6 Amino Acid Quality of Meat Proteins

Natalia S. Fanelli and Hans H. Stein

ABBREVIATIONS

AA	Amino acid
DIAA	Digestible indispensable amino acid
DIAAS	Digestible indispensable amino acid score
FAO	Food and Agriculture Organization
IAA	Indispensable amino acid
SID	Standardized ileal digestibility
USDA	US Department of Agriculture

INTRODUCTION

Meat derived from different animal species, such as poultry, pigs, cattle, and sheep, is an essential component of many cuisines around the world, offering a variety of cuts with different flavors, textures, and cooking properties suitable for a wide range of applications. However, within each type of meat, there may be distinctions based on specific cuts or preparation methods that may influence protein quality (Bailey et al. 2020a). Cultural, historical, geographical, socio-economic, and ethical factors also play a role in shaping the preferences and practices related to meat consumption and what is considered meat (Wahlqvist 2007).

Meat, in general, refers to the flesh edible part of animals (typically domesticated), including muscles, fat, ligaments, and tendons (Food and Agriculture Organization [FAO] 2021). Commonly consumed meats include poultry (including broiler chickens, laying hens, turkeys, ducks, and geese), pork, beef (including cows, steers, calves, heifers, and bulls), and lamb or mutton (from sheep). Although not widely consumed, game meat is another protein in this category and comprises meat from wild animals that are typically hunted, such as deer, boar, elk, rabbit, and game birds (quail and pheasant), among others (FAO 2018).

Several cuts are available, each with its own level of tenderness, recommended cooking methods, and nutrient contents, including amino acids (AA) and fat concentrations. Broiler chicken is the most widely consumed type of poultry and has lean flesh and mild flavor, providing cuts such as breasts, thighs, wings, and drumsticks. White meat from the breast and wings is leaner and more tender, whereas dark meat from thighs and drumsticks is richer in flavor and often juicier (Bihan-Duval et al. 2008). Beef can be divided into various cuts, the most common being rib, chuck (shoulder), brisket (chest), round (legs, thigh, and butt), tenderloin, and sirloin (rear of the animal). Meat obtained from young calves is called veal (US Department of Agriculture [USDA] and Food Safety and Inspection Service [FSIS] 2013). Similar to beef, pork can be categorized into cuts such as shoulder, ribs, loin, belly (high fat), and leg. Common cuts of pork include loin, bacon, ham, chops, and tenderloin (Bailey et al. 2020b). Lamb and mutton are meats that differ in terms of the age of the animal. Common cuts from sheep include chops, leg, loin, shoulder, and rack. Lamb refers to meat from young sheep, while mutton comes from mature animals (USDA 2022).

DOI: 10.1201/9781003597926-6

Animal-based proteins, including meats, are excellent sources of protein in human diets (Bender 1992). Proteins, more specifically indispensable amino acids (IAA), are required for muscle growth, development, and the overall health of the human body. As a result, the AA quality of animal proteins is important because it impacts the nutritional value of protein and its ability to provide IAA required for body protein synthesis and various physiological functions in humans (Bender 1992). The objective of this chapter is to provide information about AA concentration, digestibility, protein quality, and how processing affects protein quality in different meat cuts.

NUTRIENT CONCENTRATIONS

Meat is a valuable dietary source of protein and contains all the required amino acids (AA) as well as other important nutrients. Nutrient content may differ among meat cuts due to inherent physiological and anatomical variables such as muscle composition, fat distribution, and connective tissue. Nutrient concentrations also vary depending on the specific breed of the animal, age, feeding practices, and cooking methods (Bender 1992). Lean cuts have greater protein concentrations, whereas cuts with more connective tissue or fat contains less protein. The presence of IAA, contributes to the role of meat in muscle protein synthesis and the overall protein quality of meals. The type of muscle fiber in meat also affects the concentration of IAA (Franco 2010). Therefore, understanding the variations in protein concentrations and AA profiles is critical for optimizing nutritional intake and meeting dietary requirements.

