BRANCHED-CHAIN AMINO ACIDS IN SWINE NUTRITION: RESEARCH AND CHALLENGES FOR PIG PRODUCTION

Branched-Chain Amino Acids for Swine

ABSTRACT

The branched-chain amino acids (BCAAs) leucine, isoleucine, and valine are vital for pig nutrition, as they contribute to muscle protein synthesis, energy metabolism, and immune function. Their metabolism primarily occurs in skeletal muscle, where leucine activates the mTOR pathway, promoting muscle growth. Meanwhile, isoleucine and valine help maintain nitrogen balance and prevent muscle breakdown. This article reviews studies from the past decade that underscore the importance of balancing these amino acids in pig diets. This balance is especially critical when reducing crude protein intake or using high-leucine ingredients, such as dried distillers' grains with soluble (DDGS), which can lead to antagonisms and relative deficiencies of isoleucine and valine. Research has identified specific ratios of branched-chain amino acids to lysine, which is essential for better performance, gut health, and efficiency. For example, a recommended ratio for piglets is 68–74% standardized ileal digestible (SID) valine to lysine, while diets containing DDGS should aim for 65–70% SID isoleucine to lysine. Excess leucine, frequently found in corn-based coproduct diets, can decrease feed intake and hinder serotonin synthesis in the hypothalamus, negatively affecting growth. However, valine, isoleucine, or tryptophan supplementation can mitigate these adverse effects. Furthermore, individual differences in BCAA requirements (with variations of up to 10–15% among animals) highlight the importance of precision nutrition. During immune challenges, leucine can redirect amino acids for muscle synthesis, but excessive supplementation may result in increased catabolism of other BCAAs. In swine nutrition, achieving a proper balance of BCAAs requires careful consideration of complex interactions, protein sources, and production goals, and the use of research results and predictive models are valuable tools for optimizing diets, reducing costs, and optimizing swine performance.

Keyword Amino Acids, Ideal Protein, Isoleucine, Leucine, Valine

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BACKGROUND

The three branched-chain amino acids (BCAAs), leucine (Leu), isoleucine (Ile), and valine (Val), play essential roles in pig nutrition due to their metabolic functions and essentiality. Their use in catabolism is unique because they depend on enzymes present in skeletal muscle and extrahepatic tissues, where they will be destined for muscle protein synthesis, energy production, and immune modulation. Only in the early 19th century were BCAAs recognized as energy sources for mammals. Leu is converted to α-acetoacetate and β-hydroxybutyrate, Val is converted to glucose via succinate as an intermediate, and Ile can be metabolized to glucose or ketone bodies in animals (Wu, 2022).

In swine nutrition, BCAAs should be provided through the feed in proportions that meet their ideal protein ratio, according to the animal's growth phase and potential.

In pig production conditions, the proportions of BCAAs in pig feed may not be achieved. Among the conditions highlighted are the mixing of protein sources used, which may be unbalanced depending on the concentrations of amino acids. The increasing demand for reduced crude protein in the diet leads to limitations of amino acids and/or the occurrence of antagonism between them. Additionally, changes in the ideal amino acid profile under specific conditions such as immunological and environmental challenges can hinder the meeting of BCAA demands.

This article will review research carried out with BCAAs (Leu, Ile, and Val) in the last 10 years with swine. It highlights the impact of BCAA ratios commonly used in pig diets in nursery, growth, and finishing phases on performance, physiological and blood responses, the challenges with using high Leu ratios, and, most importantly, practical considerations about BCAA supplementation in swine nutrition.

Importance of BCAAs

Branched-chain amino acids (BCAAs)—leucine (Leu), isoleucine (Ile), and valine (Val)—are essential for pig nutrition due to their unique role in muscle protein synthesis, energy metabolism, and overall health. Unlike other amino acids, BCAAs are metabolized directly in skeletal muscle, accounting for approximately 35% of the essential amino acids in muscle proteins, which makes them particularly important for promoting lean tissue growth and improving feed efficiency (Wu et al., 2016). In addition to being the most abundant of the essential amino acids, BCAAs are involved in the synthesis of nitrogenous compounds and regulate glucose and lipid metabolism, protein synthesis, intestinal health, and immune function through the PI3K/AKT/mTOR signaling pathway. The levels and balance of BCAAs are closely associated with various health and disease parameters (Nie et al., 2018).

