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REVIEW

Strategies to optimize the nutritional profile of mammalian meat for infants and geriatric population

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Abstract
Early-life growth and aging represent physiological stages with increased protein requirements due to rapid tissue development, anabolic resistance and reduced ability to digest and absorb nutrients. Red meat, which includes beef, pork, lamb and goat, provides complete proteins containing all essential amino acids, and micronutrients including iron, zinc, phosphorus, selenium, B vitamins and bioactive molecules such as creatine, taurine and carnitine. This review evaluates the nutritional composition and digestibility of different meat types and meat cuts, and how processing technology may improve protein intake in infants and geriatric population. The vulnerable population require softer texture of meat to ease mastication, swallowing and digestion. Meat cuts have different amino acid profile compared to one another. With the use of moderate temperature thermal processing, high pressure processing, dry ageing/in-bag dry ageing and/or fruit enzymes, protein unfolding, denaturation and proteolysis take place. Dependent on the processing conditions, proteins may become more digestible, liberating free amino acids and short peptides of less than 3 kDa that are easily absorbed by the small intestine for their functions. Conditions can be optimized to target for a release of key amino acids that are crucial for muscle protein synthesis (eg. Branched chain amino acids, including leucine, isoleucine and valine), immunity or cognitive function, which are of particular importance to the infants and geriatric population. By taking this approach, nutritional value of a given quantity of meat can be maximized, while supporting a more sustainable approach to feeding the population with limited resources.

Keywords Meat protein digestibility · Free amino acids · Dry aging · Infant nutrition · Older adults

Introduction

Protein is a macronutrient essential for growth and maintenance of muscles, biochemical and enzymatic functions and immune support (Symons et al., 2009; Paddon-Jones & Rasmussen, 2009; He, Connolly, Cross, & Wu, 2025). Meat from mammalian sources, such as beef, pork, lamb and goat, is considered a complete protein (Young & Pellett, 1984), containing nine essential amino acids (EAAs), and provides micronutrients including heme iron, zinc, phosphorus, selenium, vitamins B6 and B12, niacin (Pereira & Vicente, 2013; Wood, 2017) and bioactive molecules such as creatine, taurine and carnitine (Pereira & Vicente, 2013; Purchas et al., 2004; Williams, 2007), which is further summarised in Table 1.

Dependent on age, the requirement of protein changes (Millward et al., 1997). The ability to digest proteins to absorb appropriate nutrients is compromised for infants (Gan et al., 2018) and geriatric population (65 + yr olds) (Rémond et al., 2015). This review evaluates the requirement of proteins for the vulnerable population groups and how cooking and processing methods and selection of meat cuts can be used strategically to enhance protein digestibility and protein bioavailability, amino acid retention.

Proteins from red meat and their nutritional roles

Proteins comprise about 20 to 25% of red meat (Williams, 2007; Williamson et al., 2005). Depending on animal species, anatomical cuts, breeds, age and diet types, variations

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Table 1 A table summarizing the average nutrient composition (per 100 g) of four different types of cooked red lean meat (Williams, 2007)

	Beef	Veal	Lamb	Mutton
Energy(kJ)	498	477	546	514
Moisture (g)	73.1	74.8	72.9	73.2
Protein (g)	23.2	24.8	21.9	21.5
Fat (g)	2.8	1.5	4.7	4.0
Cholesterol (mg)	50	51	66	66
Vitamins (mg)				
Thiamine	0.04	0.06	0.12	0.16
Riboflavin	0.18	0.20	0.23	0.25
Niacin	5.0	16.0	5.2	8.0
Vitamin B6	0.52	0.8	0.10	0.8
Vitamin B12	2.5	1.6	0.96	2.8
Pantothenic acid	0.35	1.50	0.74	1.33
Vitamin A	< 5	< 5	8.6	7.8
Beta-carotene	10	< 5	< 5	< 5
Alpha-tocopherol	0.63	0.50	0.44	0.20
Minerals (mg)				
Sodium	51	51	69	71
Potassium	363	362	344	365
Calcium	4.5	6.5	7.2	6.6
Iron	1.8	1.1	2.0	3.3
Zinc	4.6	4.2	4.5	3.9
Magnesium	25	26	28	28
Phosphorus	215	260	194	290
Copper	0.12	0.08	0.12	0.22
Selenium	17	< 10	14	< 10

Table 2 Digestible Indispensable Amino Acid Scores (DIAAS) of meat from beef, pork and lamb (Bailey et al., 2020; Wolfe et al., 2016)

Meat Type	Cut	DIAAS	Notes
Beef	Tenderloin	1.13	High leucine, low collagen
Beef	Shank	1.05	Higher collagen, requires braising
Pork	Loin	1.12	Balanced EAAs
Lamb	Leg	1.10	Moderate digestibility

in moisture and lipids have been reported and these extend to the protein content of raw meat as well (Gonzalez et al., 1983; Watanabe et al., 2004).