Fat is an important component of meat, particularly as a source of essential polyunsaturated fatty acids, contributing to its sensory attributes and nutritional value (Wyness 2016). Generally, cuts from lean steaks, tend to have the least concentration of fat. In contrast, cuts from muscles with higher intramuscular fat deposition may have greater fat concentrations (Bender 1992). As an example, ribeye or T-bone steaks from beef are known for their marbling, indicating a greater fat content and enhanced flavor. Lean cuts, on the other hand, such as chicken breast or pork tenderloin, contain less fat (Bender 1992).

Table 6.1 contains examples of IAA and fat concentrations in various cuts of meat.

Regardless of species or cooking methods, lysine is the IAA present at the greatest concentration, whereas tryptophan is present at the least concentration. Other nutrients in meats not commonly present in plant-based foods include vitamins B_{12} and B_6, as well as iron, zinc, and selenium (Bender 1992).

DIGESTIBILITY OF PROTEIN AND AA

The digestibility of protein and AA in meat cuts can vary depending on animal species, muscle type, protein structure, and individual variations due to gut microbiota composition, enzyme activity, and overall intestinal health (Stein et al. 2007). Tender cuts with less connective tissue, such as fillets or loins, are usually more easily digestible than tougher cuts requiring longer cooking times or additional tenderization techniques. Proper cooking methods can also enhance the digestibility of meat proteins, ensuring optimal utilization of the AA by the body (Bender 1992).

Because of the similarities in the digestive systems between humans and pigs, the standardized ileal digestibility (SID) of AA in human foods determined in pigs is in agreement with values determined in humans (Rowan et al. 1994; Hodgkinson et al. 2022). Generally, meat proteins are highly digestible, with an average digestibility of 90–95%. As an example, values for the SID of protein and IAA in pork products such as pork loin, bacon, ground pork, porcine heart hydrolysate, raw belly, and ham ranged from 83 to 100% (Bailey et al. 2020b; Bindari et al. 2018; Fanelli et al. 2022). Ground beef, ribeye roast, topside beef steak, and bovine muscle hydrolysate yielded SID values ranging from 88 to 100% (Bailey et al. 2020a; Bindari et al. 2018; Fanelli et al. 2022; Hodgkinson et al. 2018).

TABLE 6.1
Concentration of Protein, Fat, and Indispensable Amino Acids (IAA) of Some Meat Cuts, g/100g (% of portion)[1,2]

Item	Protein	Fat	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine
Poultry[3]											
Raw chicken breast	20.8	9.2	0.6	1.0	1.5	1.7	0.6	0.8	0.9	0.2	1.0
Cooked chicken breast	29.8	7.8	0.9	1.5	2.2	2.5	0.8	1.2	1.2	0.3	1.5
Raw chicken thigh	16.6	14.6	0.4	0.7	1.3	1.4	0.4	0.6	0.7	0.2	0.7
Cooked chicken thigh	23.3	14.7	0.7	1.0	1.9	2.1	0.6	0.9	1.0	0.2	1.1
Raw chicken wing	17.5	12.8	0.7	0.9	1.5	1.80	0.5	0.7	0.8	0.2	0.9
Cooked chicken wing	23.8	16.9	0.9	1.2	2.0	2.3	0.6	1.0	1.1	0.3	1.2
Raw chicken drumstick	9.6	44.2	0.2	0.3	0.5	0.5	0.2	0.3	0.3	0.0	0.3
Cooked chicken drumstick	16.6	44.0	0.3	0.5	0.9	0.9	0.3	0.5	0.5	0.1	0.6
Beef											
Raw beef ribs	21.3	6.8	0.8	0.9	1.6	1.7	0.7	0.8	0.8	0.2	0.9
Cooked beef ribs	27.2	9.7	1.0	1.1	2.0	2.2	0.9	1.1	1.0	0.3	1.2
Raw beef tenderloin	21.0	6.9	0.8	0.9	1.6	1.7	0.7	0.8	0.8	0.2	0.9
Cooked beef tenderloin	27.3	8.1	1.0	1.3	2.4	2.6	0.7	1.1	1.3	0.3	1.4

