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Non Ruminant Nutrition

Effects of branched-chain amino acids to lysine ratios in corn distillers dried grains with solubles containing diets on growth performance, plasma nitrogen profile, carcass traits, and economic analysis in growing–finishing pigs

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Abstract

A study was conducted to identify the effects of standardized ileal digestible (SID) branched-chain amino acids (BCAA):lysine (Lys) ratios on the growth performance, plasma nitrogen (N) profile, carcass traits, and economic analysis of growing–finishing pigs fed diets with high corn distillers dried grains with solubles (cDDGS) inclusions. A total of 1,140 pigs (initial body weight [BW] = 28.7 ± 2.0 kg) were housed in 45 pens of 25 or 26 pigs and fed one of five diets in a randomized complete block design. Experimental diets were fed in four phases based on BW. Dietary treatments were a corn–soybean meal (SBM) based diet (PC), a corn–SBM-cDDGS-based diet (NC) with SID BCAA:Lys ratio of PIC (2020) recommendation and NC diets with SID BCAA:Lys ratios targeted for the 73% SID Val:Lys, 60% SID Ile:Lys, and 144% SID Leu:Lys during the growing phases (25 to 80 kg, Grow), targeted for the 78% SID Val:Lys, 70% SID Ile:Lys, and 160% to 170% SID Leu:Lys during the finishing phases (80 to 120 kg, finish), and both during the growing and finishing phases (Grow–Finish). One pig from each pen was bled at the end of 7 and 13 wk. After the 11-wk-feeding trial, pigs were sent to a commercial abattoir to investigate carcass traits. Pigs fed the Finish diet had a greater overall average daily gain ($P < 0.05$) than pigs fed the other cDDGS diets. Dietary treatments did not affect the hot carcass weight. However, feeding the Finish diet increased ($P < 0.05$) the iodine value of pork belly samples and decreased ($P < 0.05$) carcass yield. The plasma urea nitrogen (PUN) concentration at the end of the growing phase and plasma concentrations of Leu and Val were greater ($P < 0.05$) in pigs fed the Finish diet compared to the other cDDGS diets. Feeding pigs the cDDGS diets with different BCAA:Lys ratios had no difference in income over feed cost and income over feed and facility costs compared to the corn–SBM diet. Therefore, feeding pigs cDDGS diets with SID BCAA:Lys ratios adjusted for the previously determined finishing phase (from 80 to 120 kg of BW) recommendations by SBM inclusion supported growth performance and economic benefits equal to the corn–SBM diet.

Lay Summary

A study evaluated the effects of branched-chain amino acids (BCAA) to lysine (Lys) ratios in corn distillers dried grains with solubles (cDDGS) diets on the growth performance, plasma nitrogen profile, and carcass traits in growing–finishing pigs. Dietary treatments were a corn–soybean meal (SBM)-based diet (PC) and a corn–SBM-cDDGS diet (NC) with SID BCAA:Lys recommendations of PIC (2020), and NC diets with previously determined SID BCAA:Lys recommendations for the growing phase (Grow; 73% Val:Lys, 60% Ile:Lys, and 144% Leu:Lys), the finishing phase (Finish; 78% Val:Lys, 70% Ile:Lys, and 160% to 170% Leu:Lys), or the growing and finishing phases (Grow–Finish) throughout. Overall, the average daily gain for the pigs fed the Finish diet was greater than the pigs fed other cDDGS diets. However, dietary treatment did not affect the overall feed efficiency and carcass yield. Feeding the Finish diets increased the iodine value of pork belly compared to the other cDDGS diets and increased the plasma urea nitrogen concentration and the plasma concentrations of Leu and Val during the growing phase. Therefore, cDDGS diets with the SID BCAA:Lys ratios for the finishing phase could improve the growth performance of growing and finishing pigs. However, the subsequent increase in the iodine value in the pork belly requires further investigation.

Key words: branched-chain amino acids, carcass traits, corn distillers dried grains with solubles, economic analysis, growing–finishing pigs, growth performance

Introduction

Corn distillers dried grains with solubles (cDDGS) are used primarily as an alternative ingredient in swine diets replacing a portion of the corn and soybean meal (SBM) to reduce the costs of the diets. Previous studies have reported that reduced oil (<10%) cDDGS can be included in up to 30% of swine diets without detrimental effects on growth performance when adequate energy and digestible amino acid values for cDDGS were used in the diet formulations (Cromwell et al., 2011; Kerr et al., 2015). However, other studies also reported that increasing cDDGS inclusion level by over 20% to 40% decreased the average daily gain (ADG) and average daily feed intake (ADFI) in growing–finishing pigs (Widyaratne and Zijlstra, 2007; Linneen et al., 2008; Jacela et al., 2011). Increasing the dietary inclusion of cDDGS can lead to high concentrations of leucine

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(Leu) in swine diets. For example, if a corn–SBM-based diet with 30% cDDGS is fed to growing pigs, dietary Leu will be 150% to 200% of the requirement according to NRC (2012). According to a meta-analysis (Cemin et al., 2019), high cDDGS diets with excess Leu negatively affects ADG and ADFI of pigs and reduces gain to feed ratio (G:F) caused by insufficient levels of the other branched-chain amino acids (BCAA) and so on large neutral amino acids (LNAA) relative to Leu (Cemin et al., 2019). Since the BCAA (i.e., Leu, valine (Val), and isoleucine (Ile)) are structurally similar and share the first two steps of their catabolic pathway, excess Leu may decrease the availability of Val and Ile for protein synthesis and cause reductions in protein retention (Harris et al., 2005; Wiltafsky et al., 2010). Furthermore, because Leu and tryptophan (Trp) share a common uptake pathway to cross the blood–brain barrier, excess Leu may have an inhibitory effect on the feed intake of pigs by reducing Trp uptake into the brain due to competition for amino acid (AA) transporters (Barea et al., 2009; Wessels et al., 2016a). Thus, a high cDDGS diet providing excess Leu may result in AA imbalances and reduced nitrogen (N) retention and growth performance of pigs (Morales et al., 2016; Kwon et al., 2019).

