivability from birth to 48 h of life that occurred among the larger litters of sows that consumed diets with soybean oil starting at d 112 of gestation (fat source \times time, $P = 0.035$). However, from d 2 of lactation to weaning, piglet survivability was similar across treatments ($P > 0.10$). The impact of supplemental fat sources and dietary PUFA on litter survivability within the available literature are conflicting. While some have observed positive impacts of supplemental fat as either plant or fish oils with increased LA and ALA content on pre-weaning survivability (Rooke et al., 2001; Quiniou et al., 2008; Farmer et al., 2010; Jin et al., 2017; Lavery et al., 2019), others did not observe overall

evidence for differences (Mateo et al., 2009; Rosero et al., 2012a,b). It is important to note, however, that the sample size utilized within this experiment was not intended to evaluate the impact of EFA intake on litter survivability, as the study population was relatively small. To further investigate the influence of sow EFA intake and supplemental fat sources on pre-weaning mortality, additional treatment replication is recommended.

Because of the larger litters, sows that began consuming diets with soybean oil on d 112 of gestation also produced heavier litters of piglets compared to sows that began consuming beef tallow diets on d 107 of gestation (fat source \times time, $P = 0.009$). However, overall litter gain, litter ADG, and piglet ADG were similar among treatments (fat source \times time, $P > 0.10$). Although variation in supplemental fat sources and inclusion levels that provide different PUFA profiles exists, our responses align with others that did not observe an impact of sow EFA intake on litter growth performance (Fritsche et al., 1993; Lauridsen and Jensen, 2007; Leonard et al., 2011; Smits et al., 2011; Rosero et al., 2016b; Lavery et al., 2019; McDermott et al., 2020). Even though growth performance and litter survivability do not appear to be affected by sow EFA intake in this study, it is important to still consider the positive impact of LC-PUFA incorporation to cell membranes for gastrointestinal function and inflammatory immune response of pigs (Calder, 2003; Farmer et al., 2010; Leonard et al., 2011; Calder, 2013; Peng et al., 2019; Lauridsen, 2020).

Colostrum and Milk Concentrations

There was no interactive effect of fat source and provision of treatments pre-farrow on fat content of colostrum or milk at weaning (fat source \times time, $P > 0.10$; Tables 5 and 6). However, sows that consumed diets with beef tallow had marginally greater concentrations of colostrum total fat compared to sows that consumed diets with soybean oil (fat source, $P = 0.076$).

Regardless of fat source, supplementation of diets with increased energy density through added fat has been observed to increase colostrum total lipids (Jackson et al., 1995; Christon et al., 1999; Park et al., 2008). Although fat concentration is considered to be the most variable of milk components, added fat in lactation diets commonly increases milk fat content (Tilton et al., 1999; Heo et al., 2008; Park et al., 2008; Rosero et al., 2015). Furthermore, increased milk fat content has been observed to contribute to improved litter growth performance and pre-wean litter survivability (Pettigrew, 1981; Bontempo and Jiang, 2015; Jin et al., 2017). However, in the present study, only sows provided diets with beef tallow at d 112 of gestation had greater lipid content of colostrum compared to the control diet without added fat ($P < 0.065$), and there was no evidence for differences among treatments in milk lipid content ($P > 0.10$). The similarity in milk lipid content among dietary treatments may explain the lack of response in litter growth performance in the present study.

Fatty acid composition of milk highly reflects fatty acid composition of the diet (Tilton et al., 1999; Lauridsen and Danielsen, 2004; Farmer and Quesnel, 2009; Rosero et al., 2015). Although there were no interactive effects of pre-farrow timing and fat source on colostrum fatty acid profile (fat source \times time, $P > 0.10$), the source of added fat provided to diets for sows pre-farrow modified the fatty acid profile of colostrum for all fatty acids except vaccenic acid (18:1t; fat source, $P < 0.10$). Furthermore, provision of lactation diets at either d 107 or d 112 of gestation did not influence LA composition of colostrum between sows fed low EFA supplied by beef tallow but providing lactation diets with soybean oil to sows at d 107 increased colostrum LA concentration compared to providing soybean oil diets to sows on d 112 of gestation (fat source \times time, $P = 0.084$; time, $P < 0.001$). Regardless of pre-farrow diet consumption, colostrum ALA increased when sows consumed diets with soybean oil compared to beef tallow

(fat source, $P < 0.001$). Colostrogenesis is believed to primarily occur in the last 7 to 10 days of gestation (Theil et al., 2014). However, initiation of colostrum fat synthesis prior to farrowing is yet to be determined (Theil, 2015). Previously, alteration of sow EFA intake from d 108 of gestation has been observed to influence LA and ALA content of colostrum (Yao et al., 2012; Decaluwe et al., 2014). In the present study, there was no evidence for difference between provision of lactation diets on d 107 compared to d 112 of gestation on lipid or ALA content of colostrum. Therefore, it is probable that nutritional strategies implemented at d 112 of gestation provide an equal opportunity to influence colostrum FA composition.

Fatty acid profiles of milk at weaning were also influenced by dietary fat source, however, changes in composition were not evident among every fatty acid. For sows provided beef tallow, myristic (14:0) and palmitic (16:0) fatty acid concentrations within milk were greater than for sows provided soybean oil (fat source, $P < 0.06$). Additionally, milk LA (18:2) and ALA (18:3n-3) concentration at weaning were significantly greater when sows consumed high EFA provided by soybean oil compared to low EFA provided by beef tallow in lactation diets (fat source, $P < 0.001$). Additionally, ETA (20:3n-3) content of milk tended to increase when sows were provided soybean oil compared to beef tallow (fat source, $P = 0.051$), however, ARA (20:4) was not influenced by EFA intake. These responses confirm that dietary fat sources certainly influence fatty acid profiles of colostrum and milk and that providing fat sources with high dietary EFA prior to farrowing can increase both colostrum and milk LA and ALA concentrations.

Sow Adipose Tissue

Although the lactating sow primarily secretes significant amounts of EFA in colostrum and milk, EFA can also be deposited into adipose tissue and cell membranes (Rosero et al.,

2016a). Should sows enter a negative energy balance or if daily EFA intake during lactation becomes limited, endogenous input and mobilization of EFA into milk will occur to support litter growth and development (Rosero et al., 2015; Rosero et al. 2016a). To assess changes in fatty acid profiles of adipose tissue in the lactating sow, samples were collected near the last rib on d 107 of gestation and at weaning (Table 7). As expected, fatty acid profiles among sows were similar at entry to the farrowing room on d 107 of gestation ($P > 0.05$). Additionally, fatty acid profiles of adipose tissue among sows at weaning was similar across dietary treatments, with the exception of LA and ALA fatty acids. Sows that consumed diets with high EFA supplied by soybean oil had greater concentrations of LA and ALA within adipose tissue at weaning compared to sows provided low EFA through beef tallow (fat source, $P < 0.05$). To our knowledge, this is one of the first studies conducted to assess EFA intake and adipose tissue EFA composition in lactating sows. It is important to consider the potential influence of lactation ADFI when interpreting the observed results in adipose tissue EFA composition. In the present study, sows provided diets with beef tallow had greater ADFI than sows provided diets with soybean oil. Additionally, although not statistically different ($P > 0.10$), sows assigned to diets with high EFA had numerically greater BW and backfat loss during lactation.

CONCLUSIONS

In summary, although sows consuming diets with beef tallow exhibited greater lactation ADFI, providing diets with soybean oil increased daily LA and ALA intake during the lactation period. Provision of supplemental fat sources at either d 107 or d 112 pre-farrow did not influence colostrum or milk lipid content; however, providing diets with high EFA supplied by soybean oil increased both colostrum and milk LA and ALA content compared to diets containing beef tallow or without supplemental fat. Therefore, transitioning sows to lactation

diets approximately 4 d prior to farrowing can alter colostrum and milk EFA. In the present study, these changes did not influence litter growth performance.

