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Non Ruminant Nutrition

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

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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 requirements of swine. 11th ed. Washington, DC: National Academies Press 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.

Lay Summary

The branched-chain amino acids Ile, Leu, and Val are three dietary essential amino acids necessary for both skeletal and milk protein synthesis of lactating sows. Since the late 1990s, sows are producing much larger and heavier litters and commonly receive diets with greater concentrations of crystalline amino acids. This practice unintentionally increases Leu and may create imbalances among the dietary branched-chain amino acids. Nonetheless, sow and litter growth responses to branched-chain amino acids and large neutral amino acids such as Trp are equivocal within the available literature. Therefore, a meta-regression analysis was conducted to evaluate the effects of branched-chain amino acids and their interactions in lactating sow diets to predict litter growth performance, sow bodyweight change, and sow feed intake. The developed models for litter average daily gain suggest that Leu, Ile, and Val impact litter growth, but the effects of branched-chain amino acids are much smaller than the effects of dietary net energy, Lys, and crude protein. Furthermore, the developed models suggest that increasing Leu:Lys and reducing Ile + Val:Leu ratios can positively influence sow bodyweight change during lactation. Additionally, our model suggests that reduced Leu:Trp and increased Leu:Lys positively influence sow feed intake during lactation.

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

Abbreviations: AA, amino acid;ADG, average daily gain;ADFI, average daily feed intake;BCAA, branched-chain amino acids;BIC, Bayesian information criterion;BW, bodyweight;CP, crude protein;LNAA, large neutral amino acids;NE, net energy;SBM, soybeanmeal;SID, standardized ileal digestible

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, is especially impaired.

Since the late 1990s, 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

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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 (Table 1). 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

Table 1. Summary of publications considered in the meta-regression analysis to predict the influence of branched-chain amino acids on lactating sow performance[1]

Publication	Trials	Sows, *n*	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	257	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

[1]Reported standardized ileal digestible (SID) amino acid ranges represent diet composition utilizing NRC (2012) or CVB Feed Table (2016) nutrient loading values.
[2]Standardized ileal digestible Lys ranged within some studies after diet reformulation and conversion of total Lys to SID Lys.

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

Table 2. Regression equations to predict sow and litter growth performance[1]

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

[1]Model adjusted for heterogenous errors using the inverse of squared SEM.
[2]ADG, average daily gain; ADFI, average daily feed intake; BW, bodyweight.
[3]Amino acid ratios expressed on standardized ileal digestible (SID) basis and should be represented as a whole number representing the ratio to Lys. For example, Val:Lys = 80.
[4]Bayesian information criterion.
[5]Start litter size, count of piglets placed per litter at 24 h postpartum (after cross-foster).

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; Devi et al., 2015; Gaines et al., 2006). 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, under scenarios where dietary Leu is not limiting in lactation diets, the sow may utilize Leu for maternal body protein deposition. 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 affects 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 increase 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, Trottier 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 oversupplementation 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 to maintain a low Leu:Trp in the diet 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

Table 3. Practical scenarios for prediction of sow and litter performance based on common lactation diet types[1]

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

[1]Diets formulated with the NRC (2012) nutrient loading values to meet or exceed nutrient requirements.
[2]Assumed 5.7 kg average daily feed intake.
[3]Assumed 11 pigs weaned per litter.
[4]Litter ADG, kg = −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).
[5]Litter ADG, kg = −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).
[6]Litter ADG, kg = −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).
[7]Assumed start litter size of 12 pigs.
[8]Sow BW change, kg = − 43.5295 − (0.1748 × start litter size) + (5.5202 × ADFI, kg) + (0.03143 × Leu:Lys).
[9]Sow BW change, kg = − 33.3003 − (0.5108 × start litter size) + (5.6935 × ADFI, kg) − (0.02421 × Ile + Val:Leu).
[10]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, %).

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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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

Literature Cited

Boyd, R. D., K. J. Touchette, G. C. Castro, M. E. Johnston, K. U. Lee, and I. K. Han. 2000. Recent advances in amino acid and energy nutrition of prolific sows—a review. *Asian-Australas. J. Anim. Sci.* 13:1638–1652. doi:10.5713/ajas.2000.1638.