Accounting for approximately 35% of the essential amino acids in muscle proteins Table 1, BCAAs' unique metabolism in mammalian and bird skeletal muscles makes them crucial for growth and health.

Table 1 Composition of BCAAs (%) Pig Tissue

Tissue	Leucine	Isoleucine	Valine
Muscle	5.99	3.57	3.54
Liver	5.32	2.72	3.19

Adapted from Kwon et al. (2020).

The catabolism of BCAAs shares three common steps: transamination, oxidative decarboxylation, and acyl-COA dehydrogenation, the first being high-tissue affinity reactions. In mammals and birds, the level of cytosolic protein enzyme in the liver is much lower than in skeletal muscle, kidneys, heart, and small intestine, indicating that transamination in the liver is limited at normal physiological concentrations of BCAAs. BCAAs are available to extrahepatic tissues to synthesize glutamate, glutamine, and alanine, activate the mTOR signaling pathway, and stimulate protein synthesis (Wu, 2022).

Leu, in particular, activates the mTOR pathway, stimulating muscle development, while Ile and Val support nitrogen balance and prevent muscle catabolism, ensuring optimal growth performance in pigs (Duan et al., 2021). Leu's activation of the mTOR pathway stimulates muscle protein synthesis 20-30% more effectively than other amino acids. Ile plays a crucial role in energy metabolism and immune function, particularly during the post-weaning period. As a glucogenic amino acid, it contributes up to 12% of hepatic glucose production in fasted piglets (Bertolo et al., 2008). Considering the available protein sources used for pig diets, Val is among the 3rd to 5th limiting amino acid.

In the last decade, the interest in studies with BCAAs has increased due to the demand for reduction of crude protein in diets promoting the imbalance of amino acids and/or deficiency, the availability of protein sources with excess Leu promoting competition and/or antagonism in the use of BCAAs and the availability of crystalline sources of amino acids for supplementation. Given this scenario, research has been conducted with approaches that evaluate the supplementation, deficiencies, and interactions between BCAAs on performance and physiological and metabolomic responses that help define the ideal relationships of these amino acids in pig feed.

Recommendations for BCCAs in Diets for Pigs

The high BCAA requirements of piglets are driven by rapid muscle deposition and a substantial potential for lean tissue accretion, further intensified by their limited digestive capacity. As a reference, the standardized digestible amino acid profile of BCAAs in diets for pigs in different categories was researched and is cited in nutritional references such as Swine NRC (2012) and by Hannas et al. (2024) Table 2. These references are a guideline to define the dietary levels used in pig feeding, but they must be corroborated by updates and other research results that consider animals in different categories, different evaluation models, challenges and/or interactions to allow the application of precision nutrition and obtain better animal performance and health responses.

Table 2 Leucine, Isoleucine and Valine Ratio Recommendations: Lysine SID for Pigs

	Piglets		Grower-Finisher	
	NRC (2012)	Hannas et al. (2024)	NRC (2012)	Hannas et al. (2024)
Leucine	101.1	102	101.5-102.0	100
Isoleucine	50.8	55	51,3-52.0	55
Valine	65.8	70	66.6-67.7	69

Adapted from Swine NRC (2012) and Hannas et al. (2024).

Optimizing BCAA Rations in Pig Diets:

Focus on Nursery and Growing Phases ig diets in nursery, growth, and finishing phases

Adequate Val supplementation to lysine influences the performance and intestinal health of weaned piglets. According to research by Xu et al. (2018), the weight gain of piglets showed a better response with a level of 68% SID Val:Lys, a value higher than the recommendations of the NRC (2012). This better performance was accompanied by an increase in the height of the villi of the duodenum, jejunum, and ileum and an increase in the villus height:crypt depth ratio, indicating greater absorptive capacity and intestinal cell renewal. At the same time, an increase in Val and α-ketoisovalerate plasma concentrations was observed, with a reduction in other amino acids such as aspartate and asparagine. The research also revealed that the SID Val:Lys ratio increased the gene expression of the enzymes BCATm and BCKDH in the longissimus dorsi muscle, demonstrating adaptation in the metabolism of branched-chain amino acids. These results suggest that the optimal SID Val:Lys ratio maximizes growth and promotes gut structural benefits and metabolic adjustments, highlighting the importance of Val beyond protein synthesis. These findings support the review of nutritional recommendations for weaned piglets, considering their integrated effects on performance and digestive physiology.