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Table 4.1. Diet composition (as-fed basis)

Item	Control	Beef tallow	Soybean oil
Ingredient, %			
Corn	63.28	60.05	60.05
Soybean meal, 47% CP	32.82	33.05	33.05
Beef tallow	---	3.00	---
Soybean oil	---	---	3.00
Calcium carbonate	1.25	1.25	1.25
Monocalcium phosphate (21% P)	1.15	1.15	1.15
Salt	0.50	0.50	0.50
L-Lys-HCl	0.15	0.15	0.15
DL-Met	0.08	0.08	0.08
L-Thr	0.05	0.05	0.05
Sow add pack ¹	0.15	0.15	0.15
Trace mineral premix ²	0.25	0.25	0.25
Vitamin premix ³	0.25	0.25	0.25
Phytase ⁴	0.08	0.08	0.08
Total	100.00	100.00	100.00
Calculated analysis			
SID AA, %			
Lys	1.10	1.10	1.10
Ile:Lys	70	70	70
Leu:Lys	143	141	141
Met:Lys	33	33	33
Met and Cys:Lys	59	59	59
Thr:Lys	64	64	64
Trp:Lys	21	21	21
Val:Lys	76	75	75
His:Lys	46	45	45
SID Lys:NE, g/Mcal	4.61	4.38	4.35
NE, kcal/kg	2,385	2,511	2,531
CP, %	21.2	20.9	20.9
Ca, %	0.92	0.92	0.92
STTD P, %	0.51	0.51	0.51
Linoleic acid, %	1.41	1.45	2.84
α -Linolenic acid, %	0.07	0.09	0.27

¹Provided per kg of premix: 1,653,467 IU vitamin A; 8,818 IU vitamin E; 88 mg biotin; 882 mg folic acid; 397 mg pyridoxine; 220,462 mg choline; 19,842 mg carnitine; 80 mg chromium.

²Provided per kg of premix: 1,653,467 IU vitamin A; 661,387 IU vitamin D; 17,637 IU vitamin E; 1,323 mg vitamin K; 13 mg vitamin B₁₂; 19,842 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin.

³Provided per kg of premix: 73,413 mg Zn from zinc sulfate; 73,413 mg Fe from iron sulfate; 22,046 mg Mn from manganese oxide; 11,023 mg Cu from copper sulfate; 19,841 mg I from calcium iodate; 19,841 mg Se from sodium selenite.

⁴Assumed release value of 0.12% STTD P from Ronozyme HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ).

Table 4.2. Chemical analysis of diets (as-fed basis)^{1,2}

Item, %	Control	Beef tallow	Soybean oil
Dry matter	87.91	88.46	88.22
Crude protein	20.6	19.6	20.0
Crude fat ³	2.60	5.22	5.53
Crude fiber	2.38	2.28	2.24
Ash	5.92	6.74	6.28
Linoleic acid	1.38	1.53	2.82
α -Linolenic acid	0.08	0.08	0.26

¹Diet samples were pooled by farrowing group prior to analysis. Values represent the analyzed composition from 4 samples collected between January and August 2020.

²Proximate analyses and fatty acid profile analyses were completed by the University of Missouri Experiment Station Chemical Laboratories (Columbia, MO).

³Crude fat analyses were completed by Midwest Laboratories (Omaha, NE).

Table 4.3. Effect of dietary fat source and timing of diets offered pre-farrow on lactating sow performance¹

Trait	Control	Beef tallow		Soybean oil		SEM	<i>P</i> =		
		d 107	d 112	d 107	d 112		Fat × time	Fat source	Time
Sows, n	18	16	18	19	20	---	---	---	---
Parity	1.2	1.3	1.2	1.2	1.3	0.26	0.619	0.831	0.701
Lactation length, d	19.2	19.1	19.2	19.2	18.9	0.15	0.189	0.321	0.673
Sow BW, kg									
d 107 gestation	246.0	244.1	241.5	248.0	245.8	6.40	0.947	0.102	0.338
Post-farrow	236.8	237.4	231.4	233.1	235.0	6.31	0.156	0.909	0.466
Wean	228.4	231.1	224.4	222.2	227.4	6.76	0.097	0.409	0.838
Change ²	-7.4	-4.6	-5.8	-11.4	-8.1	3.21	0.447	0.130	0.729
Sow backfat, mm									
d 107	13.4	14.0	13.1	13.9	14.3	0.55	0.166	0.270	0.619
Post-farrow	13.1 ^{ab}	13.8 ^a	12.4 ^b	12.8 ^{ab}	13.3 ^{ab}	0.52	0.058	0.862	0.318
Wean	11.1	12.0	10.8	10.9	11.1	0.50	0.132	0.367	0.309
Change ²	-1.9	-1.8	-1.5	-2.0	-2.2	0.39	0.578	0.247	0.805
Sow ADFI, kg									
Lactation	5.7	6.3	6.1	5.5	5.9	0.25	0.138	0.030	0.704
Linoleic acid intake, g/d ³	78.5 ^c	95.9 ^b	92.7 ^b	154.4 ^a	166.1 ^a	4.90	0.110	< 0.001	0.360
α-linolenic acid intake, g/d ³	4.6 ^c	5.0 ^c	4.9 ^c	14.2 ^b	15.3 ^a	0.41	0.118	< 0.001	0.216
Farrowing performance									
Total pigs born, n	16.6	15.9	16.4	17.4	18.6	0.99	0.730	0.068	0.371
Pigs born alive, %	90.3 ^{ab}	93.6 ^a	85.1 ^b	86.0 ^b	91.0 ^{ab}	2.10	< 0.001	0.446	0.271
Stillborn, %	7.3 ^{ab}	5.2 ^b	13.4 ^a	12.2 ^a	7.4 ^{ab}	1.90	< 0.001	0.521	0.255
Mummy, %	1.6	0.8	1.1	1.3	1.1	0.63	0.662	0.666	0.824
Milk yield, kg/d ⁴	5.59	5.57	5.73	5.48	5.76	0.367	0.847	0.934	0.497
Milk EFA secreted ⁵									

Linoleic acid, g/d	62.8 ^b	55.6 ^b	57.3 ^b	81.1 ^{ab}	103.8 ^a	6.48	0.102	< 0.001	0.060
α -linolenic acid, g/d	3.4 ^c	3.1 ^c	3.0 ^c	6.5 ^b	8.7 ^a	0.47	0.021	< 0.001	0.026
EFA retained ⁶									
Linoleic acid, g/d	19.4 ^b	39.4 ^b	41.4 ^b	73.7 ^a	71.7 ^a	7.16	0.758	< 0.001	0.988
α -linolenic acid, g/d	1.4 ^b	1.9 ^b	2.1 ^b	7.7 ^a	7.4 ^a	0.46	0.648	< 0.001	0.967
Wean to estrus interval, d	4.2 ^{ab}	4.3 ^{ab}	4.0 ^b	4.3 ^{ab}	4.6 ^a	0.15	0.061	0.024	0.904

^{a-c}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 91 sows (Line 241, DNA Genetics, Columbus, NE) and their litters were used in 4 farrowing groups over 28-d experimental periods with 16 to 20 sows per treatment.

²Represents change from post-farrow to wean.

³Calculated using analyzed LA and ALA values and overall lactation ADFI.

⁴Calculated using estimated milk energy output (kcal/d) \div milk energy density (kJ/g). The NRC (2012) equation was used to calculate milk energy output as $(4.92 \times \text{litter gain, g/d}) - (90 \times \text{litter size at weaning})$ and assumed milk energy content at 5.0 kJ/d (Hurley, 2015).

⁵Milk EFA secreted calculated as analyzed milk EFA (as LA or ALA) \times milk yield.

⁶EFA retained calculated as EFA intake (as LA or ALA) $-$ milk EFA secreted (as LA or ALA).