EAAs are indispensable amino acids which are synthesized in the human body in inadequate speed, such that they must be supplied from diet for functional performance across the lifespan. EAAs include histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Leucine and isoleucine are branched chain amino acids that support muscle synthesis (Kohlmeier, 2015; Xu et al., 2015). A shortage of histidine and lysine can lead to anemia, mood swing and stunted growth. Methionine plays an important role in synthesis of cysteine, which protects liver cells from destruction (Martínez et al., 2013). Lacking phenylalanine, threonine and tryptophan may lead to memory problem, mood swing and mood change (Fernstrom, 2013; Friedman & Levin, 2012). A shortfall of valine affects the myelin which covers the nerves (Fontana et al., 2016). In red meat, a generous amount of glutamic acid/glutamine is present (16.5%), followed by arginine, alanine and aspartic acid (Williams, 2007). Free amino acids (FAAs), such as leucine, isoleucine, serine, threonine, valine, and phenylalanine, are important contributors of aroma formation in meat (Madruga et al., 2010). These react with sugars and by-products of lipid oxidation in meat to produce heterocyclic compounds that contribute to the aroma and flavor of cooked meat (Penet et al., 1983).

Rising number of interests in development of plant-based protein products is evident in both scientific literature and commercial products. However, the profile of EAAs is not well-balanced compared to that found in the red meat. Lysine, methionine, and cysteine are often lacking in many of those plant-based protein products (Dimina et al., 2022).

Rather than solely relying on the quantity of proteins and amino acids present, Protein Efficiency Ratio and Protein Digestibility-Corrected Amino Acid Score (PDCAAS) has been used to assess the quality of protein. The assessment is based on amino acid composition and fecal digestibility relative to the human requirements (FAO/WHO, 1991). The major criticism of this method is that it does not account for ileal digestibility or anti-nutritional factors. The PDCAAS scores of beef (0.92 to 0.98, ground and steak, respectively), pork (0.98) and lamb (1.0) indicate superior quality compared to many of plant-sourced proteins. In 2011, Digestible Indispensable Amino Acid Score (DIAAS) was developed, considering the ileal amino acid digestibility of individual indispensable amino acid and untruncated protein scores (Marinangeli & House, 2017) and it is currently the supported method of assessing the protein quality by the Food and Agriculture Organization of the United Nations. Red meat has DIAAS values of over 100, indicating their highly digestible nature and balanced EAA profiles, as summarised in Table 2 (Bailey et al., 2020).

Protein requirements of the population

Considering the Recommended Dietary Allowance (RDAs) and Estimated Average Requirements (EAR) published in nutrition guidelines and FAO documents, consumption of constant and adequate amounts of proteins is important for our health (WHO,2007). According to the European Food Safety Authority (EFSA), EAR and RDA for adults (18—64 yr olds) are 0.66 g and 0.83 g of protein per kg of body weight per day, respectively (EFSA, 2012). Population Reference Intakes (PRIs) for protein for infants and children range from 1.31 g to 0.85 g per kg of body weight per day, respectively (EFSA, 2012). Protein intake is critical for this population group for growth and development of muscles and organs, and neurocognitive functions. For older adults, PRI sits at 0.83 g per kg of body weight per day. Early-life growth and aging represent physiological stages with increased protein requirements due to rapid tissue development, anabolic resistance or higher muscle protein turnover, respectively (Churchward-Venne et al., 2012; Paulussen et al., 2021; Pérez-Castillo et al., 2025; Phillips & Van Loon, 2011).

The amount of EAAs absorbed and utilised from a piece of steak may differ across these population groups due to their ability to digest. Digestion is a simultaneous and continuous process where mastication, bolus formation, enzymatic secretion and peristalsis reduce the size of the particles and make nutrients available for the body to absorb and utilize. Reduced ability to masticate and reduced digestive enzyme secretion and their respective enzymatic activity have been reported in both population groups (Lebenthal et al., 1983; Pedersen et al., 2002; Peyron et al., 2017). Sarcopenia and anabolic resistance in geriatric population add to the demand for high-quality protein diet. Use of meat protein hydrolysates in baby foods (Restani et al., 1997) and foods for the geriatric population has been adopted for some time (Ahhmed & Muguruma, 2010). Hydrolysates provide rapidly absorbable amino acids, without overloading renal function and they also support better for allergic responses (Lonnerdal, 2003). Understanding the digestibility and amino acid composition of different meat types and cuts is therefore critical to develop foods for these populations.

Amino acid profiles of different meat cuts

Amino acid profile of meat varies across species and anatomical cuts due to differences in muscle structure, metabolic activity, and physiological function (Jung et al., 2016). Analysis of multiple beef sub-primals (e.g., chuck, loin, and round) shows that while all cuts contain abundant EAAs, the relative concentrations of specific amino acids such as glutamate, lysine, and leucine differed, with some cuts exhibiting higher overall protein nutritional value (Wu et al., 2016). Similarly, large-scale compositional studies of retail beef cuts demonstrate variability in amino acid profiles influenced by factors such as carcass composition, fat content, and animal age (Hall & Schönfeldt, 2013). These differences are further compounded by intrinsic and extrinsic factors, including genetics, feeding regime, and post-mortem processing, all of which can influence amino acid distribution and protein quality (Young & Pellett, 1984). Collectively, the literature indicates that although meat consistently supplies a complete amino acid profile, the nutritional value is not uniform across cuts, highlighting the importance of cut-specific evaluation.