Through different amino acid ratio evaluation models, Nørgaard et al. (2017) demonstrated that plasma metabolite analysis could identify significant biological responses to varying levels of Ile, Leu, and Val in piglets weighing 8 to 9 kg. Among the 18 plasma amino acids analyzed, 11 for Ile, 16 for Leu, and 3 for Val showed linear or quadratic responses. At the same time, key metabolites such as 3-methyl-2-oxovaleric and α-ketoisovalerate were sensitive to dietary variations. The optimal levels estimated by the metabolomic models were 104% SID Leu:Lys, 54 SID Ile:Lys, and 68% SID Val:Lys, which are consistent with the references in the literature.

The adequate ratio of BCAAs, in addition to impacting piglet performance, seems to be related to changes in feed intake, as identified by Tian et al. (2019), where the use of diets deficient in branched-chain amino acids (BCAAs) reduced feed intake in piglets through two main mechanisms described by authors: regulation of T1R1/T1R3 amino acid receptors in the gut and activation of GCN2/eIF2α pathways in the hypothalamus, and adequate BCAA supplementation (0.13% L- Ile, 0.09% L- Leu and 0.23% L-Val) in the low-protein diet (17.05% CP) increased food intake, associated with a reduction in cholecystokinin secretion and modulation of hypothalamic signaling pathways, while excessive BCAA supplementation (150% of requirements) paradoxically decreased intake, indicating the importance of the precise balance of these amino acids in the regulation of food intake.

Although the BCAA ratios are defined for animals in different categories, Veira (2021) highlighted in their experiments that the responses to BCAA ratios in piglets showed significant variations depending on the individual, where the optimal SID Val:Lys ratio varied between 62 and 68% between individuals, with an average of 67% with the use of the linear model and 70% with the use of the quadratic model, while the SID Ile:Lys ratio ranged from 52 to 60%, with averages of 55 and 62%, respectively, for the linear and quadratic models. Nitrogen retention at the maximum plateau varied considerably among the animals (34.78-52.03 g for Val and 36.44-56.04 g for Ile), highlighting the importance of individual variability in precision nutrition. The findings demonstrate that the requirements of Val and Ile may differ between pigs in the same trial, with variations of up to 10% for Val and 15% for Ile, indicating that different statistical approaches may also influence nutrient recommendations. Similar results were presented by Millet et al. (2021), who identified that the ideal SID Val:Lys ranged between 68-74% to maximize piglet performance, with the recommended ratios differing by up to 6% according to the statistical model.

Research highlights the interaction between BCAAs, and in some situations, an excess of Leu can antagonize the absorption of Ile and Val, leading to reduced performance if not properly balanced (Wiltafsky et al., 2009). The antagonism of the BCAAs may occur in the transport and/or catabolism of amino acids (Wu, 2022).

The SID Val:Lys supplementation promoted improvements in weight gain and feed intake in piglets, reducing feed conversion, according to Zouaoui et al. (2021). Excess Leu exerted a substantial antagonistic effect, reducing weight gain and feed intake in pigs and intensifying the response to Val, especially in diets with high Leu content. This pattern suggests that Leu primarily modulates feed intake, not feed efficiency. The authors emphasized that the models developed allow to quantify the impact of Leu on Val requirements accurately, and it is crucial to consider its levels to optimize low-protein diets and that the balance between BCAAs should be adjusted considering the specific interactions, with Leu emerging as the primary regulator of the catabolism of these amino acids.

Investigating the complex interactions between Leu, Ile, and Val in piglets in the nursery phase using an experimental design with 15 treatments that varied the proportions of SID BCAAs:Lysine ratio, Humphrey et al. (2023) found that Val exerted a linear and quadratic effect on daily gain and feed efficiency, regardless of the levels of Leu and Ile in the diet. However, a significant interaction was observed between Leu and Ile, where the simultaneous increase of both amino acids impaired performance, while the adjustment in proportions (increase of one with reduction of the other) improved weight gain and feed conversion. One of the most relevant findings was the interaction between Leu and Val on feed intake; when Val's levels were below the NRC (2012) recommendations, the increase in leu reduced the feed intake. However, this adverse effect was completely neutralized when Val was provided in adequate amounts or higher than the recommendations. This suggests that adequate Val supplementation can offset the negative impacts of excess leu on feed intake, showing that optimal performance in piglets can be achieved with different combinations of BCAAs, depending on the production objective and the cost of the ingredients.