Table 4.4. Effects of fat source and diet consumption pre-farrow on litter performance^{1,2}

Trait	Control	Beef tallow		Soybean oil		SEM	<i>P</i> =		
		d 107	d 112	d 107	d 112		Fat × time	Fat source	Time
Litter count, n									
Birth	14.8	14.9	13.6	14.8	16.7	0.96	0.085	0.102	0.769
d 2	13.7	13.6	12.8	13.8	14.2	0.92	0.489	0.342	0.813
Wean	12.8	13.0	12.4	13.0	13.6	0.90	0.460	0.459	0.996
Piglet survivability, %									
Birth to d 2	93.6 ^{ab}	94.1 ^{ab}	94.2 ^{ab}	95.3 ^a	88.1 ^b	1.86	0.035	0.257	0.042
d 2 to wean	94.4	96.1	97.6	95.1	96.6	1.33	0.912	0.387	0.200
Litter weight, kg									
Birth	20.5 ^{ab}	22.2 ^a	19.1 ^b	20.8 ^{ab}	21.6 ^{ab}	0.78	0.009	0.459	0.102
d 2	19.3	21.5	20.1	20.8	20.4	0.86	0.536	0.787	0.249
Wean	66.9	69.1	68.8	67.9	69.6	3.46	0.767	0.942	0.820
Litter gain, kg ³	47.6	47.4	48.8	47.0	49.2	2.91	0.887	0.997	0.505
Litter ADG, kg ³	2.94	2.93	3.00	2.89	3.04	0.184	0.798	0.995	0.515
Pig bodyweight, kg									
Birth	1.37	1.51	1.41	1.40	1.30	0.067	0.985	0.103	0.123
d 2	1.42	1.62	1.62	1.52	1.47	0.064	0.618	0.042	0.624
Wean	5.21	5.41	5.62	5.22	5.16	0.212	0.477	0.101	0.685
Pig ADG, kg ³	0.192	0.194	0.206	0.188	0.193	0.0093	0.702	0.251	0.293

^{ab}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 91 sows (Line 241, DNA Genetics, Columbus, NE) and their litters were used in a 28-d study.

²Cross-fostering of piglets occurred within treatment to standardize litter size within 48-h post-farrow.

³Represents data from d 2 of lactation to wean.

Table 4.5. Effects of fat source and diet consumption pre-farrow on colostrum fatty acid composition^{1,2}

Trait	Control	Beef tallow		Soybean oil		SEM	<i>P</i> =		
		d 107	d 112	d 107	d 112		Fat × time	Fat source	Time
Total fat, %	5.16 ^b	5.35 ^{ab}	5.68 ^a	5.22 ^{ab}	5.17 ^b	0.17	0.272	0.076	0.417
Fatty acids, % ²									
14:0	1.99 ^a	2.09 ^a	1.98 ^{ab}	1.43 ^b	1.71 ^{ab}	0.154	0.153	0.004	0.571
16:0	25.03 ^a	23.67 ^{ab}	23.22 ^{ab}	21.47 ^b	22.37 ^{ab}	0.851	0.398	0.068	0.776
16:1n-9	3.29	2.99	3.13	2.61	2.76	0.214	0.981	0.078	0.485
18:0	5.79	5.77	5.78	5.00	5.20	0.268	0.697	0.019	0.685
18:1 _t	2.64	2.42	2.62	2.37	2.33	0.098	0.233	0.098	0.418
18:1n-9	28.44	32.30	33.54	29.88	29.53	1.724	0.611	0.057	0.778
18:2n-6	26.19 ^{bc}	23.25 ^c	23.64 ^c	32.13 ^a	28.25 ^b	1.219	0.084	0.155	< 0.001
18:3n-3	1.50 ^b	1.40 ^b	1.27 ^b	2.41 ^a	2.19 ^a	0.143	0.743	< 0.001	0.239
20:3n-3	0.076	0.068	0.064	0.082	0.083	0.005	0.557	0.002	0.736
20:4	1.37	1.31	1.28	1.17	1.17	0.060	0.843	0.035	0.827
Other ³	2.36 ^{ab}	2.48 ^a	2.37 ^{ab}	2.01 ^c	2.07 ^{bc}	0.092	0.342	< 0.001	0.806

^{a-c}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 91 sows (Line 241, DNA Genetics, Columbus, NE) and their litters were used in a 28-d study. 10 sows per treatment were randomly selected for collection and analysis of colostrum fatty acid profiles.

²Percentage of fatty acids by weight.

³Contains 2% or less of the following fatty acids: 17:0, 17:1, 18:3n-6, 20:0, 20:1, 20:2, and 20:3n-6.

Table 4.6. Effects of fat source and diet consumption pre-farrow on milk fatty acid composition^{1,2}

Trait	Control	Beef tallow		Soybean oil		SEM	<i>P</i> =		
		d 107	d 112	d 107	d 112		Fat × time	Fat source	Time
Total fat, %	8.03	7.27	7.59	8.15	8.30	0.572	0.885	0.161	0.672
Fatty acids, % ²									
14:0	4.05	4.42	4.57	3.85	3.93	0.222	0.855	0.006	0.603
16:0	33.88	34.90	34.47	31.94	32.60	1.300	0.659	0.058	0.927
16:1n-9	12.76	13.14	12.95	11.44	10.90	0.996	0.855	0.055	0.698
18:0	4.08	3.95	3.95	3.63	3.80	0.190	0.642	0.201	0.621
18:1 <i>t</i>	2.14	1.91	2.01	1.98	1.85	0.114	0.270	0.662	0.892
18:1n-9	30.25	28.62	30.03	29.04	27.72	1.571	0.364	0.528	0.978
18:2n-6	10.36 ^b	9.83 ^b	9.51 ^b	15.10 ^a	16.21 ^a	0.736	0.311	< 0.001	0.575
18:3n-3	0.56 ^b	0.55 ^b	0.51 ^b	1.20 ^a	1.37 ^a	0.062	0.102	< 0.001	0.290
20:3n-3	0.036	0.031	0.029	0.038	0.043	0.005	0.508	0.051	0.751
20:4	0.483	0.442	0.411	0.463	0.426	0.045	0.945	0.686	0.423
Other ³	1.65	1.65	1.68	1.73	1.48	0.15	0.350	0.663	0.449

^{a-c}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 91 sows (Line 241, DNA Genetics, Columbus, NE) and their litters were used in a 28-d study. 10 sows per treatment were randomly selected for collection and analysis of milk fatty acid profiles.

²Percentage of fatty acids by weight.

³Contains 2% or less of the following fatty acids: 17:0, 17:1, 18:3n-6, 20:0, 20:1, 20:2, and 20:3n-6.