The type of muscle fibre, either slow or fast twitch, is one of the causes in differentiation of amino acid profile. Slow-twitch (Type I) muscles contain higher total amounts of free amino acids (FAAs), particularly glutamine, glutamate, aspartate, serine, and histidine (Mashima et al., 2019). These muscle fibres are good source of delivering highly digestible form of proteins and tenderness of the meat. Slow-twitch muscles have higher rates of protein turnover, correlating with a greater FAA pool. The higher FAA content in slow-twitch muscles (red meat) contributes to a more intense flavor in cooking compared to fast-twitch muscles (white meat). Fast-twitch muscles on the other hand, contain higher concentrations of dipeptides, including carnosine and anserine, and higher amounts of free glycine and alanine (Valberg, 2008). Fast-twitch muscles have tougher and firmer texture compared to the slow-twitch muscles, and therefore not favoured by many. Table 3 further summarises commonly consumed meat cuts of different animal sources and their amino acid profiles. Collagen and collagen-related amino acids (glycine and proline) are generally present in higher amounts in shank, chuck and brisket (Toldrá et al., 2018; Wu et al., 2016, 2021) compared to other meat cuts. Glycine supplementation has been reported to improve metabolic syndrome including diabetes, obesity, hyperlipidemia and hypertension (Imenshahidi & Hossenzadeh, 2022), which would be of great use to the ageing population. The highest amount of leucine is found in beef tenderloin, supporting anabolic signalling in skeletal muscle and muscle protein synthesis in the vulnerable population.

FAAs and dipeptides are present in different quantities across different cuts of meat. The same composition of FAAs was found in *Musculus masseter* (cheek), *Musculus trapezius* (chuck) and *musculus longissimus* (full back) of raw pig muscles, however the quantities differed significantly (Cornet & Bousset, 1999). Glutamine differed significantly ($P < 0.001$) between *masseter* (808.57 µmol/100 g), *trapezius* (583.02 µmol/100 g) and *Longissimus dorsi* (447.37 µmol/100 g). Aspartic acid, glutamine and taurine contribute to raising the flavour and taste profile positively (Cornet & Bousset, 1999). The difference in AA content of different cuts is likely to be caused by a difference in oxidative and glycolytic activities of the muscles, which was also observed in lamb by Talmant et al. (1986). The oxidative ability of the muscle cuts in decreasing order is as follows: *masseter* > cardiac muscle > knuckle > heel > full back > inside cut, where the *masseter* is the most oxidative and the inside cut is the most glycolic (Franco et al., 2010). In raw beef, a significant difference in histidine has been reported, between full back and cardiac muscle, 9.71 and 96.24 mg/100 g, respectively. Taurine in *Masseter,* knuckle and inside round also differed: 111.21 mg/100 g, 69.03 mg/100 g and 74.26 mg/100 g, respectively (Franco

Table 3 A table summarizing FAAs present in different cuts of goat meat, pork and beef (a) Madruga et al., 2010; (b) Cornet & Bousset, 1999; (c) Franco et al., 2010; n.d: not detected

Amino Acid	Goat rump mg/100 g	Pork *masseter* µmol/100 g	Pork *trapezius* µmol/100 g	Pork full back µmol/100 g	Beef heel mg/100 g	Beef knuckle mg/100 g	Beef inside round mg/100 g	Beef full back mg/100 g	Beef *masseter* mg/100 g
HIS	4.7	See ALA	See ALA	See ALA	37.58	41.10	20.89	9.71	49.44
ILE	4.8	30.28	31.01	26.98	10.43	5.02	5.55	2.16	6.63
LEU	7.9	21.56	17.47	19.15	6.00	2.90	2.40	1.55	3.35
LYS	5.6	18.89	17.65	18.23	7.46	4.35	4.52	1.64	5.95
MET	1.7	9.14	8.61	10.68	4.00	1.55	1.77	0.87	1.81
PHE	3.9	5.57	5.65	5.26	7.46	3.77	4.10	2.46	4.58
THR	6.4	15.75	20.05	19.64	11.77	14.01	15.14	5.88	7.64
VAL	7.6	67.25	58.82	47.23	8.52	4.10	4.70	1.48	5.54
ARG	12.2	15.70	29.94	32.03	10.90	21.81	18.93	n.d	11.35
ALA	38.7	359.73 (ALA+HIS)	335.56 (ALA+HIS)	299.15 (ALA+HIS)	21.18	20.83	19.01	5.22	26.39
ASP	1.2	74.01	63.67	52.72	2.84	2.61	2.39	2.36	2.95
CYS	0.04	n.d	n.d	n.d	8.62	6.05	7.36	2.62	2.47
GLU	11	77.82	90.57	82.71	20.10	8.78	11.18	5.00	15.92
GLY	56.7	117.12	153.53	155.09	9.38	6.81	7.77	3.04	5.51
PRO	4.2	35.56	52.80	35.56	5.86	3.60	4.06	2.55	4.31
SER	8.9	38.07	35.67	36.79	10.09	5.54	5.75	3.02	9.55
TYR	3.7	8.50	8.75	10.01	6.87	30.80	3.54	1.50	4.13
Total FAAs	220.2	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
TAU	n.d	n.d	n.d	n.d	59.81	69.03	74.26	17.82	11.21
References	a	b	b	b	c	c	c	c	c

et al., 2010). Taurine plays a critical role in cardiovascular, skeletal muscle, retina, and the central nervous system. Particularly for the ageing population, taurine can be useful for treating bone-related disorders and neurodegenerative diseases and boost the immune system (Srivastava et al., 2022). Beef tenderloin is rich in leucine which is effective in stimulating mTOR signaling and muscle protein synthesis (Churchward-Venne et al., 2012; Symons et al., 2009). As discussed above, there are clear differences in amino acid composition and amounts across different cuts. Selective approach towards meat cuts will be beneficial to support better for the vulnerable population to meet their requirements.