Carter, S. D., G. M. Hill, D. C. Mahan, J. L. Nelssen, B. T. Richert, and G. C. Shurson. 2000. Effects of dietary valine concentration on lactational performance of sows nursing large litters. *J. Anim. Sci.* 78:2879–2884. doi:10.2527/2000.78112879x.

Cemin, H. S., M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, and R. D. Goodband. 2019. Meta-regression analysis to predict the influence of branched-chain and large neutral amino acids on growth performance of pigs. *J. Anim. Sci.* 97:2505–2514. doi:10.1093/jas/skz118.

Choi, Y., A. Hosseindoust, Y. Shim, M. Kim, A. Kumar, S. Oh, Y. Kim, and B. Chae. 2017. Evaluation of high nutrient diets on litter performance of heat-stressed lactating sows. *Asian-Astralas. J. Anim. Sci.* 11:1598–1604. doi:10.5713.ajas.17.0398.

Craig, A., W. Henry, and E. Magowan. 2016. Effect of phase feeding and valine-to-lysine ratio during lactation on sow and piglet performance. *J. Anim. Sci.* 94:3835–3843. doi:10.2527/jas2016-0648.

CVB. 2016. *Feed table. Chemical composition and nutritional value of feedstuffs. Federatie Nederlandse Diervoederketen, Rijswijk, and Wageningen Livestock Research*, Wageningen, The Netherlands.

Devi, S. M., J. W. Park, and I. H. Kim. 2015. Effects of dietary valine:lysine ratios on lactation performance of primiparous sows nursing large litters. *R. Bras. Zootec.* 44:420–424. doi:10.1590/S1806-92902015001200002.

Escobar, J., J. W. Frank, A. Suryawan, H. V. Nguyen, S. R. Kimball, L. S. Jefferson, and T. A. Davis. 2006. Regulation of cardiac and skeletal muscle protein synthesis by individual branched-chain amino acids in neonatal pigs. *Am. J. Physiol. Endocrinol. Metab.* 290:E612–E621. doi:10.1152/ajpendo.00402.2005.

Fan, Z. Y., X. J. Yang, J. Kim, D. Menon, and S. K. Baidoo. 2016. Effects of dietary tryptophan:lysine ratio on the reproductive performance of primiparous and multiparous lactating sows. *Anim. Repro. Sci.* 170:128–134. doi:10.1016/j.anireprosci.2016.05.001.

Fernstrom, J. D. 2013. Large neutral amino acids: dietary effects on brain neurochemistry and function. *Amino Acids* 45:419–430. doi:10.1007/s00726-012-1330-y.

Gaines, A. M., R. D. Boyd, M. E. Johnston, J. L. Usry, K. J. Touchette, and G. L. Allee. 2006. The dietary valine requirement of prolific lactating sows does not exceed the National Research Council estimate. *J. Anim. Sci.* 84:1415–1421. doi:10.2527/2006.8461415x.

Gao, K., G. Li, C. Zhu, L. Wang, X. Yang, X. Wen, Z. Wu, and Z. Jiang. 2019. Effect of optimizing dietary valine-to-lysine ratio in late gestation or lactation on biochemical indices and performance of lactating primiparous sows. *Anim. Feed Sci. Tech.* 253:13–21. doi:10.1016/j.anifeedsci.2019.04.015.

Gloaguen, M., N. Le Floc'h, L. Brossard, R. Barea, Y. Primot, E. Corrent, and J. van Milgen. 2011. Response of piglets to the valine content in diet in combination with the supply of other branched-chain amino acids. *Animal* 5:1734–1742. doi:10.1017/S1751731111000760.

Gloaguen, M., N. Le Floc'h, E. Corrent, Y. Primot, and J. van Milgen. 2012. Providing a diet deficient in valine but with excess leucine results in a rapid decrease in feed intake and modifies the postprandial plasma amino acid and α-keto acid concentration in pigs. *J. Anim. Sci.* 90:3135–3142. doi:10.2527/jas.2011-4956.

Gourley, K. M., G. E. Nichols, J. A. Sonderman, Z. T. Spencer, J. C. Woodworth, M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, S. J. Kitt, et al. 2017. Determining the impact of increasing standardized ileal digestible lysine for primiparous and multiparous sows during lactation. *Transl. Anim. Sci.* 1:426–436. doi:10.2527/tas2017.0043.