The interaction between BCAAs and porcine immune responses was studied by Rudar et al. (2016 and 2018). Evaluating the effects of Leu supplementation on nitrogen retention in piglets before and after an immune challenge with LPS, Rudar et al. (2016) observed that in healthy pigs, feeding a high level of Leu-induced and anabolic response to compensate for reduced nitrogen retention occurred in intermediate Leu levels.

Subsequently, Rudar et al. (2018) demonstrated that immune challenge and Leu supplementation significantly altered protein metabolism in piglets, with distinct effects on different tissues. Immune challenge acutely increased plasma concentrations of essential amino acids and urea in the first 12 hours and increased the rate of protein synthesis in the liver, while supplementation with Leu (up to 2.72% SID Leu) tended to reduce the rate of protein synthesis in the hepatic liver and increase in the gastrocnemius muscle in animals under immune challenge, suggesting a redistribution of AA for peripheral muscle protein synthesis. In addition, supplementation with Leu caused a linear decline in plasma concentrations of Ile, Val, glutamine, and urea, indicating an increase in the catabolism of these AAs, an effect exacerbated by an immune challenge. The results suggest that modulation of the SID Leu:Lys ratio may be a strategy to optimize AA utilization during immune challenges, favoring muscle protein deposition over hepatic synthesis, although further studies are needed to determine the optimal ratio that minimizes visceral protein loss and maximizes muscle gain under immune challenge conditions. These results indicate that Leu can positively modulate protein metabolism under healthy conditions, but its supplementation does not attenuate the catabolic effects induced by immune activation.

Working with growing pigs (average weight of 25 to 45 kg), Gonçalves et al. (2018) determined that the SID Val:Lys ratio was estimated at 73% for maximum weight gain and 69% for maximum feed efficiency.

In research using the deletion method, Faria (2019) determined the ratio of BCAS in diets for pigs of 25 and 60 kg of weight, respectively, were 109:57:67 and 109:56:63 for Leu:Ile: Val/SID Lys, values within the margins mentioned in the literature.

Excess Leu in the diet significantly alters the availability of other branched-chain amino acids (BCAAs) in growing pigs; when animals fed diets with an additional 0.43% L-Leu, an increase in serum Leu concentrations and a simultaneous reduction in Ile and Val levels were observed in the absorption and post-absorption phases (Morales et al., 2018). The authors found that the imbalance was fully reversed when the diet was supplemented with 0.20% L-Ile and 0.25% L-Val, demonstrating that the combined excess BCAA can counteract the adverse effects of excess Leu alone. The results suggest that excess Leu compromises the availability of Ile and Val through two main mechanisms: reduction in intestinal absorption and increase in the rate of cellular degradation of these amino acids. The study highlights that strategic supplementation of Ile and Val can correct these metabolic imbalances. However, under conditions of controlled food consumption, as in this experiment, these effects do not translate into differences in productive performance.

Considering the effects of BCAA supplementation and their interactions, Cemin et al. (2019) conducted a comprehensive meta-analysis using data from 25 articles published between 1995 and 2018, totaling 44 trials and 210 observations, to evaluate the effects of BCAAs and their interactions on the performance of growing pigs. Through statistical modeling, the researchers developed predictive equations for daily gain, daily feed intake, and feed conversion, considering variables such as body weight, crude protein, fiber, and multiple relationships between amino acids (expressed on a digestible basis). The final equations incorporated specific ratios such as Leu:Lys, Ile:Lys, and Val:Lys, demonstrating that the increase in the Leu:Lys ratio negatively impacts daily weight gain due to imbalance with other BCAAs and large neutral amino acids (LNAA) Table 3. The main results revealed that high levels of Leu in the diet impair performance by reducing feed conversion and feed intake, especially when there is a relative deficiency of other BCAAs, such as Val and Ile, or LNAAs such as tryptophan (Trp). The study identified that strategic supplementation of Val, Ile, and Trp can mitigate these adverse effects by balancing the ratios between amino acids. The developed model allows for predicting productive responses based on the relationships between amino acids, offering valuable tools to optimize diets and reinforce that nutritional strategies should consider not only the absolute levels of BCAA but especially their relative proportions, with practical implications for pig producers to maximize efficiency and performance.