(Continued)

TABLE 6.1 (CONTINUED)
Concentration of Protein, Fat, and Indispensable Amino Acids (IAA) of Some Meat Cuts, g/100g (% of portion)[1,2]

Item	Protein	Fat	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine
Raw beef brisket	14.7	14.9	0.5	0.6	1.1	1.1	0.3	0.5	0.6	0.1	0.6
Cooked beef brisket	18.2	19.0	0.6	0.8	1.4	1.5	0.5	0.7	0.7	0.2	0.9
Raw veal	18.6	13.1	0.7	0.9	1.5	1.5	0.4	0.7	0.8	0.2	1.0
Cooked veal	24.3	7.6	0.9	1.2	1.9	2.0	0.6	1.0	1.1	0.3	1.3
Pork											
Raw pork ribs	19.3	11.8	0.8	1.0	1.7	1.8	0.5	0.8	0.9	0.2	1.0
Cooked pork ribs	27.0	14.7	1.1	1.3	2.2	2.4	0.7	1.1	1.2	0.3	1.4
Raw pork chops	20.7	9.0	0.9	1.0	1.8	1.9	0.6	0.9	0.9	0.2	1.1
Cooked pork chops	25.6	11.1	1.1	1.3	2.2	2.4	0.7	1.1	1.2	0.3	1.3
Cured bacon[4]	33.9	35.1	1.4	1.6	2.8	3.0	0.9	1.4	1.5	0.4	1.7
Raw pork tenderloin	20.4	2.1	0.9	1.0	1.7	1.9	0.6	0.9	0.9	0.2	1.1
Cooked pork tenderloin	26.0	4.0	1.1	1.3	2.2	2.4	0.7	1.1	1.2	0.3	1.4
Sheep											
Raw lamb loin	15.4	26.2	0.3	0.7	1.2	1.3	0.5	0.6	0.7	0.2	0.8

(*Continued*)

TABLE 6.1 (CONTINUED)
Concentration of Protein, Fat, and Indispensable Amino Acids (IAA) of Some Meat Cuts, g/100g (% of portion)[1,2]

Item	Protein	Fat	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine
Cooked lamb loin	21.1	21.0	0.4	0.9	1.6	1.8	0.7	0.8	1.0	0.2	1.1
Raw lamb leg	18.6	14.5	0.4	0.8	1.4	1.6	0.6	0.7	0.9	0.2	0.9
Cooked lamb leg	24.8	15.6	0.8	1.2	1.9	2.1	0.6	1.0	1.0	0.3	1.3
Raw lamb shoulder	16.2	22.9	0.3	0.7	1.3	1.4	0.5	0.6	0.8	0.2	0.8
Cooked lamb shoulder[5]	20.9	23.4	0.4	0.9	1.6	1.8	0.7	0.8	1.0	0.2	1.1

[1]Values were obtained from the USDA Food Database 2023.
[2]Cooked refers to the roasting process.
[3]Meat and skin.
[4]Pan-fried.
[5]Slow-roasted.

Because AA are present alongside fat molecules in meats, and because fat influences the digestibility and availability of AA (Li and Sauer 1994; Cervantes-Pahm and Stein 2008), the concentration of fat may affect the SID of AA in specific cuts of meat. Fats can form complexes with proteins, potentially affecting the access of digestive enzymes to protein molecules and reduce AA digestibility. In contrast, fat may also slow gastric emptying and therefore increase SID of AA.