Recent studies have indicated that the poor growth performance of pigs fed high cDDGS diets with high concentrations of Leu can be ameliorated through additions of Val, Ile, or Trp in the diet formulations (Kwon et al., 2020; Kerkaert et al., 2021; Clizer et al., 2022a, 2022b). However, there is a nutrition gap between the requirements estimated from the meta-regression analysis to predict the influence of BCAA and LNAA on the growth performance of pigs (Cemin et al., 2019) and the real requirements for BCAA in the diet with inclusions of cDDGS over 20% for growing to finish pigs. Kerkaert et al. (2021) reported that a high Val:Lys ratio (76% to 80%) showed a greater ADG of pigs during the growing period (34 to 90 kg), whereas a high Ile:Lys ratio (66% to 68%) showed greater ADG and G:F for the finishing period (90 to 136 kg). Clizer et al. (2022a) found that a 30% cDDGS diet with Val:Lys ratio of 73% would provide maximum G:F of pigs during the growing period (39 to 68 kg). Also, Clizer et al. (2022b) determined that a 20% cDDGS diet with Ile:Lys ratio of 70% appeared to achieve maximum growth performance of finishing pigs (82 to 130 kg). With regards to pig performance with a dietary concentration of BCAA in those studies (Cemin et al., 2019; Kerkaert et al., 2021; Clizer et al., 2022a, 2022b), the concentrations of Val or Ile supplementation in high cDDGS diets could be different in the growing period (30 to 80 kg) vs. the finishing period (80 to 130 kg). Unlike most amino acids, the BCAA increase rapidly in systemic circulation after protein intake, initial catabolism of the BCAA takes place in the skeletal muscle, not the liver, due to the high activity of BCAA aminotransferase, and is involved in the upregulation of muscle protein synthesis (Yoon, 2016; Kwon et al., 2019). In pigs, protein deposition for muscle synthesis occurs favorably over fat deposition in the growing period whereas fat deposition occurs more favorably in the finishing period (Van Heugten et al., 2010). Application of a single ratio of BCAA:Lys in high cDDGS diets for the overall growing–finishing period may cause AA imbalances, increasing feed costs due to the expense of synthetic AA, and increased N excretion in manure. Therefore, the optimal ratios of BCAA:Lys in diets with high concentrations of Leu from high inclusions of cDDGS for growing–finishing pigs should be determined and, if necessary, applied differently for growing and finishing pig diets.

It was hypothesized that optimal standardized ileal digestible (SID) BCAA:Lys ratios in the diets containing 30% cDDGS for the growing period and 20% cDDGS for the finishing period would improve the growth performance, blood N balance, and carcass traits of pigs and reduce overall feed and production costs. Therefore, the objective of this study was to identify the effects of SID BCAA:Lys ratios on the growth performance, plasma nitrogen profile, carcass traits, and economic analysis in growing–finishing pigs fed diets with high inclusions of cDDGS.

Materials and Methods

The experimental procedures were reviewed and approved by the Institutional Animal Care and Use Committee at South Dakota State University (#2107-040E).

Experimental Animals

A total of 1,140 growing pigs (initial body weight [BW] of 28.7 ± 2.0 kg; DNA 610 × PIC) were used in a grow–finish feeding trial at South Dakota State University commercial wean to finish research facility (Flandreau, SD, United States). The pigs were allotted 45 pens of 25 or 26 pigs per pen balanced for BW and sex. Pens (3.1 × 6.9 m) had fully slated-concrete floors, metal spindle walls (1.0 m high), and solid polyvinyl chloride gates. Each pen was equipped with two cup waterers and a five-slot dry feeder (SD Industries, Alexandria, SD). The room temperature setting was reduced from 23 °C at the start of the experiment to 19 °C from 0 to 5 wk, 18 °C from 5 to 9 wk, and 16 °C from 9 wk to the end of the last pig group loading.

Experimental Diets

Experimental diets were fed in four phases based on BW; phase 1: 25 to 50 kg, phase 2: 50 to 80 kg, phase 3: 80 to 100 kg, and phase 4: 100 to 120 kg (until market). Five experimental diets were based on corn, SBM, and cDDGS in this study (Table 1). The diets contained 30% cDDGS for the growing phases (phases 1 and 2) and 20% cDDGS for the finishing phases (phases 3 and 4).

All diets were formulated to provide 95% of the SID Lys requirement for maximum protein deposition (PIC, 2020) of the given weight bracket to ensure responses in growth performance are due to changes in AA concentrations. Furthermore, based on the results of our previous studies (Clizer et al., 2022a, 2022b), the SID Val:Lys ratio of 73%, SID Ile:Lys ratio of 60%, and SID Leu:Lys ratio of 144% were formulated for the growing phase and the SID Val:Lys ratio of 78%, SID Ile:Lys ratio of 70%, and SID Leu:Lys ratio of 160 to 170% were formulated for the finishing phase (Table 3) when diets containing cDDGS were adjusted by SBM inclusion. Dietary treatments (Table 2) consists of: 1) positive control (PC): a corn–SBM based diet with SID BCAA:Lys according to PIC (2020) for the overall experimental period; 2) negative control (NC): a cDDGS diet with SID BCAA:Lys according to PIC (2020) for the overall experimental period; 3) grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; 4) finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for the overall experimental period; and 5) grow–finish: a cDDGS diet with SID BCAA:Lys targeted for the growing

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

Item	Ingredient		
	Corn	SBM*	cDDGS†
Moisture, %	13.56	10.32	11.09
Crude protein, %	7.30	46.86	30.17
Crude fat, %	1.76	0.45	6.61
Crude ash, %	0.96	6.36	4.40
Crude fiber, %	1.31	2.79	7.48
Neutral detergent fiber, %	6.86	8.86	31.24
Acid detergent fiber, %	2.65	5.73	13.47
Indispensable AA, %			
Arg	0.30	3.39	1.47
His	0.19	1.24	0.85
Ile	0.24	2.29	1.20
Leu	0.78	3.70	3.42
Lys	0.23	3.03	1.07
Met	0.14	0.66	0.56
Phe	0.32	2.38	1.39
Thr	0.24	1.87	1.16
Trp	0.04	0.66	0.23
Val	0.32	2.42	1.55
Dispensable AA, %			
Ala	0.48	2.07	1.95
Asp	0.45	5.36	1.93
Glu	1.21	8.55	4.00
Gly	0.27	2.01	1.15
Pro	0.59	2.50	2.44
Ser	0.30	2.09	1.31
Tyr	0.19	1.67	1.11

*SBM was sourced from Minnesota Soybean Processing (Brewster, MN).
†cDDGS was sourced from Valero Renewable Fuels (Aurora, SD).

phase (phases 1 and 2) and SID BCAA:Lys targeted for the finishing phase (phases 3 and 4). The SID BCAA:Lys ratios in the diets were adjusted by the SBM inclusion level rather than specific synthetic BCAA.

Experimental Design and Procedure

The five diets were allotted to the 45 pens (9 pens per diet) within a randomized complete block design. The diets were fed in four phases based on BW: phase 1: 25 to 50 kg, phase 2: 50 to 80 kg, phase 3: 80 to 100 kg, and phase 4: 100 to 120 kg (until market). During the experimental period, diets and fresh water were offered to pigs ad libitum. Pen weights and feed disappearance were measured at the end of each phase to calculate ADG, ADFI, and G:F. At the end of 7 and 13 wk, one pig of average BW from each pen was selected and bled from the jugular vein using 18 G needles and vacutainer tubes (BD Vacutainer, K_2E EDTA, Plymouth, United Kingdom).