Investigating the effect of Leu excesses on BCAA metabolism in growing pigs, Kwon et al. (2019) demonstrated that diets with high levels of Leu (100–300% of the requirement) reduced feed intake, nitrogen retention, and hypothalamic serotonin synthesis, while increasing plasma urea. Excess Leu triggers a metabolic imbalance, impairing the use of Ile and Val for protein synthesis. Significant changes were observed in the distribution of BCAAs in tissues, where hepatic BCAA concentrations increased while muscle concentrations decreased. Additionally, there was a reduction in the levels of α-keto acids derived from Val and Ile and an increase in the derivatives of Leu, suggesting that excess Leu accelerates the degradation of Ile and Val. The muscle's expression of catabolic enzymes (BCAA transaminase and BCKDH) also increased, corroborating the hypothesis of greater catabolism of these amino acids. The study also highlighted neuroendocrine impacts: the linear reduction in hypothalamic and plasma serotonin suggests that excess Leu compromises Trp uptake in the brain, affecting appetite regulation. This reduction in serotonin may explain the decrease in voluntary feed intake, which, combined with the lower availability of Val and Ile for protein synthesis, contributed to the worsening performance. The work showed that excess Leu induces an antagonism between BCAAs, reducing protein efficiency and growth through three main pathways: increased degradation of Val and Ile, dysregulation of brain serotonergic signaling, and reduced food consumption and reinforce the need to carefully balance the relationship between Leu, Val, and Ile in dietary formulations to avoid metabolic and productive impairments.

Table 3 Regression equations to predict growth performance of grow-finish pigs (Cemin et al. 2019)

ADG, g	= – 985.94 + (15.2499 × average BW (kg)) – (0.08885 × average BW × average BW) + (1.063 × Leu:Lys) + (20.2659 × Ile:Lys) – (0.1479 × Ile:Lys × Ile:Lys) + (9.2243 × (Ile+Val):Leu) – (0.03321 × (Ile+Val):Leu × (Ile+Val):Leu) – (0.4413 × Ile:Trp)
G:F, g/kg	= 648.3 – (6.2974 × average BW (kg)) + (0.02051 × average BW × average BW) + (0.5396 × Ile:Lys) + (1.7284 × Val:Lys) – (0.00795 × Val:Lys × Val:Lys) – (1.7594 × Met:Lys)
ADFI, kg	= predicted ADG/predicted G:F

ADG = average daily gain. G:F = gain-to-feed ratio. ADFI+ average daily feed intake.
Average BW = average body weight. Amino acids ratios to lysine are expressed on standardized ileal digestible basis

Nutritional Strategies to Mitigate Excess Leu in DDGS Diets

The study by Kwon et al. (2022) demonstrated that excess Leu in the diet (up to 299% of the SID Leu:Lis ratio) reduced average daily gain, feed intake, and hypothalamic serotonin levels in growing pigs. These adverse effects occurred due to competition between Leu and Trp for the blood-brain barrier, which limited the availability of Trp for serotonin synthesis, a neurotransmitter crucial for appetite regulation. However, supplementation with Trp (18-28% SID Trp:Lys) partially attenuated these impacts, especially in diets with higher excess Leu (299%), where a significant interaction between Leu and Trp levels was observed. The results revealed a complex metabolic interaction: while dietary Leu linearly increased its plasma concentration, it reduced the availability of Trp in the brain. Trp supplementation restored hypothalamic serotonin levels and improved zootechnical performance in diets with excess Leu. However, the positive effect of Trp was more pronounced when its supplementation was combined with higher levels (28% SID Trp:Lys), suggesting that complete correction of imbalances caused by excess Leu may require specific ratios between these amino acids.

Evaluating diet with Leu-rich DDGS, Kerkaert et al. (2021) demonstrated that Val or Ile supplementation significantly improved pigs' performance. During the growth phase (34-90 kg), the animals fed diets supplemented with Val showed a higher daily gain than the negative control group, while in the finishing phase (90-136 kg), supplementation with Ile showed better feed efficiency. Interestingly, supplementation with Trp did not produce the expected effects, possibly due to the insufficient proportions or the need to combine with Val and Ile to adequately counteract the impact of excess Leu.