PROTEIN QUALITY

Meats are considered high-quality proteins due to the presence of IAA and greater digestibility when compared with other foods. However, this varies depending on the cut and the composition of AA (Fanelli et al. 2022; Hodgkinson et al. 2018). Cuts with connective tissue and marbling may have the least protein concentration, but cuts with greater marbling may have greater digestibility of AA, and all types of meat usually increase the protein quality of mixed meals.

Several methods have been developed to determine protein quality in human foods. The current method recommended by the FAO to assess protein quality is called the digestible indispensable amino acid score (DIAAS; FAO 2013). This method recommends using pigs as a model when humans are unavailable because of their digestive similarities (FAO 2013; Hodgkinson et al. 2020). The DIAAS is calculated using the protein and AA composition of a food and their respective SID values. Digestible indispensable amino acid (DIAA) reference ratios are used to compare results with human AA patterns for infants, children, adolescents, and adults. The least reference ratio (first limiting AA) is then determined as DIAAS. Cut-off values are based on values ranging from 75 to 99 for foods with "good" protein quality and values of 100 or more for foods with "excellent" protein quality (FAO 2013). However, no claims can be made for foods with a DIAAS less than 75.

Protein quality in a number of different cuts of meat has been reported (Table 6.2). Generally, protein quality in meat proteins depends on cooking techniques and intrinsic individual differences.

PROCESSING

Different processing methods such as heat treatment, dehydrating, curing, smoking, fermenting, aging, and mechanical processing can impact protein quality of meats (Bailey et al. 2020a; Hodgkinson et al. 2018). Effects of processing on protein quality can vary based on the specific cut, processing conditions, and the type and amount of added ingredients. Heat treatment, such as cooking, roasting, or grilling, is essential to improve sensory characteristics, but it can also change protein structure and impact protein quality, either positively or negatively (Santé-Lhoijtellierv et al. 2008). Both overheating and underheating of meats can have a negative impact on protein quality and overall sensory attributes of the meat (Santanu et al. 2014).

Overcooking or excessive heat exposure may lead to protein denaturation, which causes changes in the three-dimensional structure and protein degradation (Yu et al. 2017). Although protein denaturation in meat at temperatures around 70°C may increase the digestibility of AA, temperatures over 100°C may cause protein aggregation and cross-linking, resulting in a more rigid and less tender meat texture as well as reduced digestibility of AA and protein quality (Di Luccia et al. 2015; Gatellier et al. 2010; Li et al. 2017). As an example, overcooked ground beef reduced protein quality by 22%, and grilling and roasting topside steak reduced protein quality by 17% and 6%, respectively, demonstrating that some meats (and processes used) may have heat damage at different levels of heating (Bailey et al. 2020a; Hodgkinson et al. 2018).

Lysine is the AA most affected by overheating because of the exposed epsilon amino group that can easily combine with a reducing sugar in the Maillard reaction, thereby preventing its use in protein synthesis. However, depending on the time and temperature used to cook, lysine in meat is often not affected by cooking or processing because of the lack of reducing sugars in meat (Bailey et al. 2020a; Hodgkinson et al. 2018). Overheating can also cause lipid oxidation, which can result in formation of potentially indigestible compounds that can impair AA availability, promote the

TABLE 6.2

Protein Quality of Different Meat Cuts as Indicated by the Digestible Indispensable Amino Acid (DIAAS) Method[1,2,3]