After the end of phase 4 (11 wk), similar numbers of pigs from each pen (and treatment) were selected based on visual BW estimation and sent to a commercial abattoir over 4 wk: first loading (11 wk): 171 pigs; second loading (12 wk): 334 pigs; third loading (13 wk): 335 pigs; and fourth loading (14 wk): 266 pigs. Hot carcass weight was recorded at the processing facility (Wholestone Farms, Fremont, NE). Prior to shipment to the processing facility, the pig group in each pen was weighed on a pen scale, and then the pig group in each pen was weighed after shipping out the selected market pigs. Carcass yield was calculated using hot carcass weight at the plant divided by average live weight at the barn on a pen basis. In the second and third shipments, four gilts from each pen (n = 36 per treatment) were selected for measurement of iodine values (IV) from the pork belly samples. Pork belly samples having all three layers of fat were collected from the right side below the second nipple of the carcass at the processing facility.

For the economic evaluation, feed costs for each feeding phase were calculated based on the purchase price of the ingredients in December 2021. Prices used for corn, SBM, and cDDGS were \$0.22, \$0.36, and \$0.18/kg, respectively. Economic comparisons were made based on actual market weights and carcass weights from the first loading to the fourth loading (1,106 pigs). Carcass price at the time of slaughter was calculated at \$2.20/kg according to the USDA report from March 2022. The carcass gain value was calculated by multiplying total carcass gain weight by carcass price. Total feed cost was calculated by multiplying feed consumption for each phase by feed cost for each phase: feed consumption for phase 4 was calculated from 10 wk to 14 wk (last market pigs loading). The facility cost was calculated by multiplying the feeding days (0 to 14 wk) by \$0.1/hd/d facility cost according to Carpenter et al. (2016). Income over feed cost (IOFC) was calculated by subtracting the total feed cost from the carcass gain value. The income over feed and facility cost (IOFFC) was calculated by subtracting the facility cost from the IOFC.

Sample Preparation and Analyses

Diet and ingredient (i.e., corn, SBM, and cDDGS) samples were ground through a 0.75-mm screening a centrifugal mill (model ZM200; Retsch GmbH, Haan, Germany). The ground samples were analyzed for moisture by oven drying at 135 °C for 2 h (method 930.15), crude ash by using muffle furnace at 600 °C for 10 h (method 942.05), crude protein (CP) by combustion analysis (method 990.03), ether extract (EE) by Soxhlet extraction (method 920.39), crude fiber by Weende method (method 978.10) as per AOAC (2007), and for acid detergent fiber (ADF) and neutral detergent fiber (NDF) by van Soest method (model 3000, Labconco, Kansas city, MO, United States). The complete amino acid profile was analyzed by HPLC according to the AOAC method (2007; 982.30).

The collected blood samples were centrifuged at 1,872 × g for 20 min at 4 °C and the sera of the centrifuged plasma samples were stored at –20 °C until further analysis. The concentration of plasma urea nitrogen (PUN) was measured by a colorimetric assay (Urea nitrogen colorimetric detection kit, Invitrogen, Carlsbad, CA).

Plasma samples were filtered by a 10K centrifugal filter (Modified PES 10K VWR Centrifugal Filter, VWR North America, Radnor, PA). The filtered plasma samples were analyzed for amino acids profile by reverse-phase high-performance liquid chromatography (HPLC; 3.9- × 300-mm PICO-TAG reverse phase column; Waters) of phenylisothiocyanate derivatives according to Urschel et al. (2011).

Pork belly samples were cut from the carcass and subjected to analysis for IV by using Fourier transform near-infrared spectrophotometry (FT-NIR spectrophotometer, Tango,

Table 2. Ingredient and chemical composition of the diets for phases 1–4 (as-fed basis)

Item	Phase 1					Phase 2				
	PC	NC	Grow	Finish	Grow–Finish	PC	NC	Grow	Finish	Grow–Finish
Ingredients, %										
Corn	68.15	50.95	47.56	43.95	47.56	75.89	58.68	55.94	51.30	55.94
Soybean meal	28.30	14.42	17.75	21.42	17.75	20.74	6.93	9.63	14.18	9.63
cDDGS	0.00	30.00	30.00	30.00	30.00	0.00	30.00	30.00	30.00	30.00
Corn oil	0.50	1.67	1.97	2.26	1.97	0.50	1.66	1.91	2.32	1.91
L-Lysine	0.31	0.57	0.47	0.35	0.47	0.31	0.57	0.48	0.34	0.48
L-methionine	0.16	0.11	0.08	0.05	0.08	0.11	0.06	0.03	0.00	0.03
L-threonine	0.24	0.25	0.20	0.13	0.20	0.21	0.22	0.17	0.10	0.17
L-tryptophan	0.02	0.07	0.05	0.03	0.05	0.03	0.08	0.06	0.03	0.06
Calcium carbonate	0.98	1.28	1.25	1.28	1.25	0.95	1.27	1.25	1.21	1.25
Monocalcium phosphate	0.65	0.15	0.15	0.00	0.15	0.57	0.00	0.00	0.00	0.00
Salt	0.51	0.34	0.34	0.34	0.34	0.51	0.34	0.34	0.34	0.34
Vitamin premix[a]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mineral premix[b]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Chemical composition										
Net energy, kcal/kg[c]	2,425	2,422	2,421	2,420	2,421	2,468	2,465	2,464	2,462	2,464
Crude protein, %[d]	18.38	19.45	20.58	21.83	20.58	15.39	16.49	17.40	18.94	17.40
Crude fat, %[d]	19.11	21.16	20.84	22.70	21.91	17.35	16.51	19.91	21.07	17.80
Crude ash, %[d]	1.64	4.33	5.07	5.07	4.55	1.67	3.76	4.62	5.20	4.92
Crude fiber, %[d]	4.84	4.78	4.66	4.86	4.95	4.04	4.06	4.18	4.84	4.08
Neutral detergent fiber, %[d]	1.82	3.36	3.42	3.71	3.39	2.02	3.26	3.17	3.55	3.31
Acid detergent fiber, %[d]	7.37	13.62	13.38	13.98	13.88	7.83	15.24	14.68	13.10	13.60
SID[e] Lys, %[c]	1.14	1.15	1.15	1.15	1.15	0.95	0.96	0.96	0.96	0.96
SID Met+Cys:Lys[c]	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.60	0.59
SID Thr:Lys[c]	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
SID Trp:Lys[c]	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
SID Val:Lys[c]	0.68	0.68	0.73	0.78	0.73	0.68	0.68	0.73	0.81	0.73
SID Leu:Lys[c]	1.20	1.36	1.43	1.50	1.43	1.25	1.45	1.52	1.63	1.52
SID Ile:Lys[c]	0.64	0.59	0.64	0.70	0.64	0.62	0.56	0.61	0.70	0.61