Gourley, K. M., J. C. Woodworth, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, and R. D. Goodband. 2020. Effects of soybean meal concentration in lactating sow diets on sow and litter performance and blood criteria. *Transl. Anim. Sci* 4:594–601. doi:10.1093/tas/txaa037.

Greiner, L., C. Neill, G. L. Allee, X. Wang, J. Connor, K. Touchette, and J. L. Usry. 2015. The feeding of dried distillers' grains with solubles to lactating sows. *J. Anim. Sci.* 93:5718–5724. doi:10.2527/jas2015-9545.

Greiner, L., C. Neill, G. L. Allee, K. J. Touchette, and J. Connor. 2017. Evaluation of the optimal standardized ileal digestible tryptophan:lysine ratio in lactating sow diets. *Transl. Anim. Sci.* 1:526–532. doi:10.2527/tas2017.0059.

Greiner, L., P. Srichana, J. L. Usry, C. Neill, G. L. Allee, J. Connor, K. J. Touchette, and C. D. Knight. 2018. The use of feed-grade amino acids in lactating sow diets. *J. Anim. Sci. Biotechnol.* 9:3. doi:10.1186/s40104-017-0223-z.

Greiner, L., A. Graham, M. Goncalves, U. Orlando, and K. J. Touchette. 2019. Evaluation of the optimal standardized ileal digestible valine:lysine ratio in lactating sow diets. *J. Anim. Sci.* 97:1965–1971. doi:10.1093/jas/skz177.

Greiner, L., P. Srichana, J. L. Usry, C. Neill, G. L. Alee, J. Connor, K. J. Touchette, and C. D. Knight. 2020. Lysine (protein) requirements of lactating sows. *Transl. Anim. Sci.* 4:751–763. doi:10.1093/tas/txaa072.

Harper, A. E., R. H. Miller, and K. P. Block. 1984. Branched-chain amino acid metabolism. *Annu. Rev. Nutr.* 4:409–454. doi:10.1146/annurev.nu.04.070184.002205.

Hojgaard, C. K., T. S. Bruun, A. V. Strathe, J. Zerrahn, and C. F. Hansen. 2019. High-yielding lactating sows maintained a high litter growth when fed reduced crude protein, crystalline amino acid-supplemented diets. *Livest. Sci.* 226:40–47. doi:10.1016/j.livsci.2019.06.002.

Huber, L., C. F. M. de Lange, U. Krogh, D. Chamberlin, and N. L. Trottier. 2015. Impact of feeding reduced crude protein diets to lactating sows on nitrogen utilization. *J. Anim. Sci.* 93:5254–5264. doi:10.2527/jas2015-9382.

Huber, L., C. F. M. de Lange, C. W. Ernst, U. Krogh, and N. L. Trottier. 2016. Impact of improving dietary amino acid balance for lactating sows on efficiency of dietary amino acid utilization and transcript abundance of genes encoding lysine transporters in mammary tissue. *J. Anim. Sci*. 94:4654–4665. doi:10.2527/jas2016-0697.

Johnston, L. J., M. Ellis, G. W. Libal, V. B. Mayrose, C. W. Weldon, and NCR-98 Committee on Swine Management. 1999. Effect of room temperature and dietary amino acid concentration on performance of lactating sows. *J. Anim. Sci*. 77:1638–1644. doi:10.2527/1999.7771638x.

Kass, R. E., and A. E. Raftery. 1995. Bayes factors. *J. Am. Stat. Assoc*. 90:773–795. doi:10.1080/01621459.1995.10476572.

Kerkaert, H. R., H. S. Cemin, J. C. Woodworth, J. M. DeRouchey, S. S. Dritz, M. D. Tokach, R. D. Goodband, K. D. Hayden, C. W. Hastad, and Z. B. Post. 2021. Improving performance of finishing pigs with added valine, isoleucine, and tryptophan: validating a meta-analysis model. *J. Anim. Sci*. 99:1–9. doi:10.1093/jas/skab006.

Kwon, W. B., K. J. Touchette, A. Simongiovanni, K. Syriopoulos, A. Wessels, and H. H. Stein. 2019. Excess dietary leucine in diets for growing pigs reduces growth performance, biological value of protein, protein retention, and serotonin synthesis. *J. Anim. Sci*. 97:4282–4292. doi:10.1093/jas/skz259.