Digestibility of meat proteins from different species and cuts

Often a static in vitro digestion model is used to study digestibility of meat proteins into peptides and free amino acids (Zhang et al., 2021). The INFOGEST model (Minekus et al., 2014) is largely driven by enzymatic hydrolysis with the use of simulated digestion secretions, in temperature and pH-controlled environment (Zhou et al., 2023). Mastication process is replaced with mincing the sample with simulated salivary fluid, and digesta samples are collected every hour for further analysis. Liberation of FAAs and peptides are used to calculate % digestibility (Zhang et al., 2021). Large intestine is not considered because the main absorption occurs in small intestine. The INFOGEST model is the most widely used in vitro digestion model in the literature, owing to its simplicity and consistency, without the need of ethics approval. However, some criticisms towards over-simplification and inadequate enzyme concentration have been reported in the past (Le Feunteun et al., 2021). Adaptations in the INFOGEST model have been made to accommodate for higher gastric pH and reduced digestive enzymes and bile salts for infants (Corrigan & Brodkorb, 2020; Ménard et al., 2018) and older adults (Menard et al., 2023; Gwala et al., 2025; Hinssen et al., 2025). In vitro methods have been reported to provide a lower protein digestibility compared to in vivo assay (Yi et al., 2016). *Longissimus dorsi* remains the most widely studied meat cut to date, where glutamic acid and aspartic acid have consistently been found to be the most abundant FAAs across all species.

There are several factors that contribute to the digestibility of proteins. Firstly, the type of meat cuts. Lean meat cuts including tenderloin and breast, generally have a faster enzymatic hydrolysis compared to collagen-rich cuts like shank, brisket and thigh. Some studies have reported significantly reduced absorption of amino acids from tougher cuts of meat (Farouk et al., 2019; Kaur et al., 2023). Muscle structure, connective tissue content, and protein physicochemical properties also affect digestibility of meat proteins.

Comparative studies across species have shown that digestibility is not uniform; for example, pork generally exhibits higher in vitro digestibility than beef, while chicken and fish often demonstrate faster hydrolysis and greater peptide release during digestion (Chen et al., 2023; Lee et al., 2023; Wen et al., 2015). In particular, fish proteins tend to be more readily digested due to their lower connective tissue content and weaker muscle structure, resulting in higher degrees of hydrolysis compared to red meats such as pork (Chen et al., 2023).

Variation in collagen content influences digestibility, with more tender cuts typically exhibiting higher protein digestibility than tougher, collagen-rich cuts. Bioactive peptides derived from hydrolyzed collagen may also exhibit antioxidant, anti-inflammatory, and metabolic regulatory functions, which are particularly important for older adults (Wang et al., 2022). Additionally, processing factors such as cooking conditions can significantly alter protein structure and thus affect ileal digestibility and overall protein quality (Hodgkinson et al., 2018). At a broader level, animal-derived proteins consistently demonstrate higher digestibility and amino acid bioaccessibility than plant-based alternatives, largely due to differences in protein structure and the absence of anti-nutritional factors (Diao et al., 2025; Xie et al., 2022). Overall, the literature indicates that protein digestibility is a dynamic property influenced by species, anatomical cut, and processing conditions, emphasizing the importance of considering these variables when evaluating the nutritional quality of meat.

Effects of cooking and processing methods on enhancing digestibility of meat proteins

In vitro digestion studies have consistently demonstrated that cooking methods significantly influence the digestibility of meat proteins by altering their structural and physicochemical properties. A choice of cooking methods affects the overall nutritional value of meat proteins, particularly the protein bioavailability and digestibility due to protein coagulation, aggregation, oxidation and proteolysis during cooking (Kaur et al., 2014; Loveday, 2023; Santé-Lhoutellier et al., 2008). Most of the undigested proteins which cannot be absorbed by small intestine get wasted into faeces. It is therefore vital to maximise the digestibility of meat through processing. Table 4 and Fig. 1 further summarize the digestibility of meat under different cooking conditions.

Table 4 Digestibility of cooked meat

Treatment	Digestibility change vs control	FAA increase	Relative ranking
Boiling	Baseline	Moderate	Low
Sous vide	+3–5%	Moderate-high	Medium
HPP	+5–10%	High	High
HPP+sous vide	+10–12%	Highest	Very high

Thermal processing by boiling typically results in protein digestibility of 85–88% though milder thermal processing by sous vide can improve digestibility to 90–92%, likely due to reduced thermal aggregation (Wang et al., 2023; Wen et al., 2015). Adoption of HPP treatments can enhance digestibility further, to 92–95% and combining HPP with mild thermal processing will maximise the digestibility to 95–97% (Lee et al., 2023; Xue et al., 2020). Across treatments, lysine, leucine, and glutamate consistently demonstrated increased liberation, indicating improved enzymatic accessibility following structural disruption of myofibrillar proteins.