Table 4.7. Effects of fat source and diet consumption pre-farrow on last-rib adipose tissue fatty acid composition^{1,2}

Trait	Control	Beef tallow		Soybean oil		SEM	<i>P</i> =		
		d 107	d 112	d 107	d 112		Fat × time	Fat source	Time
d 107 gestation									
Fatty acid profile, % ²									
14:0	1.22	1.19	1.10	1.15	1.06	0.108	0.990	0.715	0.424
16:0	23.32	22.59	22.65	23.45	22.47	0.655	0.401	0.580	0.463
16:1n-9	2.10	2.09	2.29	2.26	2.10	0.149	0.184	0.913	0.919
18:0	13.17	12.95	12.43	16.08	12.78	1.978	0.471	0.365	0.321
18:1 _t	2.80	2.95	3.07	2.94	2.94	0.154	0.644	0.627	0.642
18:1n-9	40.14	40.91	41.11	38.22	40.62	1.558	0.462	0.286	0.391
18:2n-6	13.55	13.46	13.15	14.20	14.04	0.447	0.851	0.575	0.056
18:3n-3	0.61	0.57	0.53	0.65	0.54	0.047	0.390	0.089	0.308
20:3n-3	0.32	0.35	0.33	0.27	0.32	0.056	0.175	0.085	0.407
20:4	0.19	0.22	0.24	0.22	0.25	0.030	0.943	0.948	0.366
Other ³	2.73	2.94	2.91	2.83	2.84	0.126	0.890	0.443	0.919
Weaning									
Fatty acid profile, % ²									
14:0	1.03	0.86	0.88	0.97	0.80	0.151	0.500	0.909	0.627
16:0	22.62	21.20	21.61	22.21	21.46	0.607	0.340	0.470	0.775
16:1n-9	1.91	1.84	2.11	2.01	1.93	0.147	0.178	0.996	0.454
18:0	14.20	14.12	13.11	13.52	14.09	0.782	0.231	0.764	0.737
18:1 _t	2.85	2.98	3.18	2.79	3.05	0.162	0.837	0.252	0.116
18:1n-9	39.11	41.18	40.84	38.94	39.98	0.804	0.284	0.019	0.587
18:2n-6	13.93 ^{ab}	13.34 ^{ab}	13.73 ^b	14.95 ^a	14.32 ^{ab}	0.512	0.262	0.018	0.794
18:3n-3	0.46	0.49	0.46	0.59	0.55	0.046	0.966	0.048	0.467
20:3n-3	0.36	0.36	0.37	0.35	0.38	0.029	0.818	0.883	0.473
20:4	0.27	0.35	0.65	0.24	0.36	0.189	0.588	0.250	0.221
Other ³	3.27	3.24	3.25	2.07	3.17	0.166	0.743	0.357	0.705

^{a-c}Means within row with different superscripts differ ($P < 0.05$).

¹A total of 91 sows (Line 241, DNA Genetics, Columbus, NE) and their litters were used in a 28-d study. A subset of sows ($n = 49$; 9 to 10 sows/treatment) were randomly selected and biopsied for evaluation of adipose tissue essential fatty acid composition.

²Percentage of fatty acids by weight.

³Contains 1% or less of the following fatty acids: 17:0, 17:1, 18:3n-6, 20:0, 20:1, 20:2, and 20:3n-6.

Chapter 5 - Effects of increasing soybean meal in corn-based diets on the growth performance of late finishing pigs

ABSTRACT

Three experiments were conducted to determine the effects of increasing soybean meal (SBM) levels in replacement of feed-grade amino acids (AA) in corn, corn-dried distillers grains with solubles (DDGS), and corn-wheat midds-based diets on growth performance of late finishing pigs ($n = 4,406$) raised in commercial facilities. Across all experiments, pens of pigs were blocked by initial bodyweight (BW) and randomly assigned to 1 of 5 dietary treatments. All diets were formulated to contain 0.70% standardized ileal digestible (SID) Lys and varying amounts of feed grade AA to meet or exceed NRC (2012) AA requirement estimates. In Exp. 1, 1,793 pigs (initially 104.9 ± 1.4 kg) were fed corn-based diets and pens of pigs were assigned treatments with increasing SBM from 5 to 20%. Overall, average daily gain (ADG) and feed efficiency (G:F) improved (linear and cubic, $P \leq 0.02$) as dietary SBM increased, with the greatest improvement observed as SBM increased from 5 to 8.75% and little improvement thereafter. In Exp. 2, 1,827 pigs (initially 97.9 ± 1.1 kg) were used in a study similar to Exp. 1, but all diets contained 25% DDGS and SBM levels increased from 0 to 16%. Overall, feed efficiency marginally improved (linear, $P \leq 0.10$) as SBM increased, with the greatest performance observed when diets contained 8% SBM and similar performance thereafter with 12 or 16% dietary SBM. In Exp. 3, 786 pigs (initially 96.7 ± 1.1 kg) were used with diets that contained 30% wheat midds and increased dietary SBM from 0 to 16%. Final BW of pigs increased (linear, $P < 0.05$), and overall ADG and G:F improved as SBM increased (linear and cubic, $P < 0.05$). The combined results of the three experiments suggest that inclusion at least 4

to 8% dietary SBM at the expense of feed-grade amino acids in corn-based diets with or without grain co-products can improve growth performance of late-finishing pigs.

Keywords: amino acids, crude protein, finishing pigs, growth performance, soybean meal

INTRODUCTION

Soybean meal (SBM) is a key dietary component and commonly used protein source for swine due to its high digestibility, consistent processing methods, and excellent amino acid (AA) profile. However, diets for late-finishing pigs are often formulated to contain increasing amounts of feed-grade AA and grain co-products such as corn dried distillers grains with solubles (DDGS) and wheat midds to maintain animal growth performance while reducing the economic impact of feed costs and minimizing nitrogen excretion. Due to widespread availability and competitive costs of feed-grade AA, complete swine diets can be formulated to meet individual AA requirements that will result in partial or complete replacement of intact protein sources such as SBM that also provide non-essential AA. As a result, pigs in the late-finishing phase of growth often consume diets with little to no SBM.

Formulation of corn-based diets that meet AA requirements for swine through supplementation of feed-grade AA and low SBM inclusion contain low crude protein (CP) concentrations, which may compromise growth performance and carcass characteristics of finishing pigs (Soto et al., 2019). Recent studies that have evaluated replacement of SBM with other intact protein sources such corn gluten meal and soy protein concentrate in diets containing 12% CP observed linear reductions in growth performance of late-finishing pigs (Soto et al., 2018a; 2018b). Therefore, replacement of dietary SBM with other intact protein sourced from corn or wheat co-products may yield sub-optimal performance of pigs in the late-finishing phase

of growth if dietary CP is limiting and may suggest specific biological benefits to the pig when utilizing SBM.

Soybean meal contains biologically active compounds such as isoflavones, saponins, proteins, peptides, and omega-3 fatty acids that may be beneficial for immune response and growth performance of pigs exposed to health challenges (Omomi and Aluko, 2005; Smith and Dilger, 2018). Previously, diets with elevated SBM and reduced feed-grade AA have partially mitigated the negative impact of disease on growth performance of nursery and growing-finishing pigs (Johnston et al., 2010; Rochell et al., 2015).

Although the mechanism for the positive influence of dietary SBM on performance of health-challenged pigs is unclear, the impact of SBM bioactive components must be considered when considering optimal growth performance for late-finishing pigs. Additionally, the influence of partial or complete replacement of SBM through inclusion of feed-grade AA and grain co-products such as corn DDGS and wheat midds must be further evaluated for late-finishing pigs. Therefore, the objective of this experiment was to determine the level of SBM necessary in corn, corn-DDGS, and wheat midds-based diets for optimal growth performance of late-finishing pigs from approximately 100 kg to market.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. A total of three experiments were conducted at commercial research facilities in southwestern Minnesota (New Horizon Farms, Pipestone, MN and New Fashion Pork, Jackson, MN) between November 2019 and December 2020.

Ingredient Chemical Analysis

Prior to initiation of Exp. 1 and 3, samples of corn, SBM and wheat middlings were collected from each feed mill location and submitted to the University of Missouri Agricultural Experimental Station Chemical Laboratories (Columbia, MO) for proximate analyses and complete AA profiles. Standard procedures (AOAC International, 2006) were followed for analysis of amino acid content (method 982.30), moisture (method 934.01), CP (990.03), ether extract (method 920.39), crude fiber (method 978.10), and ash (method 942.05). The analyzed AA content and corresponding AA standard ileal digestible (SID) coefficients reported by NRC (2012) and proximate analysis values were utilized for diet formulation (Table 1). In Exp. 2, nutrient loading values and SID digestibility coefficients were derived from NRC (2012).

For each experimental diet within trial, representative diet samples were collected and stored at -20 °C until analysis. Complete diet samples were also analyzed for moisture, CP, ether extract, crude fiber, and ash content as per the standard procedures (Agricultural Experimental Station Chemical Laboratories, University of Missouri, Columbia, MO; Tables 2-4).