Item	Phase 3					Phase 4				
	PC	NC	Grow	Finish	Grow–Finish	PC	NC	Grow	Finish	Grow–Finish
Ingredients, %										
Corn	81.65	69.90	67.77	63.73	63.73	86.28	73.51	71.94	68.02	68.02
Soybean meal	15.17	6.19	8.28	12.36	12.36	10.77	2.82	4.34	8.16	8.16
cDDGS	0.00	20.00	20.00	20.00	20.00	0.00	20.00	20.00	20.00	20.00
Corn oil	0.51	1.32	1.51	1.83	1.83	0.50	1.39	1.53	1.88	1.88
L-lysine	0.30	0.47	0.41	0.28	0.28	0.30	0.44	0.39	0.27	0.27
L-methionine	0.07	0.04	0.02	0.00	0.00	0.04	0.00	0.00	0.00	0.00
L-threonine	0.18	0.18	0.15	0.08	0.08	0.17	0.16	0.13	0.07	0.07
L-tryptophan	0.03	0.06	0.05	0.03	0.03	0.03	0.06	0.05	0.03	0.03
Calcium carbonate	0.91	1.10	1.08	1.10	1.10	0.86	1.06	1.04	1.01	1.01
Monocalcium phosphate	0.47	0.15	0.15	0.00	0.00	0.36	0.00	0.00	0.00	0.00
Salt	0.51	0.40	0.40	0.40	0.40	0.49	0.37	0.37	0.37	0.37
Vitamin premix[a]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mineral premix[b]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Chemical composition										
Net energy, kcal/kg[c]	2,500	2,499	2,498	2,496	2,496	2,528	2,526	2,526	2,524	2,524
Crude protein, %[d]	12.35	15.05	15.51	17.74	16.82	14.49	13.60	14.06	14.08	14.67
Crude fat, %[d]	1.55	3.17	3.68	3.43	4.03	1.49	2.93	3.01	3.43	3.58
Crude ash, % [d]	3.52	4.17	3.40	4.16	3.53	3.78	3.59	3.53	3.67	3.53

Table 2. Continued

Item	Phase 3					Phase 4				
	PC	NC	Grow	Finish	Grow–Finish	PC	NC	Grow	Finish	Grow–Finish
Crude fiber, %[d]	1.65	1.99	2.00	2.91	3.10	2.29	2.67	2.58	2.96	3.15
Neutral detergent fiber, %[d]	8.04	11.53	11.35	10.84	11.25	10.09	11.44	11.57	12.53	12.79
Acid detergent fiber, %[d]	2.81	4.97	4.71	4.86	4.92	4.23	4.38	4.62	4.46	5.26
SID[5] Lys, % [c]	0.81	0.82	0.82	0.82	0.82	0.70	0.71	0.71	0.71	0.71
SID Met + Cys:Lys [c]	0.59	0.59	0.59	0.61	0.61	0.59	0.59	0.61	0.66	0.66
SID Thr:Lys[c]	0.67	0.67	0.67	0.67	0.67	0.68	0.68	0.68	0.68	0.68
SID Trp:Lys[c]	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
SID Val:Lys[c]	0.68	0.69	0.73	0.82	0.82	0.68	0.71	0.75	0.84	0.84
SID Leu:Lys[c]	1.31	1.47	1.53	1.65	1.65	1.37	1.59	1.64	1.76	1.76
SID Ile:Lys [c]	0.60	0.56	0.61	0.70	0.70	0.58	0.56	0.56	0.70	0.70

[a]Provided the following per kilogram of diet: 11,011 IU vitamin A, 1,652 IU vitamin D_3, 55 IU vitamin E, 0.04 mg vitamin B_{12}, 4.4 mg menadione, 9.9 mg riboflavin, 61 mg pantothenic acid, 55 mg niacin, 1.1 mg folic acid, 3.3 mg pyridoxine, 3.3 mg thiamine, and 0.2 mg biotin.
[b]Provided the following per kilogram of diet: 165 mg Zn as $ZnSO_4$, 23 mg Fe as $FeSO_4$; 17 mg Cu as $CuSO_4$, and 44 mg Mn as $MnSO_4$.
[c]Calculated value.
[d]Analyzed value.
[e]SID: standardized ileal digestible.

Table 3. Standardized ileal digestible BCAA:Lys ratio in the experimental diets

Item	Target ratio	Calculated SID BCAA:Lys ratio adjusted by SBM				
		PC*	NC	Grow	Finish	Grow–Finish
Growing phase, (phase 1, phase 2)						
SID Val:Lys, %	68, 68	68, 68	68, 68	73, 73	78, 81	73, 73
SID Ile:Lys, %	60, 60	64, 62	59, 56	64, 61	70, 70	64, 61
SID Leu:Lys, %	140–150	120, 120	136, 136	143, 143	150, 150	143, 143
Finishing phase, (phase 3, phase 4)						
SID Val:Lys, %	78, 78	68, 68	69, 71	73, 75	82, 84	82, 84
SID Ile:Lys, %	70, 70	60, 58	56, 56	61, 60	70, 70	70, 70
SID Leu:Lys, %	150–170	131, 137	147, 159	153,164	165, 176	165, 176

Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period;
Negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period;
A cDDGS diet with SID BCAA:Lys targeted for the growing phase for overall experimental period;
A cDDGS diet with SID BCAA:Lys targeted for the finishing phase for overall experimental period;
A cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.

Bruker, Billerica, MA). The selected samples were cut and blended, and placed on a glass petri dish located directly above the quartz window of the integrating sphere spectrometer. Samples were scanned across the NIR spectral range (12,500 to 4,000/cm) with a resolution of 8/cm and were measured five times at different sampling points and an average spectrum value was taken to calculate the IV.

Statistical Analysis

Data were subjected to analysis of variance using the GLIMMIX procedure (SAS Inst. Inc., Cary, NC, United States) in a randomized complete block design with a pen as the experimental unit. The phase was the repeated term in models involving time and initial BW was used as a covariate for growth performance data. Pair-wise comparisons using the Tukey test (pdmix macro of SAS) were used to evaluate differences between treatment means when the overall analysis of variance was $P < 0.10$. To test the hypotheses, $P < 0.05$ was considered significant. If pertinent, trends ($0.05 \le P < 0.10$) are also reported.

Results

A target value for the SID Val, Ile, and Leu to Lys ratios in the cDDGS diets for the growing and finishing phases were established using Clizer et al. (2022a, 2022b; Table 3) as a reference. However, because the SID BCAA:Lys ratios in the cDDGS diets were adjusted by SBM inclusion rather than individual crystalline AA, there was a limitation to formulating the diets to contain identical SID BCAA:Lys ratios. For example, the SID Val:Lys ratio in the Grow diet for phases 1 and 2 was greater than the targeted value by 5% units, the SID Val:Lys ratios in Grow diets were lower than the targeted value by 5% and 3% units and the Finish diets were greater than the targeted values by 4% to 6% units for phases 3 and 4, respectively.