Thermal processing

Thermal processing induces protein denaturation, aggregation, and changes in connective tissue, which can either enhance or reduce enzymatic accessibility depending on the severity of treatment. Moderate cooking temperatures generally improve protein digestibility by unfolding protein structures and exposing cleavage sites to digestive enzymes. Sous vide cooking, also known as vacuum cooking, is a method to cook vacuum-packed food in water bath with a moderate temperature of 55 to 60 °C, with a relatively longer cooking time (normally 2 h) (Vaudagna et al., 2002). It aims to maximize the nutrition retention and retain moisture, for both inside and outside. It is suitable for cooking tough cuts with high collagen, to improve gelatinization and digestibility (Kim et al., 2025).

Excessive and prolonged heating of over 100 °C may decrease the enzymatic proteolysis by formation of aggregates and intermolecular cross-links, hence influencing amino acid release and digestibility (Kaur et al., 2014; Wang et al., 2023). Grilling or frying may reduce lysine availability through Maillard reactions, while steaming or braising preserves amino acid integrity (Symons, Sheffield-Moore, Wolfe, & Paddon-Jones, 2007). Moist–heat methods (braising, stewing) increase digestibility in tough cuts by gelatinizing collagen and improve the release of peptides (Symons, Sheffield-Moore, Wolfe, & Paddon-Jones, 2007). Cooking-induced modifications to intramuscular connective tissue play a critical role, as collagen denaturation can either facilitate digestion or, when excessively cross-linked, hinder proteolysis. Infants and older adults require well-cooked, tender cuts to achieve maximal amino acid absorption due to reduced gastric acid and protease activity (DiPalma et al., 1991; Saber & Bayumi, 2016; Salles, 2007).

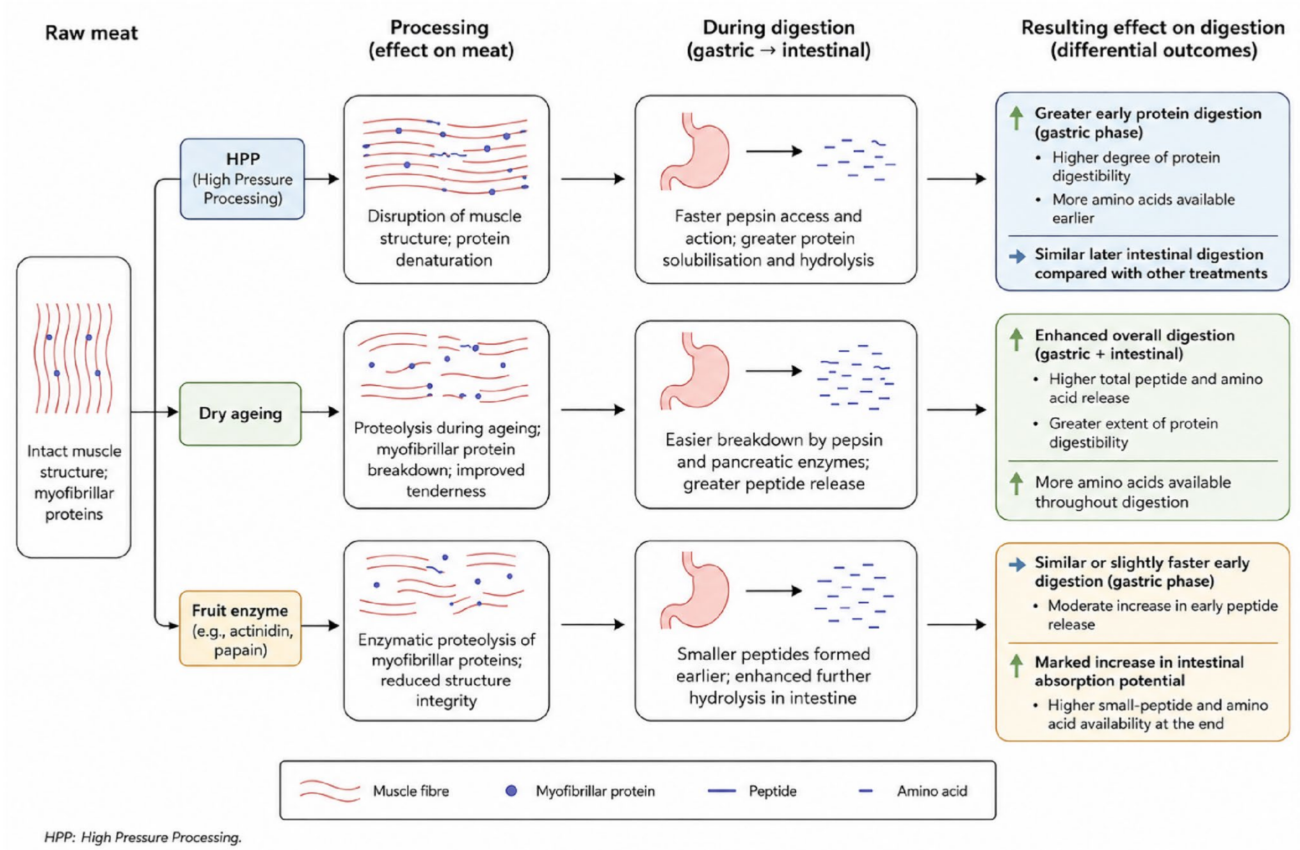

Fig. 1 A schematic diagram of processing treatments and their effects on meat protein digestibility