Animals and Diets

Experiments 1 and 2 were completed at a commercial research facility in southwestern Minnesota (New Horizon Farms, Pipestone, MN). The facility was a naturally ventilated and double-curtained-sided barn. Each pen (3.0 × 5.5 m) was equipped with a four-hole stainless steel dry feeder (Thorp Equipment Inc., Thorp, WI) and one cup waterer to allow *ad libitum* access to feed and water. Experiment 3 was completed in a tunnel-ventilated barn with completely slatted flooring over deep pits for manure storage (New Fashion Pork, Jackson, MN). Each pen (2.4 × 5.8 m) was equipped with a three-hole stainless steel dry feeder (Thorp Equipment Inc., Thorp, WI) and a pan waterer to allow *ad libitum* access to feed and water. For

all experiments, daily feed additions for each pen were recorded through a robotic feeding system (FeedPro, Feedlogic Corp., Wilmar, MN).

In Exp. 1, two groups with a total of 1,793 pigs (L337 × 1050, PIC, Hendersonville, TN; initially 104.9 ± 1.1 kg) were used with 22 to 27 pigs placed per pen and 12 to 14 pens per treatment. Pens of pigs were blocked by initial BW and randomly assigned to 1 of 5 dietary treatments in a randomized complete block design. Soybean meal levels within corn-based diets gradually increased from 5 to 20% in 3.75% increments and replaced feed grade AA. All dietary treatments were formulated to be isocaloric and contained 0.70% SID Lys (Table 2). Furthermore, additions of feed grade AA within diets were adjusted to ensure similar ratios for Leu, Ile, Met & Cys, Thr, Trp, Val, and His among treatments between the two experimental groups. The NE of SBM used in diet formulation was 2,672 kcal/kg (as-fed basis) to represent 100% of the corn NE reported in the NRC (2012). Pens of pigs were weighed and feed disappearance measured on d 0, 13, and 23 or on d 0, 14, and 35 for group one and two, respectively, to determine average daily gain (ADG), average daily feed intake (ADFI), and feed efficiency (G:F). On d 13 and 21 of the experimental period for groups one and two, respectively, three pigs within each pen were marketed. The remaining pigs were then marketed at the conclusion of the experiment.

In Exp. 2, a total of 1,827 pigs (L337 × 1050, PIC; initially 97.9 ± 1.1 kg) were used in two groups with 23 to 27 pigs per pen and 14 pens per treatment. Pens of pigs were blocked by initial BW and randomly assigned to 1 of 5 dietary treatments in a randomized complete block design. Experimental diets were corn-based with 25% DDGS and feed grade AA. Soybean meal levels increased from 0 to 16% in 4% increments and replaced feed grade AA. All diets were formulated using assumed ingredient AA composition and SID from the NRC (2012).

Furthermore, the NE of SBM used in diet formulation was 2,672 kcal/kg (as-fed basis) to represent 100% of the corn NE reported in the NRC (2012). The DDGS were assumed to contain 91% of the NE of corn or 2,432 kcal/kg. Thus, diets were formulated to be isocaloric and contained 0.70% SID Lys (Table 3). Dietary additions of feed grade AA were adjusted to meet or exceed the minimum essential AA requirements in relation to Lys among treatments between experimental groups. Pens of pigs were weighed, and feed disappearance measured on d 0, 15, and 29 or on d 0, 19, 34, and 42 for groups one and two, respectively, to determine ADG, ADFI, and G:F. Additionally, two pigs within each pen were marketed on d 15 and 19 of the experimental period for groups one and two, respectively. The remaining pigs were marketed at the conclusion of the experiment. Due to slower growth performance of pigs within group 2, the experimental period was extended from 34 to 42 d to achieve similar final BW between the two studies.

In Exp. 3, a total of 786 pigs (PIC TR4 × (Fast LW × PIC L02); initial BW = 96.7 ± 1.1 kg) were used in a 40-d trial with 15 to 19 pigs per pen and 9 pens per treatment. Pens of pigs were blocked by initial BW and randomly assigned to 1 of 5 dietary treatments in a randomized complete block design. Dietary treatments were corn-based with 30% wheat midds and feed grade AA. As in Exp. 2, soybean meal levels increased from 0 to 16% in 4% increments and replaced feed grade AA. The analyzed nutrient compositions of ingredients were utilized in diet formulation such that all diets were isocaloric and contained 0.70% SID Lys (Table 4). Additionally, the NE of SBM used in diet formulation was 2,672 kcal/kg (as-fed basis) to represent 100% of the corn NE reported in the NRC (2012). Pens of pigs were weighed, and feed disappearance measured on d 0, 20, 32, and 40 to determine ADG, ADFI, and G:F.

Statistical Analysis

Data were analyzed using the GLIMMIX procedure in SAS (Version 9.4, SAS Institute, Inc., Cary, NC) with pen as the experimental unit. The statistical model considered fixed effects of dietary treatment and random effects of group and block. Means were separated with linear, quadratic, and cubic contrasts. All data are reported as least square means and considered statistically significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

RESULTS

Experiment 1

Overall, increasing dietary SBM from 5 to 20% in corn-based diets improved overall ADG from 0.74 to 0.83 kg and G:F from 265 to 302 g/kg for pigs in the late-finishing phase of growth (linear, $P \leq 0.001$; Table 5). Interestingly, the observed improvements in overall ADG and feed efficiency were not only linear with increasing SBM, but there was evidence for a cubic response ($P < 0.05$). The greatest improvements in growth performance were initially observed as SBM levels increased from 5 to 8.75% but then further improved as dietary SBM was elevated from 16.25 to 20%. However, final BW of pigs were similar regardless of dietary SBM level ($P > 0.05$).

Experiment 2

When provided corn-based diets that included 25% DDGS, increasing dietary SBM from 0 to 16% did not influence final BW of pigs in the late-finish period of growth (Table 6; $P > 0.05$). Although there was no evidence for differences among increasing SBM levels on overall ADG or ADFI ($P > 0.05$), a tendency for improved overall feed efficiency was observed as dietary SBM levels increased from 0 to 16% (linear, $P = 0.100$).

Experiment 3

Overall, increasing dietary SBM from 0 to 16% in diets containing 30% wheat midds improved ADG for pigs during the late-finishing phase of growth (linear, $P = 0.005$; Table 7). Additionally, overall feed efficiency improved as SBM increased from 0 to 16% (linear, $P < 0.001$). The advantages in growth performance supported heavier final BW of pigs as dietary SBM levels increased from 0 to 16% (linear, $P < 0.05$). The observed advantages in overall ADG and G:F not only tested linear with increasing SBM, but cubic effects were also observed ($P < 0.05$). Initial benefits in growth performance were observed as SBM increased from 0 to 4% of the diet, but then further improved from 12 to 16% of the diet.

Removals and Mortality

Throughout all three experiments, pigs did not exhibit clinical health challenges. Removal rate was 2.3%, 1.4%, and 0.2% and mortality rate before removal was 0.3%, 0.0%, and 0.2% in experiments 1, 2, and 3, respectively. Common reasons for removal included lameness, belly ruptures, and fallback pigs.

DISCUSSION

Soybean meal is largely considered the standard plant protein (amino acid) source in diet formulation to complement cereal grains in corn or wheat-based diets that may otherwise be deficient in AA for swine. Behind Brazil, the United States is the second-largest global producer of soybeans and produced a total of 112.5 million metric tons in 2020 (ASA, 2021). Further processing of hulled and de-hulled soybeans to extract soybean oil include expelling and solvent extraction, both of which provide a high-quality and consistent SBM co-product for utilization in livestock feeds (Stein, 2013). Soybeans naturally contain anti-nutritional factors such as trypsin inhibitors, lectins, raffinose, and stachyose that can negatively influence nutrient utilization

(Leiner, 1994; Gu et al., 2010). However, application of thermal treatments such as heating or toasting soybeans during the oil extraction process significantly reduces the anti-nutritional factors without compromising the nutrient value of SBM. In the U.S., de-hulled, solvent extracted SBM is often utilized in swine diet formulation due to its high CP content, balanced AA profile, and high digestibility of essential AA ranging from 85% to 94% (NRC, 2012).