	DIAAS		
Item	**Infants (0 to 6 Months)**	**Children (6 Months to 3 Years)**	**Older Children, Adolescents, and Adults**
Porcine plasma hydrolysate[4]	60 (Isoleucine)	87 (Sulfur AA)	102 (Sulfur AA)
Porcine muscle hydrolysate[4]	21 (Tryptophan)	42 (Tryptophan)	54 (Tryptophan)
Porcine heart hydrolysate[4]	38 (Tryptophan)	76 (Tryptophan)	87 (Isoleucine)
Pork raw belly[5]	—	111	119
Smoked bacon[5]	—	109	117
Smoked-cooked bacon[5]	—	126	142
Non-cured ham[5]	—	115	124
Cured ham[5]	—	117	126
Raw pork loin[6]	55 (Histidine)	78 (Histidine)	97 (Histidine)
Roasted pork loin[5,6]	60 (Tryptophan)	107–129	117–139
Grilled pork loin[6]	61 (Tryptophan)	112	123
Fried pork loin[6]	69 (Tryptophan)	112	126
Salami[7]	—	107	120
Back ribs[8]	63 (Aromatic AA)	106	114
Shoulder butt[8]	64 (Aromatic AA)	107	115
Tenderloin[8]	66 (Aromatic AA)	115	124
Coppa[8]	63 (Aromatic AA)	115	128
Prosciutto[8]	70 (Aromatic AA)	127	137
Speck[8]	72 (Tryptophan)	111	119
Chorizo sausage[8]	65 (Tryptophan)	99 (Sulfur AA)	113
Italian sausage[8]	72 (Tryptophan)	113	122
Bratwurst sausage[8]	64 (Tryptophan)	101	117
Raw ground beef[7]	—	111	121
Cooked ground beef[7]	—	92 (Leucine)	99 (Leucine)
Ground pork 80% lean, burger[9]	—	111	119
Ground beef 80% lean, burger[9]	—	102	110
Ground beef 93% lean, burger[9]	—	111	119
Bologna[7]	—	118	128
Bovine muscle hydrolysate[4]	32 (Tryptophan)	63 (Tryptophan)	81 (Tryptophan)
Ribeye roast[7]	—	99 (Leucine)–121	107–130
Beef jerky[7]	—	102	120
Raw beef topside steak[10]	—	97 (Valine)	—
Boiled beef topside steak[10]	—	99 (Valine)	—
Grilled beef topside steak[10]	—	80 (Valine)	—
Pan-fried beef topside steak[10]	—	98 (Valine)	—
Roasted beef topside steak[10]	—	91 (Valine)	—

(*Continued*)

TABLE 6.2 (CONTINUED)

Protein Quality of Different Meat Cuts as Indicated by the Digestible Indispensable Amino Acid (DIAAS) Method[1,2,3]

	DIAAS		
Item	**Infants (0 to 6 Months)**	**Children (6 Months to 3 Years)**	**Older Children, Adolescents, and Adults**
Roasted beef tenderloin[8]	—	120	—
Roasted turkey breast[8]	—	111	—

[1]Values are DIAAS followed by first-limiting amino acid (AA) in parentheses. If DIAAS values >100, no limiting AA is present.
[2]The DIAAS values were determined using pig as the animal model.
[3]Values not reported are noted by "-".
[4]Bindari et al. 2018.
[5]Bailey et al. 2020b.
[6]Mathai 2018.
[7]Bailey et al. 2020a.
[8]Fanelli et al. 2024.
[9]Fanelli et al. 2022.
[10]Hodgkinson et al. 2018.

Maillard reaction, and have negative effects on flavor, as well as potentially form harmful compounds. Overcooking can also cause moisture loss from the meat, resulting in a dry and less succulent texture (Bender 1992).

Undercooking meats may result in insufficient protein denaturation, leaving the proteins in their native state. This can lead to a chewy and rubbery texture due to the lack of protein breakdown and tenderization (Bender 1992). Undercooked meat may also have reduced protein digestibility due to the presence of enzymes or protein structures that are more resistant to digestion and can fail to eliminate harmful bacteria that may be present in raw meat (Bender 1992). Nevertheless, when appropriate processing is used, the digestibility of IAA and protein quality are increased, as demonstrated when ribeye was heated to 64°C (Bailey et al. 2020a). Therefore, to ensure optimal protein quality, it is important to cook meats properly and avoid both overheating and underheating (Hodgkinson et al. 2018). The ideal cooking temperature and cooking time vary depending on the type of meat, cut, and desired doneness, which can vary among individuals and cultures. Using cooking methods that allow for precise temperature control (i.e., the use of a thermometer) can help achieve the desired level of doneness while preserving protein quality.