Apart from a difference in FAAs arising from different types of muscles in raw meat, cooking method also contribute towards the final composition of FAAs in meat. Studies in the past have shown that the total FAAs in cooked goat, beef and pork (150.9, 120.36 and 70.40 mg/100 g) was lower than the raw form (220.2, 131.08 and 100.92 mg/100 g), respectively (Madruga et al., 2010; Penet et al., 1983). According to Penet et al. (1983), the most abundant FAAs in cooked goat meat were glycine (38 mg/100 g), alanine (30.4 mg/100 g) and glutamine (23.9 mg/100 g) (Madruga et al., 2010). Heating causes a loss of sugars and protein denaturation that reduces the amount of FAAs of up 30 to 50%, particularly in leucine, isoleucine, threonine, phenylalanine and valine.

Pressure processing

High-pressure processing (HPP) has been shown to significantly enhance digestibility of meat by disrupting muscle structure, causing protein denaturation and conformational unfolding, thereby increasing enzyme accessibility and accelerating proteolysis. HPP causes conformational changes in myofibrillar proteins such as myosin and actin by disrupting actomyosin complexes, decreasing α-helix structures, and increasing β-sheet formation, which improves susceptibility to digestive proteases and increases the release of FAAs and low-molecular-weight peptides (Lee et al., 2023). The degree of denaturation is dependent on the type of muscle fiber type, the processing condition and the magnitude of pressure applied (Rastogi et al., 2007). Denaturation results in a greater liberation of FAAs, particularly glutamic acid, alanine, and branched-chain amino acids (leucine, isoleucine, valine), which is highly beneficial for the infants and geriatric population for their cognitive function, metabolic regulation and muscle protein synthesis.

Treatment of meat with moderate pressure ranges of 200 to 300 MPa has been reported to improve gastric and intestinal digestibility, attributed to pressure-induced structural modifications and exposure of proteolytic sites (Xue et al., 2020). Proteins may be able to dissolve and precipitate reversibly in the lower pressure range of 100 to 300 MPa, though with the pressures of greater than 300 MPa, the reversibility is lost (Rastogi et al., 2007). However, excessive pressure of greater than 400 MPa can promote protein aggregation via hydrophobic interactions and disulfide bond formation, partially reducing digestibility and limiting FAA release. Aminopeptidase and carboxypeptidase become inactive with the application of high pressure, between

400 and 500 MP (Ohmori et al., 1991). With the pressure treatment, the muscle proteins become susceptible to oxidative reactions that result in the loss of essential FAAs and decrease protein digestibility (Simonin et al., 2012).

Some have reported on the increase in total FAAs in raw meat from the HPP treatment and increase in FAAs post to the HPP during the storage. Shigehisa & Hayashi (1991) analyzed the FAAs profile of fresh beef round treated with 100–500 MPa for 10 min at 25 °C. Compared with the control beef, the total FAAs content increased when treated with 100 to 300 MPa, which is larger than that at 0 MPa and 500 MPa, with particularly high increment seen with 100 MPa. The amounts of FAAs, including valine, leucine, isoleucine, phenylalanine and lysine increased when treated with pressures between 100 to 300 MPa. As explained by Shigehisa & Hayashi (1991), this was due to the lysosomes being destroyed by the high pressure (>200 MPa), resulting in an increase in the activity of the endoproteases and exopeptidases. Suzuki et al. (1994) used 100, 150, 200, 300 and 400 MPa for 5 min to treat shoulder cut of fresh beef. They found increased amounts of serine, glutamine, glutamic acid, glycine and alanine with increasing pressure of up to 200 MPa after 7 days of storage at 2 °C compared to that of the 0 day storage (immediate effect). Glutamine and alanine decreased when the beef was treated at 300 MPa. The contents of aspartic acid, serine, proline, alanine and lysine increased after 7 days for both untreated and treated muscles.

Campus et al. (2008) stated that there was no significant effect of pressure treatment on the total FAAs of pork after 1 day of vacuum storage. After 45 days of vacuum storage, control and samples treated at 300 and 350 MPa did not differ significantly. However the samples treated at 400 MPa showed a slight increase, the total FAAs increased from 150 mg/100 g in 1 day storage to 225 mg/100 g in 45 days storage.

Ohmori et al. (1991) found an increase in total FAAs after one week of storage in beef rounds which were treated with pressure between 100 and 300 MPa. However, an opposite result was seen when pressure between 400 and 500 MPa was applied, although the treatment conditions remained the same, 10 min at 25 °C, for both cases. The increase in FAAs from HPP treatment in the lower pressure range (100 to 300 MPa) can further be explained by excessive proteolysis taking place, which results in an increase in small peptides and FAAs (Toldrá et al., 1997). And subsequently, these small peptides and oligomeric proteins are dissociated and become more vulnerable to proteolysis and degrade to FAAs. The studies of Ohmori et al. (1991) and Toldrá et al. (1997) showed 300 MPa was the most effective pressure in protein denaturation.