There was a tendency of treatment effects ($P = 0.06$) in phase 4 BW such that providing the cDDGS diet with SID BCAA:Lys ratios for the finishing phase improved ($P < 0.05$) the BW of pigs at the end of phase 4 compared to the other cDDGS diets (Table 4). Furthermore, the BW of pigs fed the PC diet was not different than the BW of pigs fed the cDDGS diet with SID BCAA:Lys ratios for the finishing phase. Pigs

Table 4. Growth performance of growing–finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion

Item	Treatment†					SEM‡	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
Body weight (BW), kg							
Initial	28.9	28.7	28.7	28.7	28.7	0.70	0.999
Phase 1*	48.9	48.5	48.7	49.2	48.7	0.84	0.986
Phase 2	80.2	78.2	79.1	80.6	79.2	0.99	0.496
Phase 3	101.8	100.3	100.3	103.5	100.1	1.02	0.110
Phase 4	110.0^{ab}	107.9^{b}	107.3^{b}	111.4^{a}	107.3^{b}	1.20	0.064
Average daily gain (ADG), g/d							
Phase 1	951	944	954	976	951	19.6	0.824
Phase 2	1,116^{a}	1,062^{b}	1,086^{ab}	1,122^{a}	1,091^{ab}	14.4	0.038
Phase 3	1,032^{ab}	1,052^{ab}	1,010^{b}	1,090^{a}	991^{b}	21.6	0.023
Phase 4	1,371	1,256	1,157	1,328	1,208	61.4	0.111
Overall	1,067^{ab}	1,042^{b}	1,034^{b}	1,089^{a}	1,034^{b}	13.6	0.023
Average daily feed intake (ADFI), g/d							
Phase 1	1,843	1,781	1,782	1,816	1,795	33.0	0.636
Phase 2	2,463	2,503	2,443	2,511	2,511	59.5	0.891
Phase 3	3,072^{a}	3,106^{a}	3,016^{a}	3,132^{a}	2,860^{b}	49.6	0.003
Phase 4	3,196	3,196	3,236	3,334	3,331	58.1	0.243
Overall	2,527	2,533	2,491	2,565	2,485	34.2	0.459
Gain to feed ratio (G:F)							
Phase 1	0.516	0.530	0.536	0.537	0.531	0.0064	0.164
Phase 2	0.458	0.425	0.446	0.449	0.434	0.0117	0.314
Phase 3	0.336	0.339	0.335	0.349	0.347	0.0060	0.322
Phase 4	0.430^{a}	0.392^{ab}	0.358^{b}	0.399^{ab}	0.363^{b}	0.0186	0.060
Overall	0.423	0.411	0.416	0.425	0.416	0.0051	0.325

[abc] Within a row means without a common superscript differ ($P < 0.05$).
*Phase 1: 0 to 3 wk, phase 2: 3 to 7 wk, phase 3: 7 to 10 wk, and phase 4: 10 to 11 wk.
†Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
‡Standard error of the means.

fed the PC diet had greater ($P < 0.05$) ADG within phase 2 compared to pigs fed the NC diet. Pigs fed the cDDGS diet with SID BCAA:Lys for the finishing phase (Finish diet) had greater ($P < 0.05$) ADG during phase 2 than pigs fed the NC diet and during phase 3 than pigs fed the cDDGS diets with SID BCAA:Lys for growing phase and growing–finishing phases (Grow and Grow–Finish diets, respectively). During the overall period, pigs fed the Finish diet had a greater ADG ($P < 0.05$) than pigs fed the other cDDGS diets and had no difference in the overall ADG compared to pigs fed the PC diet. The ADFI during phase 3 was lower ($P < 0.05$) for the pigs fed the Grow–Finish diet compared to the other diets. The cDDGS diets without or with adjustments of the SID BCAA:Lys ratios did not affect the G:F for phases 1 to 3 and the overall period. However, there was a tendency (P = 0.06) of treatment effect in G:F for phase 4 such that pigs fed the Grow or Grow–Finish diets had reduced ($P < 0.05$) G:F compared to pigs fed the PC diet.

There were no differences observed in hot carcass weight according to dietary treatment (Table 5). However, pigs fed the Finish diet showed a lower carcass yield compared to pigs fed other cDDGS diets, but not lower than pigs fed the PC. The IV of pork belly samples from the pigs fed cDDGS diets were greater ($P < 0.05$) compared to pigs fed a corn–SBM diet without cDDGS inclusion (i.e., PC). Furthermore, pigs fed the Finish diets had a greater ($P < 0.05$) IV within the pork belly samples than pigs fed other cDDGS diets.

The PUN concentration from pigs fed the cDDGS diet with SID BCAA:Lys for the finishing phase was greater ($P < 0.01$) than other dietary treatments at the end of phase 2 (Table 6). However, had no effect on the PUN concentration at the end of phase 4.

At the end of phase 2, the plasma concentrations of Leu were higher ($P < 0.01$) in the samples from pigs fed cDDGS diets compared to samples from pigs fed a corn–SBM diet (Table 7). Pigs fed the Finish diet had greater ($P < 0.05$) plasma concentrations of Ile, Phe, and Val compared to pigs fed the other cDDGS diets. The plasma concentration of Thr from pigs fed the cDDGS diets adjusted with the SID BCAA:Lys were lower ($P < 0.05$) than that of pigs fed the PC diet. Pigs fed the Finish diet showed a greater ($P < 0.05$) plasma concentration of Arg and His than pigs fed the NC diet. Alternatively, pigs fed the Finish diets showed lower ($P < 0.05$) plasma concentrations of Glu than pigs fed the Grower and NC diet and showed lower ($P < 0.05$) plasma concentrations of Gly than pigs fed other diets.

At the end of 13 wk, during the phase 4 feeding period, the plasma concentrations of Leu were higher ($P < 0.05$) in the

Table 5. Carcass traits of growing–finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion

Item	Treatment*					SEM**	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
No. of head, *n*	216	223	223	221	223		
Group average BW, kg***	119.4^{ab}	118.3^{ab}	114.0^{c}	121.6^{a}	115.7^{b}	1.37	0.001
Hot carcass weight, kg	88.9	89.0	88.0	88.6	88.2	0.66	0.770
Carcass yield, %	74.7^{bc}	75.4^{ab}	77.6^{a}	73.0^{c}	76.6^{ab}	0.85	0.002
Iodine value†	67.04^{c}	77.43^{b}	78.19^{b}	80.61^{a}	77.96^{b}	0.433	<0.001

^{abc} Within a row means without a common superscript differ ($P < 0.05$).
*Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for the overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
**Standard error of the means.
***Pig group in each pen was weighed the day before shipment and, thus, 2 d before harvest.
†Iodine values were investigated from the 36 carcasses for second and third loadings.