EFFECTS OF OTHER PROTEINS

In this chapter, AA quality of meat proteins was discussed regarding nutrient concentrations, AA digestibility, protein quality, and processing. However, consideration must be given to other proteins, such as soy and milk proteins. The digestibility of AA and quality of proteins, including soy protein isolate, soy flour, whey protein isolate, milk protein concentrate, whey protein concentrate, and skim milk powder, are relatively close to the quality of meat proteins (Fanelli et al. 2022; Mathai et al. 2017). However, most plant-based proteins, including proteins from corn, peas, oats, rice, beans, and wheat, have reduced protein quality compared with meats because of concentrations of limiting AA and the extensive processing that is sometimes applied to these types of foods (Mathai et al.

2017; Rutherfurd et al. 2015). Because proteins are usually consumed together with other foods in combined meals, the excellent protein quality of meat can compensate for the low-quality proteins in plant-based ingredients. As an example, burgers are usually consumed with burger buns. Thus, if animal-based burgers are combined with a burger bun, this combination can provide enough digestible AA for individuals older than three years old, although the protein quality of the burger bun is very poor (Fanelli et al. 2022). However, if a pea-based burger was combined with a burger bun, complementarity was less than with animal-based burgers, and sulfur AA was still limiting in the combined diet (Fanelli et al. 2022). In addition, milk can complement lower-quality cereal-based proteins such as cornflakes and oats in traditional breakfast-style porridge combinations and provide an AA-balanced meal (Fanelli et al. 2021).

CONCLUSIONS

Meat supplies not only high-quality protein but also IAA, vitamins, and minerals that are essential for human health. The many cuts and varieties of meats that are available provide a wide range of culinary possibilities. Meat generally has excellent protein quality due to greater digestibility of AA than in plant-based foods, but the quality can be influenced by processing methods and fat content. The protein quality of meat, as evaluated by the DIAAS method, also varies depending on the specific cut and cooking techniques. Cooking and processing procedures must be considered when evaluating protein quality because they affect protein digestion and overall meat quality. Therefore, understanding the effects of processing procedures on protein quality is necessary for retaining the nutritional value of meat.

MINI DICTIONARY OF TERMS

- **Connective tissue:** Structural tissue that supports and connects different components of an animal, which are made up of collagen.
- **Flesh:** Soft, edible part of an animal's body, typically referring to the muscle tissue consumed as food.
- **Marbling:** The distribution of fat within muscle fibers contributes to the tenderness and juiciness of specific cuts.
- **Tenderness:** The degree of softness or ease with which the meat can be chewed or cut.
- **Texture:** Physical consistency and mouthfeel of the meat.

SUMMARY POINTS

- Each type of meat has distinct cuts that affect protein quality.
- Factors such as culture and ethics influence meat preferences.
- Meat usually provides IAA for human growth and health.
- Individuals can maximize the benefits of nutrients that meat provides as part of a well-balanced diet by carefully selecting and preparing meat pieces.
- All meat cuts have much greater protein quality than most plant proteins, and meat will, therefore, contribute to a well-balanced diet if consumed in combination with lower-quality plant proteins.
- Lean cuts have greater protein concentrations, whereas cuts with more connective tissue have lower protein content.
- Protein quality is affected by the type of cuts, animal species, cooking procedures, and intrinsic characteristics of a food.
- Overheating can result in protein degradation, whereas undercooking may result in insufficient protein denaturation.

REFERENCES

Bailey, H. M., J. K. Mathai, E. P. Berg and H. H. Stein. 2020a. Most meat products have digestible indispensable amino acid scores that are greater than 100, but processing may increase or reduce protein quality. *British Journal of Nutrition* 124:14–22.