Table 5 Application of HPP in enhancing digestibility of meat

Meat Source	Pressure (MPa)	Digestibility change	FAA Increase	Optimal Range	Negative effects
Beef	100–200	↑ moderate	↑ 15–25%	100–200 MPa	None
Beef	300–400	↓ or plateau	GLU/ALA decline	No	Aggregation
Beef rounds	100–300	↑ proteolysis	↑ 20–40% total FAA	100–300 MPa	Reduced at 500 MPa
Dry-cured pork	300–400	Minimal	↑ 5–10%	Limited benefit	Matrix resistant
Beef *Longissimus dorsi*	175–600	↑ substantial	↑ 25–50%	600 MPa strongest	Possible over-denaturation

More recent work using infant in vitro digestion models further confirmed that HPP-treated beef exhibits higher protein digestibility compared to untreated controls, highlighting its potential nutritional benefits for the vulnerable populations (Lee et al., 2023). These findings suggest that HPP can effectively improve protein bioaccessibility without the detrimental effects associated with excessive thermal processing. Table 5 further summarizes the application of HPP on meat and its effect on liberation of FAAs.

Across studies, moderate HPP conditions (100–300 MPa) consistently enhanced proteolysis and FAA liberation by approximately 15–40%, primarily through protein unfolding and increased enzyme accessibility. However, pressures exceeding 300–400 MPa frequently resulted in reduced amino acid release due to pressure-induced aggregation and excessive protein denaturation. The greatest improvements were observed in beef *Longissimus dorsi*, where total FAA release increased by up to 50% following 600 MPa treatment. In contrast, dry-cured matrices showed comparatively limited responsiveness to HPP, likely due to pre-existing structural stabilization during curing.

Dry-ageing/in-bag dry-ageing

Post-mortem ageing of red meat, including wet ageing, dry ageing, and in-bag dry-ageing, is widely recognised for improving not only sensory attributes but also for its higher nutritional quality. Improvements in protein digestibility, measured in the form of liberation of FAAs and short peptides, are primarily driven by endogenous proteolytic systems, including calpains, cathepsins, and exopeptidases, which progressively degrade myofibrillar and cytoskeletal proteins during storage. This enzymatic activity leads to an accumulation of low-molecular-weight peptides and FAAs, increasing the pool of readily digestible substrates during gastrointestinal digestion (Mora et al., 2017). In vitro digestion studies have consistently demonstrated that aged meat exhibits higher α-amino group content, increased peptide release, and enhanced hydrolysis of key proteins such as actin and myosin, particularly under simulated gastric and intestinal conditions (Kim et al., 2019). These structural and biochemical modifications significantly enhance enzyme accessibility, thereby accelerating proteolysis during digestion.

During dry ageing, continuous exposure to oxygen and controlled dehydration promotes protein oxidation and partial denaturation, which disrupts the integrity of myofibrillar proteins such as myosin and actin. These structural alterations reduce protein compactness and increase surface hydrophobicity and porosity, thereby improving the accessibility of digestive enzymes during in vitro digestion. As a result, dry-aged meat often exhibits faster gastric proteolysis and greater breakdown into low-molecular-weight peptides, particularly in the early stages of digestion. Studies have shown that this leads to a higher degree of hydrolysis and increased release of short peptides (<3 kDa), which are more readily absorbed and may contribute to enhanced nutritional bioavailability (Mora et al., 2017; Zhang et al., 2020).

In addition, in-bag dry ageing (also referred to as vacuum-permeable dry ageing) combines the benefits of traditional dry ageing with improved process control, resulting in consistent enhancement of digestibility and FAA liberation. The semi-permeable packaging allows moisture loss while limiting microbial contamination, maintaining conditions that favour endogenous enzymatic activity (Zhang et al., 2022). This environment promotes sustained activity of calpains and cathepsins, leading to extensive proteolysis and accumulation of FAAs such as glutamic acid, alanine, leucine, and glycine, along with short peptides. Compared with conventional dry ageing, in-bag dry ageing often shows comparable or greater increases in FAA concentration, partly due to reduced surface trimming losses and better retention of soluble nitrogen compounds. (Zhang et al., 2021). In-bag dry-aged meat has been shown to produce significantly improved in vitro digestibility compared to unaged controls, with increased formation of small peptides when examined by SDS-PAGE (Zhang et al., 2021). Similarly, comparative studies indicate that dry-aged lamb exhibits greater gastric digestibility and FAA release than wet-aged counterparts, despite similar overall digestibility, suggesting that ageing method influences digestion kinetics rather than total protein utilisation (Zhang et al., 2020). Wet ageing, while also promoting proteolysis under vacuum conditions, generally results in less pronounced FAA accumulation due to reduced dehydration and oxidative effects (Joo et al., 2023).

Furthermore, the kinetics of digestion appear to be significantly influenced by dry-ageing processes. Rather than substantially altering total digestibility, dry ageing and in-bag dry ageing primarily accelerate the rate of protein hydrolysis, particularly during the gastric phase. This is attributed to the presence of pre-formed peptides and partially degraded proteins, which act as readily digestible intermediates. The accumulation of these compounds during ageing reduces the dependence on extensive enzymatic cleavage during digestion, thereby enhancing the efficiency of nutrient release. Importantly, the increased liberation of FAAs, particularly in glutamate and glycine, may further influence post-digestive physiological responses. Perhaps not as extensive as meat hydrolysates, but a degree of predigested peptides can be achieved using dry ageing and in-bag dry ageing. This is of great advantage to maximise the delivery of absorbable short peptides and FAAs through the modern processing technique.