Table 6. Plasma urea nitrogen (PUN) concentration of growing–finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion

Item	Treatment*					SEM**	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
PUN, mg/dL							
Phase 2†	10.43^{b}	9.18^{b}	9.65^{b}	15.00^{a}	10.32^{b}	0.740	<0.001
Phase 4††	12.86	11.14	12.64	12.98	12.85	0.952	0.623

^{abc} Within a row means without a common superscript differ ($P < 0.05$).
*Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for the overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
**Standard error of the means.
†At the end of 7 wk.
††At the end of 13 wk.

pigs fed cDDGS diets compared to that of pigs fed a corn–SBM diet (Table 8). Pigs fed the Finish diet showed greater ($P < 0.05$) plasma concentrations of Ile and Val than the pigs fed the NC and Grow diets, but similar to pigs fed PC. Pigs fed the Grow–Finish diets showed lower ($P < 0.05$) plasma concentrations of Lys and Thr than the pigs fed the PC and NC diets. In contrast, pigs fed the Grow diet only had greater ($P < 0.05$) concentrations of plasma Met than the pigs fed the NC diet. Pigs fed the Finish or Grow–Finish diets showed a greater ($P < 0.05$) concentration of plasma Arg than pigs fed the NC diet. Pigs fed the adjusted SID BCAA:Lys cDDGS diets showed greater ($P < 0.05$) concentrations of plasma His and Pro than pigs fed the PC diet.

The cDDGS diets with adjusted SID BCAA:Lys ratios by SBM inclusion had lower feed price per metric ton for phases 1 to 4 by 4.7%, 4.6% to 5.2%, 3.0% to 3.3%, and 2.2% to 3.2% compared to the corn–SBM diet (Table 9). Considering production economics, feeding the cDDGS diets with the SID BCAA:Lys ratios adjusted by SBM had no difference in IOFC and IOFFC compared to feeding the corn–SBM diet and cDDGS diet (NC).

DISCUSSION

The final BW and overall ADG of pigs fed the cDDGS diets with the recommended SID BCAA:Lys according to Clizer et al. (2022b) for the finishing phase were greater than for pigs fed the other cDDGS diets and similar to pigs fed the corn–SBM based diet. High levels of Leu in cDDGS-containing diets have been shown to have adverse effects on the growth performance of growing–finishing pigs as a result of an imbalance in BCAA and LNAA relative to Leu (Cemin et al., 2019; Kwon et al., 2019; Kerkaert et al., 2021). Kerkaert et al. (2021) reported that a high SBM diet with 30% cDDGS containing the highest dietary Leu content had a greater growth performance of growing–finishing pigs than a low SBM diet with 30% cDDGS and synthetic amino acids containing the lowest dietary Leu content. In the current study, the SID BCAA:Lys ratios in the cDDGS diets were adjusted by the SBM inclusion level without using synthetic BCAA with regards to the observations of Clizer et al. (2021) and Anderson (2021), which both suggested that dietary SBM inclusion improved pig growth performance compared to cDDGS diets with synthetic AA. In the study of Kerkaert et al. (2021), the increased levels of SBM in the cDDGS diets resulted in an increase in the dietary level of Val, Ile, and so on Trp. In the current study, the Finish diet had a higher concentration of Val and Leu with a greater inclusion level of SBM to meet the SID BCAA:Lys ratio for the finishing phase. Thus, the greater growth performance of pigs fed the cDDGS diets with the recommendations of SID BCAA:Lys for the finishing phase could partly have been due to higher inclusions of SBM and higher dietary intakes of Val and Ile during the overall period.

Table 7. Plasma amino acid profile of growing–finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion (phase 2; at the end of 7 wk)

Item	Treatment*					SEM**	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
Indispensable amino acids, μmol/L							
Arg	88.9^{ab}	68.3^{b}	66.9^{b}	93.9^{a}	72.3^{ab}	7.68	0.053
His	50.4^{b}	53.6^{b}	61.3^{a}	62.1^{a}	55.9^{ab}	2.50	0.009
Ile	64.4^{a}	43.0^{b}	44.4^{b}	66.9^{a}	49.6^{b}	3.45	<0.001
Leu	131.7^{b}	163.3^{a}	161.5^{a}	182.7^{a}	181.9^{a}	7.43	<0.001
Lys	217.8	240.3	184.6	194.4	192.1	20.16	0.288
Met	26.4	25.6	23.5	22.0	24.3	1.19	0.113
Phe	43.1^{b}	43.2^{b}	45.5^{b}	54.7^{a}	47.3^{b}	2.07	0.002
Thr	175.0^{a}	148.7^{ab}	133.5^{b}	138.2^{b}	134.5^{b}	9.48	0.019
Trp	6.7	8.0	7.0	8.1	7.7	0.82	0.704
Val	144.8^{ab}	111.2^{c}	116.2^{c}	168.0^{a}	129.6^{bc}	9.71	0.001
Dispensable amino acids, μmol/L							
Ala	408.9^{a}	406.8^{a}	348.4^{ab}	328.0^{b}	411.4^{a}	21.7	0.021
Asp	24.5	26.0	22.3	22.6	25.5	2.04	0.635
Glu	199.6^{bc}	251.3^{ab}	205.0^{bc}	178.3^{c}	265.8^{a}	19.75	0.017
Gly	873.3^{b}	986.6^{a}	902.1^{ab}	770.7^{c}	915.8^{ab}	34.77	0.002
Pro	214.1	244.0	241.2	244.3	268.8	14.03	0.128
Ser	141.0	142.2	126.8	139.8	136.9	7.76	0.634
Tyr	79.0^{c}	82.2^{bc}	87.8^{abc}	96.2^{a}	89.1^{ab}	3.18	0.005

^{abc} Within a row means without a common superscript differ ($P < 0.05$).
*Positive control (PC): a corn-SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for the overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
**Standard error of the means.

During phase 3, pigs fed the Grow and Grow–Finish diets showed lower ADG compared to pigs fed the Finish diet. Because the Finish diet for phase 3 was formulated to meet the requirement of BCAA for the finishing phase and the Grow diet for phase 3 was formulated to meet the requirement of BCAA for the growing phase, the lower ADG in pigs fed the Grow diet was not unexpected. However, the ADG and ADFI of pigs fed the Grow–Finish diet were lower than pigs fed the same diet (Finish diet) in phase 3. In general, the growth of pigs is positively related to voluntary feed intake or nutrient intake. Therefore, the decreased ADFI of pigs fed the Grow–Finish diet for phase 3 would explain the decreased ADG of those pigs. Kwon et al. (2019) observed that increasing dietary Leu decreased plasma Trp concentration and decreased serotonin concentrations in plasma and the hypothalamus. Dietary Trp is a substrate for the synthesis of serotonin in the brain, which plays a critical role in appetite regulation (Shen et al., 2012; Höglund et al., 2019). The LNAA, including Trp, share the same brain transporters with BCAA across the blood–brain barrier (Barea et al., 2009), which implies that high intake of dietary BCAA could have been negatively correlated with Trp uptake and serotonin synthesis in the brain (Wessels et al., 2016a, 2016b). Low intake of dietary Trp reduced the voluntary feed intake of pigs due to the decreased serotonin synthesis in the hypothalamus (Henry et al., 1992; Wessels et al., 2016b). Thus, the lower ADFI and ADG of pigs fed the Grow–Finish diet could partly have been explained by the dramatic increase in dietary BCAA levels from phase 2 to phase 3 such as SID Val:Lys, SID Ile:Lys and SID Leu:Lys by 9%, 9%, 22%; The increase in dietary BCAA levels for Grow diet from phase 2 to phase 3 were 1% for SID Val:Lys, 0% for SID Ile:Lys, and 15% for SID Leu:Lys.