With increased commercial availability, feed-grade sources of Lys, Met, Thr, Trp, Val, and Ile are often incorporated in swine diets to either partially or completely replace intact protein sources such as SBM in efforts to reduce diet costs and limit excess nitrogen excretion. Previously, growth performance and carcass composition of growing-finishing pigs provided diets with reduced CP and increased feed-grade AA supplementation can be maintained when compared to provision of diets with elevated CP provided by SBM (Kerr et al., 2003; Hinson et al., 2009; Tous et al., 2014; Molist et al., 2016). However, recent evaluation of diets formulated to meet NRC (2012) AA requirements but with linear CP reduction from 13 to 9% suggests that late-finishing pigs require at least 12 to 13% dietary CP to mitigate impaired gain and feed efficiency in the late-finishing phase of growth (Soto et al., 2019). Additionally, it is unclear if beneficial growth responses for late-finishing pigs in response to greater dietary CP are specific to inclusion of intact protein sources that may also provide non-essential AA or if the response is specific to SBM. Evaluations of replacement protein sources for SBM such as corn gluten meal and soy protein concentrate in diets formulated to 12% CP for late-finishing pigs demonstrated linear reductions in growth performance as SBM was replaced (Soto et al., 2017a; 2018). These responses suggest that there may be biologically significant benefits for pigs provided diets with SBM, specifically.

Soybean meal contains biologically active compounds such as isoflavones, saponins, phytosterols, and omega-3 fatty acids that contain anti-viral, anti-inflammatory and antioxidant properties that can positively influence immune response and growth performance of pigs (Omoni and Aluko, 2005; Smith and Dilger, 2018). The positive influence of SBM beyond its nutritive role was first recognized by Boyd et al. (2010) in a study containing disease-challenged growing pigs. Advantages in final market BW, ADG, and feed efficiency were observed when finishing pigs were provided diets with elevated SBM compared to low SBM diets supplemented with feed-grade AA. The advantages to dietary SBM have also been observed among disease-challenged nursery pigs. Additional studies completed with porcine respiratory and reproductive syndrome (PRRS)-positive nursery pigs have also observed improved feed efficiency when dietary SBM increased from 12.5 to 22.5% (Rocha et al., 2013) or from 17.5 to 29% (Rochell et al., 2015). However, increasing dietary SBM for nursery pigs reared with high health conditions did not influence growth performance (Rochell et al., 2015).

As stated in a review by Smith and Dilger (2018), bioactive compounds of SBM such as supplemental soy isoflavones that provide anti-inflammatory, antioxidative and anti-viral properties may improve immunological status and growth of pigs exposed to disease challenges but may not benefit healthy pigs. A recent study with nursery pigs observed greater ADFI and final BW of pigs provided corn-SBM diets or diets with soy protein concentrate-based diets plus pure soy isoflavones compared to a soy protein concentrate-based diet that naturally contained lower isoflavones relative to SBM (Li et al., 2020). Additionally, four experiments conducted by Cemin et al. (2020) with healthy nursery pigs observed consistent linear improvements in feed efficiency as SBM increased from 27.5 to 37.5%. Among wean-to-finish pigs, however, there was no evidence for differences in growth performance when pigs were provided diets with

either SBM or soy protein concentrate (Kuhn et al., 2004). Furthermore, dietary inclusion of pure isoflavones to soy protein concentrate-based diets was observed to negatively influence growth performance of late-finishing pigs when compared to SBM-based diets (Payne et al., 2001).

Although there are other bioactive compounds within SBM, it is not clear why elevated SBM levels in diets positively influences growth performance in some pig populations, but not others.

In Exp. 1 of the present study that evaluated corn-SBM based diets with increasing SBM from 5 to 20%, we observed linear improvements in overall ADG and feed efficiency. Among the dietary treatments, CP increased from 11 to 14%, which may have supported the observed advantage in growth performance of late-finishing pigs that received diets with elevated SBM. The results of our study align with those of Anderson (2021), where increased supplementation of feed-grade AA and reduced SBM from 21.75% to 2.85% in phase 1 and from 18.75% to 3.35% in phase 2 of corn-based diets provided to finishing pigs (initial BW = 83.1 kg) linearly reduced overall ADG and feed efficiency of pigs.

Increased dietary SBM from 0 to 16% in diets that contained 25% DDGS in Exp. 2 marginally improved feed efficiency of late-finishing pigs in the present study, but did not influence final BW or ADG. Cemin et al. (2021) found a similar response where increasing feed-grade Lys at the expense of dietary SBM in diets containing 10% DDGS resulted in a quadratic decrease in feed efficiency of late-finishing pigs. Additionally, Anderson (2021) observed a linear reduction in overall ADG and final BW of finishing pigs provided corn DDGS-based diets with decreasing dietary SBM levels from 18.4 to 0% and 15.4 to 0% in phases 1 and 2, respectively. In Exp. 2, diets contained 25% DDGS and analyzed CP of all dietary treatments exceeded the 13% crude protein requirement estimate established by Soto et al. (2019). However, diets within the Anderson (2021) study contained 20% DDGS and linear CP

reductions from approximately 18.5 to 12.5% and 18.3 to 11.8% across both phases of the late-finishing period. Therefore, it is possible that late-finishing swine diets with lower DDGS levels and CP may benefit from increasing SBM.

Wheat middlings have much lower CP content (15.8%) than corn DDGS (27.4%; NRC, 2012). As a result, inclusion of 30% wheat middlings in diets for late-finishing pigs in Exp. 3 resulted in diets containing 11.1 to 16.4% CP as SBM levels increased from 0 to 16%. Similar to Exp. 1, advantages in growth performance were observed for pigs provided diets with elevated SBM. However, not only were the observed improvements in overall ADG and feed efficiency linear with increasing SBM, but there was also evidence for cubic responses in both Exp. 1 and 3. We suspect that the cubic responses may be due to the elevated SID Trp:Lys of 21.6 in corn-based diets that contained 20% SBM, or 23.1 in corn-wheat midds-based diets whereas all other treatments maintained similar SID Trp:Lys ratios of 20.0. Although no feed-grade Trp was utilized in diets with the highest SBM inclusions, the additional Trp naturally provided by SBM may have been responsible for the cubic response.

Currently, the NRC (2012) requirement estimate for SID Trp:Lys is 18.0 for pigs between 100-135 kg of BW. Amino acid requirement estimates are influenced by several factors such as dietary Lys concentration, AA profile, range of AA levels evaluated, age and sex of the animal, and the performance response criteria measured. However, recent evaluation of the optimal SID Trp:Lys has been reported as 17.0% for maximum G:F of gilts fed low crude protein diets (Ma et al., 2015). Similarly, Goncalves et al. (2018) reported a minimum SID Trp:Lys at 16.9% for maximum G:F of growing-finishing gilts, but also reported 23.5% for maximum ADG. Increasing SID Trp:Lys above 20% has not consistently increased growth performance of growing-finishing pigs (Soto et al., 2017b; Williams et al., 2020). However, the

increase in SID Trp:Lys may explain the observed cubic responses to increased dietary SBM in Experiments 1 and 3.