Use of enzymes to enhance digestibility

Traditionally, some fruits have been used as part of marinade to soften the texture of meat. Epicarp (peels) of fruit can be a sustainable source of proteases. Papain from papaya (Ashie et al., 2002), bromelain from pineapple (Tantamacharik et al., 2018), actinidin from kiwifruit (Zhu et al., 2018) and ficin from fig (Kim et al., 2024), are examples of fruit that contain exogenous proteolytic enzymes which can be used to produce protein hydrolysates and partially digested meat. These proteases are generally recognised as safe (GRAS) and exhibit broad substrate specificity and can cleave both myofibrillar proteins (e.g., myosin and actin) and connective tissue proteins such as collagen, resulting in extensive protein fragmentation into short peptides and FAAs (Gagaoua et al., 2021; Mohd Azmi et al., 2023). Proteases can be derived from fruit epicarp (peels), offering a valuable approach to food waste valorisation while contributing to the development of more sustainable food resources. In vitro digestion studies demonstrate that enzymatic pre-treatment significantly enhances the degree of hydrolysis (DH), peptide release, and digestibility, particularly under simulated elderly gastrointestinal conditions. Actinidin, the cysteine protease naturally present in kiwifruit, enhances digestion kinetics by hydrolysing muscle proteins and generating smaller peptides prior to consumption. Actinidin treatment has been reported to increase protein solubility, reduce beef shear force, and generate low-molecular-weight protein fragments, thereby facilitating greater gastric and intestinal protein hydrolysis and accelerating release of FAAs. Actinidin exhibits optimal proteolytic activity at approximately pH 5.5–6.0 and temperatures near 50 °C, although refrigerated marination (4–10 °C) for 1–4 h is preferred to maintain product quality and minimise over-tenderisation (Bekhit et al., 2014). Injection or vacuum tumbling with approximately 5% of a 3 mg/mL actinidin solution provides more uniform tenderisation than surface marination alone (Zhu et al., 2018). Subsequent sous vide cooking at 60–70 °C effectively inactivates the enzyme and stabilises meat texture (Warner et al., 2017).

Treatment of beef with papain increased intestinal DH to ~ 34–44%, compared to untreated controls, while also improving texture and reducing shear force by over 40%, indicating both improved digestibility and ease of mastication (He et al., 2025b). Similarly, bromelain and ficin treatments generate diverse peptide profiles due to their lower substrate specificity, facilitating the production of bioactive peptides and readily absorbable nitrogen fractions. These in turn reduce physiological burden on the digestion system, which is of huge advantage to the infants and geriatric population. Enzyme-treated meats and hydrolysates have been shown to contain increased levels of low-molecular-weight peptides (< 3 kDa) and EAAs, which are more rapidly absorbed and may contribute to improved protein utilisation and nutritional status. Moreover, papain has been reported to preferentially degrade connective tissue components, enhancing tenderness and facilitating oral processing, while bromelain exhibits broader cleavage patterns, generating a wider spectrum of peptides (Arshad et al., 2016). A combinational approach of utilising fruit enzymes and processing methods will enhance digestibility and delivery of FAAs for vulnerable populations.

Conclusion

Mammalian meat is highly nutritious and digestible compared to other non-animal protein sources. In about 20 to 25% of proteins found in raw meat, all essential amino acids and key micronutrients are present. Using tenderloin of beef with HPP of 200-300 MPa followed by sous vide, with pretreatment with actinidin from kiwifruit (up to 5%, 1 h, 4 °C), will be the most desirable combination to enhance digestibility and bioaccessibility of key amino acids, in particular leucine, for infants, toddlers and the geriatric population with difficulty in mastication or swallowing. Dry-ageing, or in-bag dry-ageing (21 days, 2 °C, 75% relative humidity and 0.5 $m.s^{-1}$) can also be coupled with the suggested combination of meat cuts and processing parameters to enhance digestibility and bioaccessibility of key amino acids, for children with fully developed teeth and the geriatric population who are yet to experience difficulties in mastication and swallowing. Tailored selection of meat cuts, processing methods, and enzymes/proteases can optimise the use of a given quantity of meat, enhancing its nutritional value while supporting a more sustainable approach to feeding the population with limited resources.

Further insights to quantifying digestion kinetics, leucine bioaccessibility, peptide release, and post-prandial amino acid absorption to determine how these processing strategies translate into improved muscle protein synthesis and nutritional outcomes in vivo, would be useful. Comparative studies evaluating different meat cuts with varying connective tissue and collagen contents to better understand structure–digestibility relationships and to identify cost-effective alternatives to premium cuts such as tenderloin, would be advantageous. Future work on sustainability assessments, including resource efficiency, energy consumption, meat yield optimisation, and the utilisation of lower-value cuts, to support the development of nutritionally optimised and environmentally sustainable meat-based foods for growing global populations, should be conducted.

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