The IV of carcass fat (measured as grams of I_2 absorbed per 100 g sample) has been considered as an index of pork fat quality. Packers have recommended maximum acceptable carcass fat IV ranging from 70 to 75 (Benz et al., 2011). The carcass IV has been considered as a measurement of the degree of fatty acid unsaturation (i.e., linoleic acid; C18:2) in carcass fat and fatty acid composition in swine diet would influence the carcass fat composition and carcass IV (Boyd et al., 1997; Nemechek et al., 2015; Kellner et al., 2016). The IV of belly fat from the pigs fed cDDGS diets in the current study was similar to the IV of backfat from the pigs fed the diet with 30% cDDGS reported by Cromwell et al. (2011). However, in the current study, the IV of belly fat from pigs fed the cDDGS diets with the requirement of SID BCAA:Lys for the finishing phase were greater than those of other pigs fed the cDDGS diets and also above the recommended maximum, reaching 80. McClelland et al. (2012) reported that a high IV of belly fat at 79.5 from feeding cDDGS did not negatively affect the slicing yield of cured bellies, quality of fresh bacon slices, or eating quality of bacon, sausage, or loin chops. Thus, IV ranging from 77 to 80 could provide acceptable pork quality for packers and customers. However, further research is required to determine if the IV of belly fat from pigs fed cDDGS diets formulated for the finishing phase SID BCAA:Lys recommendations can be reduced. The increased IV from pigs fed the Finish diet could partly be explained by

Table 8. Plasma amino acid profile of growing-finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion (phase 4; at the end of 13 wk)

Item	Treatment*					SEM**	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
Indispensable amino acids, µmol/L							
Arg	97.7[a]	82.6[b]	81.0[b]	100.8[a]	101.4[a]	4.75	0.004
His	42.7[c]	48.8[bc]	57.3[a]	52.8[ab]	56.0[ab]	2.50	0.001
Ile	48.4[ab]	41.4[b]	42.1[b]	53.2[a]	47.0[ab]	2.54	0.013
Leu	129.9[b]	153.0[a]	151.0[a]	157.6[a]	153.5[a]	5.30	0.006
Lys	222.0[a]	210.8[ab]	205.0[ab]	181.8[bc]	166.7[c]	12.12	0.021
Met	28.9[a]	23.3[b]	26.9[a]	25.3[ab]	25.4[ab]	1.27	0.043
Phe	41.9	40.6	41.5	47.5	44.0	2.02	0.138
Thr	144.8[a]	138.7[a]	128.4[ab]	128.6[ab]	114.2[b]	7.44	0.073
Trp	4.42	4.06	4.23	4.16	4.14	0.34	0.953
Val	132.6[b]	127.4[b]	123.9[b]	153.0[a]	135.3[ab]	7.00	0.051
Dispensable amino acids, µmol/L							
Ala	358.9[a]	301.8[bc]	341.1[ab]	293.5[c]	319.0[abc]	16.16	0.038
Asp	23.5	21.5	26.1	21.6	29.4	2.37	0.130
Glu	152.2	168.3	184.2	140.1	188.4	15.71	0.177
Gly	710.7[c]	812.6[abc]	865.9[a]	723.9[bc]	844.6[ab]	42.37	0.036
Pro	179.1[b]	212.0[ab]	229.6[a]	217.5[a]	223.5[a]	11.56	0.035
Ser	114.6	134.1	127.1	130.0	126.3	6.82	0.352
Tyr	78.2	83.0	85.0	90.2	87.4	3.41	0.159

[abc]Within a row means without a common superscript differ ($P < 0.05$).
*Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
**Standard error of the means.

Table 9. Economic performance of growing–finishing pigs fed the cDDGS diets with different SID BCAA:Lys ratio adjusted by SBM inclusion

Item	Treatment*					SEM**	*P*-value
	PC	NC	Grow	Finish	Grow–Finish		
Feed cost, $ per tonne							
Phase 1	300.9	285.8	286.9	286.8	286.9		
Phase 2	287.5	271.7	272.6	274.4	272.6		
Phase 3	277.3	267.4	268.2	268.9	268.9		
Phase 4	269.3	259.5	260.6	263.3	263.3		
Output, $ per pig							
Carcass gain value***	196.7	196.1	194.1	195.4	196.4	1.58	0.777
Input, $/pig							
Total feed cost†	68.8	67.3	65.9	68.1	68.0	0.97	0.288
Facility cost††	8.9	8.8	8.8	8.9	8.9	0.03	0.176
Net income, $ per pig							
IOFC†††	128.0	128.8	128.2	127.4	128.4	1.79	0.986
IOFFC‡	119.1	120.0	119.4	118.5	119.5	1.80	0.984

[abc]Within a row means without a common superscript differ ($P < 0.05$).
[xyz]Within a row means without a common superscript show tendency to differ ($P < 0.10$).
*Positive control (PC): a corn–SBM based diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; negative control (NC): a cDDGS diet with SID BCAA:Lys of PIC (2020) for the overall experimental period; Grow: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for the overall experimental period; Finish: a cDDGS diet with SID BCAA:Lys targeted for the finishing phase for the overall experimental period; Grow–Finish: a cDDGS diet with SID BCAA:Lys targeted for the growing phase for phases 1 and 2 and SID BCAA:Lys targeted for the finishing phase for phases 3 and 4.
**Standard error of the means.
***Average carcass gain value from first pigs loading (11 wk) to last pigs loading (14 wk).
†Feed cost x total feed consumption from initial to last loading (14 wk).
††Facility cost at $0.10/hd/d (until the last loading; 14 wk).
†††Income over feed cost = carcass gain value – total feed cost.
‡Income over feed and facility cost = IOFC – facility cost.

the higher inclusion level of corn oil and SBM in the Finish diets compared to the other cDDGS diets. High dietary intakes of unsaturated fatty acids are known to increase the IV of finishing pigs (Paulk et al., 2015; Wu et al., 2016). Paulk et al. (2015) reported that IV of the pork carcass was positively correlated with C18:2 and C18:3 fatty acids contents in the Finish diets. Wu et al. (2016) demonstrated that cDDGS diets containing higher corn-oil content with higher C18:2 fatty acid content showed a positive correlation with IV of backfat and belly and jowl fat in pork carcass.