The results of Kerkaert et al. (2021) revealed that the prediction model of Cemin et al. (2019) accurately predicted the differences in weight gain between main treatments but overestimated the effect of supplementation with Trp, confirming that the imbalance between BCAA (especially the relative deficiency of Val and Ile) may significantly impact performance more than the imbalance with large neutral amino acids. In addition, it was observed that feed intake was higher in the Val group, indicating that these amino acids may play an essential role in maintaining food intake in diets with high Leu content. The research also reinforces the need for further studies to validate prediction models when combinations of Val, Ile, and Trp are used in diets with high levels of Leu, particularly to optimize feed efficiency at different stages of production.

Clizer et al. (2022) evaluating the ideal SID Ile:Lys ratio in diets with 20% DDGS for finishing pigs (82.3 kg initial), showed that, although different levels of SID Ile:Lys (55% to 75%) did not affect zootechnical performance, the 65% ratio optimized carcass parameters, reducing backfat thickness, increasing loin depth and tending to increase the percentage of lean meat. Comparing diets, animals fed with corn-soybean meal had daily intake 3% higher than those with DDGS and 70% SID Ile:Lys, allowed higher final weight and daily gain, concluding that the SID Ile:Lys ratio of 70% in diets with 20% DDGS provides performance similar to that of the conventional corn-soybean meal diet, while the range between 65%-70% is ideal for carcass traits. The results highlight the importance of adjusting amino acid balance when including DDGS. However, more research is needed to define the optimal relationship at different levels of DDGS inclusion and elucidate the metabolic mechanisms involved. The data indicate that the requirement of Ile can vary according to the composition of the diet, even without significant changes in growth.

Recently, Kwon et al. (2024) demonstrated that strategic supplementation of Val and Trp can mitigate the adverse effects of excess Leu in the diet of pigs containing DDGS in pigs. Evaluating nitrogen retention, the isolated addition of Ile reduced nitrogen retention, while Trp increased retention when added alone or with Ile. A control diet (corn-soybean meal) out performed diets with excess Leu, except when supplemented with Val+Trp, which presented similar results to the control. The combined analysis revealed that adding Val (0.15× above the requirement) and Trp (0.25×) was more effective than Ile in improving performance, indicating that the use of DDG corn protein in swine diets requires special attention to the balance between BCAAs and that the simultaneous correction of multiple imbalances (Leu-Val-Trp) is more effective than isolated interventions, highlighting the importance of integrated approaches in the formulation of diets with high levels of corn by-products.

Summarized Research Results with BCAAs

The data shown in Table 4 summarizes the main findings of the studies, highlighting interactions between BCAAs, optimal requirements, and impacts on animal performance. These results provide valuable subsidies for formulating more accurate diets, considering herd averages and individual variations in amino acid utilization. The results emphasize the metabolic complexity of BCAAs and the importance of considering their interactions in dietary formulations.