Libal, G. W., D. J. Uttecht, and C. R. Hamilton. 1997. Tryptophan needs of lactating sows fed diets supplemented with crystalline lysine. *J. Anim. Sci*. 75:417–422. doi:10.2527/1997.752417x.

Liu, Y., M. S. F. Oliveira, and H. H. Stein. 2018. Canola meal produced from high-protein or conventional varieties of canola seeds may substitute soybean meal in diets for gestating and lactating sows without compromising sow or litter productivity. *J. Anim. Sci*. 96:5179–5187. doi:10.1093/jas/sky356.

Ma, C., Y. Liu, S. Liu, C. L. Levesque, F. Zhao, J. Yin, and B. Dong. 2020. Branched chain amino acids alter fatty acid profile in colostrum of sows fed a high fat diet. *J. Anim. Sci. Biotech*. 11:9. doi:10.1186/s40104-019-0423-9.

Meyer, F., C. Jansen van Rensburg, and R. M. Gous. 2017. The response of weaned piglets to dietary valine and leucine. *Animal* 11:1279–1286. doi:10.1017/S1751731116002834.

Millet, S., M. Aluwe, B. Ampe, and S. De Campeneere. 2015. Interaction between amino acids on the performances of individually housed piglets. *J. Anim. Physiol. Anim. Nutr. (Berl)* 99:230–236. doi:10.1111/jpn.12227.

Moser, S. A., M. D. Tokach, S. S. Dritz, R. D. Goodband, J. L. Nelssen, and J. A. Loughmiller. 2000. The effects of branched-chain amino acids on sow and litter performance. *J. Anim. Sci*. 78:658–667. doi:10.2527/2000.783658x.

NRC. 2012. *Nutrient requirements of swine. 11th ed*. Washington, DC: National Academies Press.

Pardridge, W. M. 1977. Kinetics of competitive inhibition of neutral amino acid transport across the blood-brain barrier. *J. Neurochem*. 28:103–108. doi:10.1111/j.1471-4159.1977.tb07714.x.

Pettigrew, J. E. 1993. *Amino acid nutrition of gestating and lactating sows. Biokyowa Technical Reviews*. St. Louis, MO.

Richert, B. T., M. D. Tokach, R. D. Goodband, J. L. Nelssen, J. E. Pettigrew, R. D. Walker, and L. J. Johnston. 1996. Valine requirement of the high-producing lactating sow. *J. Anim. Sci*. 74:1307–1313. doi:10.2527/1996.7461307x.

Richert, B. T., M. D. Tokach, R. D. Goodband, J. L. Nelssen, R. G. Campbell, and S. Kershaw. 1997a. The effect of dietary lysine and valine fed during lactation on sow and litter performance. *J. Anim. Sci*. 75:1853–1860. doi:10.2527/1997.7571853x.

Richert, B. T., M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 1997b. Increasing valine, isoleucine, and total branched-chain amino acids for lactating sows. *J. Anim. Sci*. 75:2117–2128. doi:10.2527/1997.7582117x.

Shang, Q., H. Liu, S. Liu, T. He, and X. Piao. 2019. Effects of dietary fiber sources during late gestation and lactation on sow performance, milk quality, and intestinal health in piglets. *J. Anim. Sci*. 97:4922–4933. doi:10.1093/jas/skz278.

Song, M., S. K. Baidoo, G. C. Shurson, M. H. Whitney, L. J. Johnston, and D. D. Gallaher. 2010. Dietary effects of distillers dried grains with solubles on performance and milk composition of lactating sows. *J. Anim. Sci*. 88:3313–3319. doi:10.2527/jas.2009-2309.

Sotak-Peper, K. M., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, and J. L. Nelssen. 2015. The effects of corn- or sorghum-based diets with or without sorghum dried distillers grains with solubles on lactating-sow and litter performance. *Prof. Anim. Sci*. 31:185–190. doi:10.15232/pas.2014-01352.

Southern, L. L., F. M. LeMieux, J. O. Matthews, T. D. Bidner, and T. A. Knowles. 2000. Effect of feather meal as a source of valine for lactating sows. *J. Anim. Sci*. 78:120–123. doi:10.2527/2000.781120x.