The PUN concentration in pigs has been considered an index for determining the protein requirement of pigs because excessive intakes of amino acids are inefficiently metabolized and circulated in the blood before urinary excretion (Whang and Easter, 2000; Hong et al., 2016). The greater PUN concentration in pigs fed the Finish diet at the end of the growing phase could partly have been due to the excessive intake of BCAA compared to the requirements. Kwon et al. (2019) reported that pigs fed a 300% SID Leu:Lys diet showed greater PUN concentrations than pigs fed a 100% SID Leu:Lys diet. They also observed that increasing the SID Val:Lys ratio in the diet from 60% to 80% decreased the PUN concentration in growing pigs, which implied that the optimal requirement of Val in growing pigs is close to the 70% to 80% of SID Val:Lys, which is in agreement with the observations of Clizer et al. (2022a) of 73% SID Val:Lys for growing pigs and 78% SID Val:Lys for finishing pigs (Cemin et al., 2019). The PUN concentration in pigs showed a negative correlation with weight gain and feed efficiency of growing pigs fed the same diet under fixed blood collection conditions (Whang and Easter, 2000). However, the current study did not observe any correlation between PUN and ADG or G:F. This is because we formulated the cDDGS diets with targeted SID BCAA:Lys ratio by adjustment of SBM and synthetic amino acids, including Lys, Met, Thr, and Trp, to meet the 95% of the SID Lys requirement (PIC, 2020) and maintain the ideal amino acid pattern. Lys and Met are typically considered the first- and second-limiting amino acids in a corn–SBM-based diet for pigs with respect to growth performance (van Milgen and Dourmad, 2015; Yang et al., 2020). Thus, no correlation between PUN and growth performance in the current study could partly have been due to the similar content of SID Lys and SID Met among the dietary treatments.

Greater plasma concentrations of Val and Ile in pigs fed the Finish diet were observed in the current study, which could be explained by the higher dietary intake of BCAA compared to the other diets. Kwon et al. (2019) reported that increasing dietary SID Leu from 100% to 300% relative to the requirement increased the plasma Leu concentration linearly. Considering the other LNAA, plasma concentrations for Trp were not affected by the different levels of SID BCAA:Lys in the cDDGS diet, which was in agreement with the observation of Kwon et al. (2019) such that SID Leu relative to the requirement from 150% to 250% had no difference in the plasma Trp concentration. However, plasma concentrations for Tyr and Phe were increased at the end of the growing phase when the pigs were fed the cDDGS Finish diet. Since the BCAA and other LNAA, including Ile, Leu, Val, Phe, Trp, and Tyr, share the same brain transporters (Henry et al., 1992; Fernstrom, 2005), excess intakes of dietary BCAA could limit the utilization of the dietary LNAA and, subsequently, as neurotransmitter precursors. Kwon et al. (2019) reported that increasing SID Leu relative to the requirement from 100% to 300% linearly increased the plasma concentration for Phe, but not for Tyr. Thus, the increased level of plasma Phe and Tyr at the end of the growing phase could partly have been due to the higher intake of BCAA in the cDDGS diet targeting the SID BCAA:Lys requirement of finishing pigs. However, additional research is required to determine if the other BCAA, including Ile and Val, change the plasma LNAA concentrations.

In the current study, plasma concentrations of Thr were decreased in pigs fed the cDDGS diets. The high fiber content in cDDGS results in increased endogenous losses of digestive enzymes, enterocytes, and mucin (Dilger et al., 2004; Urriola et al., 2010). Threonine is a crucial component for mucin secretion (Montagne et al., 2003) and increased mucin production reduced body Thr retention (Schaart et al., 2005; Munasinghe et al., 2017). Mathai et al. (2016) reported that a high fiber diet containing soybean hulls at 15% required greater SID Thr:Lys (76% to 80%) than the requirement of NRC (2012; 60% to 65%) in growing pigs. Thus, the decreased level of plasma Thr could partly have been due to the higher mucosal secretion and increased SID Thr:Lys requirement by the dietary high fiber intake from the cDDGS diets.

The changes in the plasma concentrations of Pro, Arg, Gln, and Gly were affected by their concentrations in the cDDGS and the corn–SBM diets. The cDDGS used in the current study contained half of Arg, Glu, Gly, and similar Pro contents compared to the corn–SBM diet. In the current study, the SID BCAA:Lys ratios in the cDDGS diets were adjusted by SBM inclusion level without using synthetic BCAA. Thus, the changes in the plasma concentrations of Pro, Arg, Gln, and Gly followed the trend of the diet AA contents adjusted by the SBM and 30% cDDGS.

Interestingly, the plasma Lys concentration at the end of 13 wk was decreased in the pigs fed the cDDGS Finish diet. The Lys–Arg antagonism is a well-established AA interaction theory (Ball et al., 2007). Because Lys and Arg share some common chemical properties, excess dietary Arg increased the requirement for Lys in pigs, which resulted in a decreased blood concentration of Lys (Hagemeier, 1982). However, additional research is needed to investigate if the changes in blood Lys and Arg are caused by the Lys–Arg antagonistic effect from the cDDGS diet or the other factors.

Because of the lower cost of cDDGS compared to corn and SBM feedstuffs, the costs for the cDDGS diets were less than the corn–SBM diet. Although the growth rate of pigs fed the Finish diet was greater than other cDDGS diets, the Finish diet showed the numerically lowest IOFC and IOFFC in comparison due to relatively lower carcass gain value and higher total feed cost. Nemechek et al. (2015) reported that pigs fed diets with cDDGS had poorer growth performance, decreased hot carcass weight, reduced carcass yield, and higher carcass fat IV than pigs fed the corn–SBM diet. In the current study, pigs fed the cDDGS diets had no difference in carcass weight, whereas pigs fed the Finish diet showed greater IV and less carcass yield compared to those of pigs fed other cDDGS diets. Increased IV and decreased carcass yield for cDDGS diets could affect the carcass price paid and, therefore, the IOFC and IOFFC would be altered. Considering the net income from pigs fed the Finish diet compared to the net income from pigs fed the corn–SBM-based diet and other cDDGS diets within this project, the feeding strategy did not deliver an economic benefit.

In conclusion, high inclusions of cDDGS in diets for pigs during the growing and finishing phases (30% and 20%, respectively) with the SID BCAA:Lys ratios increased by SBM inclusion to more recent recommendations for the finishing phase (78% Val:Lys, 70% Ile:Lys, and 160% to 170% Leu:Lys) improved the growth performance of the pigs compared to a standard corn–SBM diet. However, the same feeding strategy resulted in greater PUN concentrations at the end of the growing phase and greater IV of the carcass fat, which require further investigation.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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