CONCLUSIONS

The results of these experiments suggest that increasing dietary SBM in partial or full replacement of feed-grade AA can benefit growth performance of late-finishing pigs. Although the biological mechanism responsible for the advantages in performance is unknown for finishing pigs, corn-SBM based diets should contain at least 8% SBM to optimize ADG and feed efficiency. Among diets that contained 25% DDGS, dietary, SBM level did not appear to influence growth, but tended to improve feed efficiency of late-finishing pigs. For pigs fed corn-SBM based diets with 30% wheat midds, inclusion of at least 4% SBM can improve ADG and feed efficiency of late-finishing pigs. Further research to understand the cubic response to the highest SBM inclusion rate in studies that utilized corn-SBM or corn-SBM-wheat midds based diets may be warranted.

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Table 5.1. Average proximate and total amino acid analysis of ingredients (as-fed basis)^{1,2}

Item, %	Corn			Soybean meal			DDGS	Wheat Midds
	Exp. 1		Exp. 3	Exp. 1		Exp. 3	Exp. 2	Exp 3.
	Group 1	Group 2	---	Group 1	Group 2	---	---	---
Dry matter	85.55	86.75	82.08	87.52	88.94	88.27	88.94	87.54
Crude protein	7.90	6.74	6.00	48.48	47.31	45.27	27.74	16.24
Crude fiber	1.57	1.49	1.39	2.85	2.91	4.15	8.12	9.04
Ether extract	1.09	2.39	2.30	0.51	0.49	0.90	6.09	3.40
AA								
Alanine	0.44	0.44	0.44	2.00	2.04	1.93	1.75	0.86
Arginine	0.28	0.28	0.35	3.38	3.40	3.20	1.21	1.24
Aspartic acid	0.43	0.42	0.46	5.34	5.34	4.99	1.74	1.25
Cysteine	0.15	0.14	0.15	0.70	0.70	0.63	0.55	0.37
Glutamic acid	1.10	1.08	1.05	8.70	8.51	7.99	3.39	4.07
Glycine	0.25	0.25	0.28	1.93	1.99	1.92	1.02	0.95
Histidine	0.19	0.18	0.19	1.25	1.27	1.18	0.78	0.48
Isoleucine	0.23	0.24	0.23	2.29	2.35	2.24	1.16	0.59
Leucine	0.71	0.71	0.66	3.66	3.67	3.50	3.17	1.10
Lysine	0.22	0.22	0.27	3.04	3.07	2.93	1.01	0.78
Methionine	0.13	0.13	0.14	0.66	0.67	0.60	0.48	0.25
Phenylalanine	0.31	0.30	0.29	2.49	2.47	2.32	1.46	0.70
Proline	0.51	0.53	0.54	2.35	2.35	2.20	2.08	1.04
Serine	0.29	0.27	0.28	2.03	1.93	1.93	1.17	0.63
Threonine	0.23	0.22	0.22	1.82	1.80	1.69	1.08	0.56
Tryptophan	0.05	0.05	0.05	0.67	0.66	0.64	0.20	0.20
Tyrosine	0.15	0.18	0.19	1.76	1.74	1.61	1.11	0.46
Valine	0.30	0.30	0.31	2.32	2.39	2.27	1.43	0.85

¹A representative sample of each ingredient within experiment was collected and submitted for proximate and amino acid profile analyses to the University of Missouri Experiment Station Chemical Laboratories (Columbia, MO) prior to diet formulation.

²NRC (2012) values for proximate and total AA content were used for corn, SBM, and DDGS in Exp. 2 diet formulation as proximate and total AA analyses were not received prior to initiation of the experiment. The DDGS analysis are after the completion of the experiment.

Table 5.2. Ingredient and nutrient composition of diets, Exp. 1 (as-fed basis)

Ingredient, %	Soybean meal, %				
	5.00	8.75	12.50	16.25	20.00
Corn	90.70	87.30	83.95	80.55	77.00
Soybean meal (47% CP)	5.00	8.75	12.50	16.25	20.00
Choice white grease	0.85	0.95	1.00	1.00	1.05
Calcium carbonate	0.80	0.80	0.77	0.77	0.77
Monocalcium phosphate (21.5% P)	0.65	0.60	0.55	0.50	0.45
Salt	0.50	0.50	0.50	0.50	0.50
L-Lys-HCl	0.53	0.41	0.28	0.16	0.04
DL-Met	0.16	0.12	0.08	0.05	0.01
L-Thr	0.22	0.17	0.12	0.07	0.02
L-Trp	0.07	0.05	0.03	0.01	---
L-Val	0.18	0.11	0.04	---	---
L-Ile ¹	0.15	0.07	0 or 0.01	---	---
His ¹	0.025	0 or 0.010	0 or 0.005	---	---
Vitamin trace mineral premix ²	0.15	0.15	0.15	0.15	0.15
Phytase ³	0.025	0.025	0.025	0.025	0.025
Total	100.00	100.00	100.00	100.00	100.00
Calculated nutrient analysis					
SID AA, %					
Lys	0.70	0.70	0.70	0.70	0.70
Ile:Lys	60	60	60	69	79
Leu:Lys	103	117	132	146	160
Met:Lys	40	38	35	33	30
Met and Cys:Lys	60	60	60	60	60
Thr:Lys	65	65	65	65	65
Trp:Lys	20.0	20.0	20.0	20.0	21.6
Val:Lys	72	72	72	75	85
His:Lys	32	34	39	44	49
SID Lys:NE, g/Mcal	2.62	2.62	2.62	2.62	2.62
NE, kcal/kg	2,665	2,665	2,665	2,665	2,665
CP, %	10.1	11.3	12.6	13.9	15.2
Ca, %	0.48	0.48	0.48	0.48	0.48
STTD P, % ⁴	0.33	0.33	0.33	0.33	0.33
Analyzed composition, % ⁵					
DM	85.8	87.5	87.4	87.2	87.5
CP	11.0	11.8	12.5	12.3	14.1
Crude fat	2.4	2.7	2.5	2.8	3.2
Crude fiber	1.8	2.5	2.0	2.1	2.3

¹Range of values reflect diet composition fed from 104.9 kg to market in groups one and two, respectively.

²Provided the following nutrients per kg of premix: 3,527,360 IU vitamin A; 881, 840 IU vitamin D; 17,637 IU vitamin E, 1,764 mg vitamin K, 15.4 mg vitamin B₁₂, 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin, 74 g Zn from Zn sulfate; 74 g Fe from Fe sulfate; 22 g Mn from Mn oxide; 11 g Cu from Cu sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite.

³Optiphos 2000 PF (Huvepharma Inc. Peachtree City, GA).

⁴STTD P = standardized total tract digestible phosphorus.

⁵A composite sample of each treatment was collected and submitted to the University of Missouri Agricultural Experiment Station Chemical Laboratories (Columbia, MO) for proximate analysis.

Table 5.3. Ingredient and nutrient composition of diets, Exp. 2 (as-fed basis)¹

Ingredient, %	Soybean meal, %				
	0	4	8	12	16
Corn	71.40	67.70	63.95	60.10	56.30
Corn DDGS (7.5% oil)	25.00	25.00	25.00	25.00	25.00
Soybean meal (47% CP)	---	4.00	8.00	12.00	16.00
Beef tallow	1.00	1.00	1.00	1.00	1.00
Calcium carbonate	0.95	0.95	0.95	0.97	0.97
Monocalcium phosphate (21.5% P)	0.20	0.15	0.10	0.05	---
Salt	0.50	0.50	0.50	0.50	0.50
L-Lys-HCl	0.57	0.45	0.32	0.19	0.07
L-Thr	0.12	0.06	0.01	---	---
L-Trp	0.06	0.04	0.02	---	---
L-Val	0.005	---	---	---	---
L-Ile	0.020	---	---	---	---
Vitamin trace mineral premix ²	0.15	0.15	0.15	0.15	0.15
Phytase ³	0.025	0.025	0.025	0.025	0.025
Total	100.00	100.00	100.00	100.00	100.00
Calculated nutrient analysis					
SID AA, %					
Lys	0.70	0.70	0.70	0.70	0.70
Ile:Lys	55	62	71	81	91
Leu:Lys	182	196	209	223	237
Met:Lys	32	34	37	40	42
Met and Cys:Lys	61	66	71	76	82
Thr:Lys	65	65	65	72	79
Trp:Lys	19.5	19.5	19.5	19.9	23.1
Val:Lys	70	78	88	97	107
His:Lys	41	46	52	57	63
SID Lys:NE, g/Mcal	2.68	2.68	2.68	2.68	2.68
CP, %	13.6	15.0	16.4	17.9	19.4
NE, kcal/kg	2,611	2,611	2,611	2,611	2,611
Ca, %	0.47	0.48	0.48	0.49	0.50
STTD P, % ⁴	0.33	0.33	0.33	0.33	0.33
Analyzed composition, % ⁵					
DM	87.0	87.5	87.4	87.2	87.5
CP	13.7	13.2	14.9	17.4	19.1
Crude fat	6.5	4.3	4.2	4.5	4.6
Crude fiber	4.1	2.7	2.9	3.4	3.2

¹Experimental diets were fed from 97.9 kg to market.