Table 4 Summary of publications cited and results

Author	Year	Phase - Weigth	Treatments	Results
Morales et al.	2015	Piglets (31.8 ± 1.2 kg)	Excess Leu or Leu + Ile + Val	Excess Leu reduces serum concentration of Leu and Val, but does not affect performance. Ile and Val supplementation restores serum levels.
Nørgaard et al.	2017	Piglets (8-9 kg)	Dose-response of Ile, Leu, Val	Estimated optimal levels: 0.54 SID Ile:Lys, 1.04 SID Leu:Lys, 0.68 SID Val:Lys.
Xu et al.	2017	Weaned piglets	SID Val:Lys (dose-response)	Optimal SID Val:Lys level: 68% to maximize ADG and intestinal morphology
Gonçalves et al.	2018	Piglets (25-45 kg)	SID Val:Lys (59-78%)	SID Val:Lys requirement ranges from 63.2% (99% G:F maximum) to 73.0% (ADG maximum).
Huepa et al.	2018	Piglets (15.16 ± 1.15 kg)	SID Val (0.58-1.03%) and SID Leu (1.20-1.77%)	Optimal SID Val level for ADG: 0.703%. Elevated fluid increases plasma urea only with low Val.
Rudar et al.	2018	Piglets (14.5 ± 0.8 kg)	SID Leu (1.36-2.72%)	Leu supplementation can redirect AA for muscle synthesis during immune challenge.
Ma et al.	2019	Finishing sows (93.8 ± 5.5 kg)	Diets with low CP and AA supplementation	Supplementation with Val improved ADG in diets with 10.5% CP.
Cemin et al.	2019	Piglets (meta-analysis)	BCAA, LNAA, interactions	Prediction equations for ADG, G:F, ADFI. Excess Leu:Lys negatively impacts ADG. Addition of Val, Ile, and Trp can counteract negative effects of excess Leu.
Kwon et al.	2019	Piglets (30.0 ± 2.7 kg)	Leu (100-300% requirement)	Excess Leu reduces performance, N and serotonin retention, increasing Ile and Val catabolism.
Tian et al.	2019	Piglets	Diets with CP reduction and BCAA supplementation	BCAA deficiency reduces intake via T1R1/T1R3 receptors and via GCN2/eIF2α in the hypothalamus.
Millet et al.	2020	Piglets (4-9 weeks)	Val:Lys dose-response	Val:Lys SID requirement: 68-74% for optimal intake and growth
Veira et al.	2021	Piglets (20-30 kg)	SID Val:Lys (0.56-0.74) and SID Ile:Lys (0.43-0.61)	Individual requirements vary: Val:Lys (0.62-0.68), Ile:Lys (0.52-0.60).
Zouaoui et al.	2021	Piglets (meta-analysis)	SID Val, Leu, Ile Response to Val is modulated by leu	Excess of Leu reduces ADG and ADFI.
Kerkaet et al.	2021	Pigs (33.6 kg)	Diets with DDGS and supplementation of Val, Ile, Trp	Addition of Val or Ile reverses negative effects of excess Leu. Trp had no significant effect
Clizer et al.	2022	Finishing pigs (82.3 kg)	SID Ile:Lys (55-75%) in diets containing 20% DDGS	Optimal SID Ile:Lys level: 65-70% for carcass traits.
Kwon et al.	2022	Piglets (28.2 ± 1.9 kg)	Leu (101-299% SID Leu:Lys) and Trp (18-28% SID Trp:Lys)	Trp attenuates negative effects of excess Leu on ADG, ADFI and hypothalamic serotonin.
Humprey et al.	2023	Piglets (10-20 kg).	SID Leu, Ile, Val (dose-response)	Val impacts ADG and G:F. Excess Leu and Ile reduces performance, but is mitigated with Val adjustment
Kwon et al.	2024	Piglets (33.9 ± 2.6 kg and 28.6 ± 2.5 kg)	Val, Ile, Trp in diets with excess Leu	Combination of Val and Trp improves N retention and performance. Isolated ile reduces N retention.

ADG: Average daily weight gain; G:F: Gain:food ratio; ADFI: Average daily feed intake. BCAA: Branched-chain amino acids (Val, Ile, Leu), SID: Standardized ileal digestibility; DDGS: Dried distillers grains with solubles.

CONCLUSIONS

Research in recent years suggests that BCAA ratios may differ from the ideal fixed protein standards, considering modern genotypes of high lean meat deposition and interactions with BCAAs. In some situations, higher or lower BCCAs can lead to reduced performance if not properly balanced. Low-protein diets supplemented with crystalline AAs are increasingly used to reduce nitrogen excretion; these diets can promote BCAA deficiencies if not properly formulated. Val and Ile become limiting in low-protein diets, and inadequate supplementation can depress feed intake and growth. Similarly, excess Leu in low-protein diets may induce BCAA imbalances, exacerbating Ile and Val deficiencies. In practice, dietary protein sources vary in BCAA content; corn and soybean meal diets typically provide enough Leu but may not have Val and Ile relative to Lys. Alternative proteins, such as wheat and canola meal, have different BCAA profiles, requiring adjustments. Excess Leu reduces the availability of Ile, Val, and Trp, impacting growth and feed intake. Strategic supplementation of Val, Ile, or Trp can correct imbalances, especially in diets with corn/DDGS, where the Leu is in excess.

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Not applicable' for that section.

Ethics approval and consent to participate

Not applicable' for that section.

Consent for publication

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Availability of data and materials

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