Bailey, H. M., J. K. Mathai, E. P. Berg and H. H. Stein. 2020b. Pork products have digestible indispensable amino acid scores (DIAAS) that are greater than 100 when determined in pigs, but processing does not always increase DIAAS. *The Journal of Nutrition* 150:475–482.

Bender, A. 1992. *Meat and meat products in human nutrition in developing countries*. FAO food and nutrition paper 53. Food and Agriculture Organization of the United Nations. Rome. http://www.fao.org/docrep/t0562e/T0562E00.htm (accessed June 18, 2023).

Bihan-Duval, L., M. Debut, C. M. Berri, N. Sellier, V. Santé-Lhoutellier, Y. Jégo and C. Beaumont. 2008. Chicken meat quality: Genetic variability and relationship with growth and muscle characteristics. *BMC Genetics* 9:1–6.

Bindari, Y. R., H. N. Lærke, and J. V. Nørgaard. 2018. Standardized ileal digestibility and digestible indispensable amino acid score of porcine and bovine hydrolyzates in pigs. *Journal of the Science of Food and Agriculture* 98:2131–2137.

Cervantes-Pahm, S. K. and H. H. Stein. 2008. Effect of dietary soybean oil and soybean protein concentration on the concentration of digestible amino acids in soybean products fed to growing pigs. *Journal of Animal Science* 86:1841–1849.

Di Luccia, A., B. La Gatta, A. Nicastro, G. Petrella, C. Lamacchia and G. Picariello. 2015. Protein modifications in cooked pork products investigated by a proteomic approach. *Food Chemistry* 172:447–455.

Fanelli, N. S., H. M. Bailey, L. V. Guardiola and H. H. Stein. 2021. Values for digestible indispensable amino acid score (DIAAS) determined in pigs are greater for milk than for breakfast cereals, but DIAAS values for individual ingredients are additive in combined meals. *The Journal of Nutrition* 151:540–547.

Fanelli, N. S., H. M. Bailey, T. W. Thompson, R. Delmore, M. N. Nair and H. H. Stein. 2022. Digestible indispensable amino acid score (DIAAS) is greater in animal-based burgers than in plant-based burgers if determined in pigs. *European Journal of Nutrition* 61:461–475.

Fanelli, N. S., J. C. F. R. Martins and H. H. Stein. 2024. The digestible indispensable amino acid scores (DIAAS) in pork cuts, hams, and sausages is close to or above 100 and pork ingredients can complement ingredients with lower protein quality. *Journal of the Science in Food and Agriculture Reports* 4:326–335.

FAO. 2013. *Dietary protein quality evaluation in human nutrition: Report of an FAO expert group*. FAO food and nutrition paper 92. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a-i3124e.pdf (accessed June 21, 2023).

FAO. 2018. *Game meat – production and trade in the UNECE region*. The United Nations Economic Commission for Europe. https://unece.org/fileadmin/DAM/timber/meetings/2018/20180321/game-meat-draft-2018-03.pdf (accessed June 18, 2023).

FAO. 2021. *Indicator 10: Individual average daily consumption of meat*. Milan Urban Food Policy Pact. https://www.fao.org/3/CB4058EN/CB4058EN.pdf (accessed June 18, 2023).

Franco, D., L. Gonzalez, E. Bispo, P. Rodriguez, J. I. Garabal and T. Moreno. 2010. Study of hydrolyzed protein composition, free amino acid, and taurine content in different muscles of Galician blonde beef. *Journal of Muscle Foods* 21:769–784.

Gatellier, P., A. Kondjoyan, S. Portanguen and V. Sante-Lhoutellier. 2010. Effect of cooking on protein oxidation in n-3 polyunsaturated fatty acids enriched beef. Implication on nutritional quality. *Meat Science* 85:645–650.