²Provided the following nutrients per kg of premix: 3,527,360 IU vitamin A; 881, 840 IU vitamin D; 17,637 IU vitamin E, 1,764 mg vitamin K, 15.4 mg vitamin B₁₂, 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin, 74 g Zn from Zn sulfate; 74 g Fe from Fe sulfate; 22 g Mn from Mn oxide; 11 g Cu from Cu sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite.

³Optiphos 2000 PF (Huvepharma Inc. Peachtree City, GA).

⁴STTD P = standardized total tract digestible phosphorus.

⁵A composite sample of each treatment diet was collected and submitted to the University of Missouri Agricultural Experiment Station Chemical Laboratories (Columbia, MO) for proximate analysis.

Table 5.4. Ingredient and nutrient composition of diets, Exp. 3 (as-fed basis)¹

Ingredient, %	Soybean meal, %				
	0	4	8	12	16
Corn	65.57	61.97	58.34	54.63	50.89
Wheat middlings	30.00	30.00	30.00	30.00	30.00
Soybean meal (47% CP)	---	4.00	8.00	12.00	16.00
Choice white grease	1.00	1.05	1.11	1.13	1.11
Calcium carbonate	1.28	1.28	1.25	1.25	1.25
Monocalcium phosphate (21.5% P)	0.30	0.25	0.20	0.15	0.10
Salt	0.50	0.50	0.50	0.50	0.50
L-Lys-HCl	0.49	0.37	0.25	0.12	---
DL-Met	0.120	0.085	0.050	0.020	0.005
L-Trp	0.06	0.04	0.01	---	---
L-Val	0.125	0.055	---	---	---
L-Ile	0.160	0.090	0.025	---	---
Thr ²	0.280	0.215	0.150	0.085	0.025
Vitamin trace mineral premix ³	0.10	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00	100.00
Calculated nutrient analysis					
SID AA, %					
Lys	0.70	0.70	0.70	0.70	0.70
Ile:Lys	60	61	62	69	79
Leu:Lys	91	106	120	135	150
Met:Lys	37	34	32	30	30
Met and Cys:Lys	60	60	60	60	63
Thr:Lys	65	65	65	65	65
Trp:Lys	19.5	19.5	19.5	20.0	23.1
Val:Lys	70	71	73	83	93
His:Lys	32	37	42	48	53
SID Lys:NE, g/Mcal	2.81	2.81	2.81	2.81	2.81
CP, %	9.8	11.1	12.4	13.8	15.2
NE, kcal/kg	2,502	2,502	2,502	2,502	2,502
Ca, %	0.60	0.60	0.60	0.60	0.60
STTD P, % ⁴	0.28	0.28	0.28	0.28	0.28
Analyzed composition, % ⁵					
DM	86.7	86.9	86.9	86.5	86.5
CP	11.1	12.4	14.1	14.7	16.4
Crude fat	3.82	4.03	3.90	3.57	3.63
Crude fiber	3.64	3.64	4.01	4.02	3.57

¹Experimental diets were fed from 96.7 kg to market.

²L-Threonine 80% with BioMass (CJ America Bio, Downers Grove, IL).

³Provided the following nutrients per kg of premix: 4,729,048 vitamin A; 207,077 vitamin D₃; 15,530 mcg vitamin D; 21,650 IU vitamin E; 1,792 mg riboflavin; 9,911 mg niacin; 6,577 mg pantothenic acid; 930 mg vitamin K; 60 mg Zn; 37.5 mg Fe; 12 mg Mn; 9 mg Cu; 0.2 mg I; 0.2 mg Se.

⁴STTD P = standardized total tract digestible phosphorus.

⁵A composite sample of each treatment was collected and submitted to the University of Missouri Agricultural Experiment Station Chemical Laboratories (Colombia, MO) for proximate analysis.

Table 5.5. Effects increasing levels of soybean meal in corn-based diets on late-finishing pig growth performance, Exp. 1¹

Item	Soybean meal, %					SEM	Probability, <i>P</i> =		
	5.00	8.75	12.50	16.25	20.00		Linear	Quadratic	Cubic
BW ² , kg									
Initial	105.4	104.9	104.6	104.8	104.8	1.41	0.592	0.644	0.906
Final	124.8	127.1	126.3	126.3	127.2	1.38	0.129	0.490	0.125
Overall									
ADG, kg	0.74	0.82	0.80	0.80	0.83	0.017	0.001	0.142	0.011
ADFI, kg	2.80	2.85	2.79	2.79	2.75	0.036	0.118	0.331	0.624
G:F, g/kg	265	287	288	287	302	6.7	<0.001	0.373	0.020

¹A total of 1,793 pigs (L337×1050, PIC) were used with 22 to 27 pigs per pen and 12 to 14 replications per treatment.

²BW = bodyweight.

Table 5.6. Effects of increasing levels of soybean meal in corn and soybean meal-based diets containing 25% DDGS on late-finishing pig growth performance, Exp. 2¹

Item	Soybean meal, %					SEM	Probability, <i>P</i> =		
	0	4	8	12	16		Linear	Quadratic	Cubic
BW ² , kg									
Initial	98.1	97.8	97.8	97.8	98.0	1.15	0.661	0.218	0.735
Final	124.1	124.3	125.3	124.4	124.0	0.81	0.960	0.107	0.865
Growth performance									
ADG, kg	0.77	0.76	0.80	0.79	0.78	0.023	0.317	0.231	0.321
ADFI, kg	2.65	2.61	2.66	2.64	2.61	0.080	0.637	0.594	0.188
G:F, g/kg	291	294	300	298	299	4.2	0.100	0.380	0.957

¹A total of 1,827 pigs (L337 × 1050, PIC) were used in 2 groups with 23 to 27 pigs per pen and 14 replications per treatment.

²BW = bodyweight.

Table 5.7. Effects of increasing soybean meal in corn and soybean meal-based diets containing 30% wheat midds on late-finishing pig growth performance, Exp. 3¹

Item	Soybean meal, %					SEM	<i>P</i> =		
	0	4	8	12	16		Linear	Quadratic	Cubic
BW ² , kg									
Initial	96.1	96.7	96.8	97.3	96.7	1.08	0.213	0.244	0.809
Final	129.7	131.3	131.1	130.6	133.4	1.41	0.042	0.620	0.113
Growth performance									
ADG, kg	0.97	1.00	1.01	0.98	1.06	0.018	0.005	0.396	0.032
ADFI, kg	3.39	3.44	3.42	3.39	3.49	0.051	0.358	0.615	0.214
G:F, g/kg	285	291	295	290	305	3.6	< 0.001	0.495	0.035

¹A total of 786 pigs (PIC TR4 × (Fast LW × PIC L02)) were used in a 40-d experiment with 15 to 19 pigs per pen and 9 replications per treatment.

²BW = bodyweight.