St. Pierre, N. R. 2001. Invited review: integrating quantitative findings from multiple studies using mixed model methodology. *J. Dairy Sci*. 84:741–755. doi:10.3168/jds.S0022-0302(01)74530-4.

Stein, H. H. 2021. Monogastric Nutrition Laboratory. Feed ingredient database. University of Illinois at Urbana-Champaign. Accessed February 13, 2021. Accessed from: https://nutrition.ansci.illinois.edu/static/feed_database.html.

Strathe, A. V., T. S. Bruun, J. -E. Zerrahn, A. -H. Tauson, and C. F. Hansen. 2016. The effect of increasing the dietary valine-to-lysine ratio on sow metabolism, milk production, and litter growth. *J. Anim. Sci*. 94:155–164. doi:10.2527/jas2015-9267.

Strathe, A. V., T. S. Bruun, N. Geertsen, J. -E. Zerrahn, and C. F. Hansen. 2017. Increased dietary protein levels during lactating improved sow and litter performance. *Anim. Feed Sci. Techn*. 232:169–181. doi:10.1016/j.anifeedsci.2017.08.015.

Tian, M., J. Heng, H. Song, K. Shi, X. Lin, F. Chen, W. Guan, and S. Zhang. 2019. Dietary branched-chain amino acids regulate food intake partly through intestinal and hypothalamic amino acid receptors in piglets. *J. Agric. Food Chem*. 67:6809–6818. doi:10.1021/acs.jafc.9b02381.

Tokach, M. D., M. B. Menegat, K. M. Gourley, and R. D. Goodband. 2019. Review: nutrient requirements of the modern high-producing lactating sow, with an emphasis on amino acid requirements. *Animal* 13:2967–2977. doi:10.1017/S1751731119001253.

Torrazza, R. M., A. Suryawan, M. C. Gazzaneo, R. A. Orellana, J. W. Frank, H. V. Nguyen, M. L. Fiorotto, S. El-Kadi, and T. A. Davis. 2010. Leucine supplementation of a low-protein meal increases skeletal muscle and visceral tissue protein synthesis in neonatal pigs by stimulating mTOR-dependent translation initiation. *J. Nutr*. 140:2145–2152. doi:10.3945/jn.110.128421.

Touchette, K. J., G. L. Allee, M. D. Newcomb, and R. D. Boyd. 1998a. The use of synthetic lysine in the diet of lactating sows. *J. Anim. Sci*. 76:1437–1442. doi:10.2527/1998.7651437x.

Touchette, K. J., G. L. Allee, M. D. Newcomb, and R. D. Boyd. 1998b. The lysine requirement of lactating primiparous sows. *J. Anim. Sci*. 76:1091–1097. doi:10.2527/1998.7641091x.

Trottier, N. L., and R. A. Easter. 1995. Dietary and plasma branched-chain amino acids in relation to tryptophan: effect on voluntary feed intake and lactation metabolism in the primiparous sow. *J. Anim. Sci*. 73:1086–1092. doi:10.2527/1995.7341086x.

Velayudhan, D. E., and C. M. Nyachoti. 2017. Effects of increasing dietary canola meal inclusion on lactation performance, milk composition, and nutrient digestibility of lactating sows. *J. Anim. Sci*. 95:3129–3135. doi:10.2527/jas2016.1191.

Xu, Y., Z. Zeng, X. Xu, Q. Tian, X. Ma, S. Long, M. Piao, Z. Cheng, and X. Piao. 2017. Effects of the standardized ileal digestible valine:lysine ratio on performance, milk composition, and plasma indices of lactating sows. *Anim. Sci. J*. 88:1082–1092. doi:10.1111/asj.12753.

Zhang, S., M. Qiao, and N. L. Trottier. 2019. Feeding a reduced protein diet with a near ideal amino acid profile improves amino acid efficiency and nitrogen utilization for milk production in sows. *J. Anim. Sci*. 97:3882–3897. doi:10.1093/jas/skz220.

Zhang, S., J. S. Johnson, and T. N. L. 2020. Effect of dietary near ideal amino acid profile on heat production of lactating sows exposed to thermal neutral and heat stress conditions. *J. Anim. Sci. Biotech*. 11:75. doi:10.1186/s40104-020-00483-w.