Hodgkinson, S. M., C. A. Montoya, P. T. Scholten, S. M. Rutherfurd and P. J. Moughan. 2018. Cooking conditions affect the true ileal digestible amino acid content and digestible indispensable amino acid score (DIAAS) of bovine meat as determined in pigs. *The Journal of Nutrition* 148:1564–1569.

Hodgkinson, S. M., H. H. Stein, S. de Vries, W. H. Hendriks and P. J. Moughan. 2020. Determination of true ileal amino acid digestibility in the growing pig for calculation of digestible indispensable amino acid score (DIAAS). *The Journal of Nutrition* 150:2621–2623.

Hodgkinson, S. M., N. Stroebinger, N. van der Wielen, C. Montoya, W. H. Hendriks, H. H. Stein and P. J. Moughan. 2022. Comparison of true ileal amino acid digestibility between adult humans and growing pigs. *The Journal of Nutrition* 152:1635–1646.

Li, L., Y. Liu, X. Zou, J. He, X. Xu, G. Zhou and C. Li. 2017. In vitro protein digestibility of pork products is affected by the method of processing. *Food Research International* 92:88–94.

Li, S. and W. C. Sauer. 1994. The effect of dietary fat content on amino acid digestibility in young pigs. *Journal of Animal Science* 72:1737–1743.

Mathai, J. K. 2018. *Digestible indispensable amino acid scores (DIAAS) for various food proteins and assessment of intra-experiment variation of DIAAS*. PhD diss. University of Illinois at Urbana-Champaign. https://www.ideals.illinois.edu/items/109804 (accessed June 22, 2023).

Mathai, J. K., Y. Liu and H. H. Stein. 2017. Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than values calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). *British Journal of Nutrition* 117:490–499.

Rowan, A. M., P. J. Moughan, M. N. Wilson, K. Maher and C. Tasman-Jones. 1994. Comparison of the ileal and faecal digestibility of dietary amino acids in adult humans and evaluation of the pig as a model animal for digestion studies in man. *British Journal of Nutrition* 71:29–42.

Rutherfurd, S. M., A. C. Fanning, B. J. Miller and P. J. Moughan. 2015. Protein digestibility-corrected amino acid scores and digestible indispensable amino acid scores differentially describe protein quality in growing male rats. *The Journal of nutrition* 145:372–379.

Santanu, D. C., S. Haines, D. Harland, S. Clerens, C. van Koten and J. Dyer 2014. Effect of cooking on meat proteins: mapping hydrothermal protein modification as a potential indicator of bioavailability. *Journal Agricultural Food Chemistry* 62:8187–8196.

Santé-Lhoijtellier, V., T. Astrijc, P. Marinova, E. Greve and P. Gatellier. 2008. Effect of meat cooking on physicochemical state and in vitro digestibility of myofibrillar proteins. *Journal Agricultural Food Chemistry* 56:1488–1494.

Stein, H. H., B. Sève, M. F. Fuller, P. J. Moughan and C. F. M. De Lange. 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. *Journal of Animal Science* 85:172–180.

USDA. 2022. *Sheep, lamb and mutton*. U.S. Department of Agriculture. https://www.ers.usda.gov/topics/animal-products/sheep-lamb-mutton/ (accessed June 18, 2023).

USDA and FSIS. 2013. *Veal from farm to table*. U.S. Department of Agriculture and Food Safety and Inspection Service. https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/meat/veal-farm-table (accessed June 18, 2023).

USDA Food Database. 2023. https://fdc.nal.usda.gov/index.html (accessed June 19, 2023).

Wahlqvist, M. L. 2007. Regional food culture and development. *Asia Pacific Journal of Clinical Nutrition* 16:2.

Wyness, L. 2016. The role of red meat in the diet: Nutrition and health benefits. *Proceedings of the Nutrition Society* 75:227–232.

Yu, T. Y., J. D. Morton, S. Clerens and J. M. Dyer. 2017. Cooking-induced protein modifications in meat. *Comprehensive Reviews in Food Science and Food Safety* 16:141–159.