Re-Veal the Beef Industry: Strategies to Produce High-Quality Beef From Young Cattle in Pastoral Systems

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Abstract: Veal is a high-value meat produced from young cattle less than 12 mo of age. The characteristic light red/pink color, tenderness, and low-fat content of veal products (especially milk-fed white veal or bobby veal) are the main features preferred by consumers. However, consumer concerns over the impact of meat production and consumption on the environment and animal welfare have increased significantly in recent years, becoming a threat to the sustained growth of the meat sector. On the other hand, processing veal from young calves (especially bobby calves) has threatened the social license to operate for both dairy and meat industries. Recently, research has been conducted to develop alternative strategies to produce beef with reduced environmental impacts and to improve animal welfare. One of the strategies could be to accelerate the beef production cycle by producing beef from younger animals of 8 to 12 mo old (i.e., vealers), especially those from dairy surplus, meanwhile reducing the number of mature animals, which are the main contributors to greenhouse gases. Information on veal from feedlots with concentrate diets is more available in the literature, compared to the equivalent from veal produced in pastoral systems, limiting the strategies that can be developed to improve the quality of veal as a whole. The present review aimed to overview the factors affecting the nutritional composition and quality of veal reported in the literature and to offer some strategies to produce value-added veal products to support the sustainable growth of veal in the dairy and beef industries.

Key words: veal, meat quality, nutritional composition, value-adding, sustainable production

Introduction

Veal is a high-value meat product with low-fat content and favorable organoleptic characteristics (e.g., tenderness) preferred especially by elderly people and young children (Brscic et al., 2013). Veal is a form of beef that is generally produced from young cattle under the age of 12 mo. The definitions of veal differ across publications or countries. Generally, the veal calf can be grouped into several categories based on the age at slaughter, live/carcass weight, and feeding system (Ngapo & Gariépy, 2006; Domaradzki et al., 2017). Bobby calf refers to young calves with the age generally less than 2 to 4 wk and a live weight of less than 45 to 70 kg. The meat produced from these animals is also called bobby veal. Vealer is produced from older calves which are raised specifically for producing meat at around 8 to 9 mo of age and carcass weight less than 160 kg. A calf with an age older than 8 mo may be called young cattle which can produce veal (sometimes called rosé veal or young beef) up to 12 mo of age. Veal can also be differentiated based on the feeding systems, for example, milk-fed veal is produced from calves fed only milk-based feeds (dam’s milk or milk replacers) until slaughter. “White veal” could also fall into this category with a slaughter age around 16 to 19 wk. There are also other categories differentiated by their feeding or rearing systems.
(e.g., milk-fed, grain-fed, grass-fed, and other specially fed veal) and specific geographies and genotypes. For example, some veal products are labeled with PGO (“Protected Designation of Origin”) or PGI (“Protected Geographic Identification”) in European countries to recognize the reputation of the specific product quality and characteristics to the geographical origin.

Europe (especially Spain, France, Italy, and Germany) is the primary market for veal products (Gira Consultancy and Research, 2020), especially milk-fed veal or bobby veal with a light pink color, which is considered as high-quality meat product and distinguished from the commercial beef produced from mature animals. However, producing veal from young calves is controversial and of ethical concerns for consumers, especially from bobby calves slaughtered within the first week of life. The production of bobby calves is considered a threat to the social license to operate for the meat sector due to the increasing interests and demands from consumers about whether the meat is ethically produced and processed, how the consumption of the meat aligns with public values, and the impacts of the processes on the environment (Ghvanidze et al., 2016). Miller (2020) highlighted that for consumers, beef preferences are influenced by their personal beliefs or emotions in relationship to animal welfare, environmental issues, health, sustainability, and other social issues. This is corroborated by recent surveys conducted in New Zealand (Realini et al., 2023), Uruguay (Realini et al., 2022), and a study of consumers’ concerns about farm animal welfare in Spain (Alonso et al., 2020). These studies provided evidence of the emergence of animal welfare concerns mainly by younger consumers, women, and individuals with higher levels of education (Liu et al., 2023).

Results from the consumer survey in New Zealand indicated that animal welfare certification was considered important by about half of the participants (58%), who were willing to pay 19% more for meat products with animal welfare certification (Realini et al., 2023). Furthermore, when participants were asked to indicate the top 3 factors or words that they considered important to define sustainability for meat production, the most frequent words indicated were “animal welfare”, “environmental impact”, and “grass-fed” (Realini et al., 2023).

Further, meat production is currently under the spotlight due to its perceived impact on the environment and climate change (Leahy et al., 2019). Responsible industries have started investigating low-emission and more sustainable strategies to support the global mission of reducing greenhouse gas (GHG) emissions. An alternative beef system is being researched recently in New Zealand, which produced grass-fed veal from dairy surplus calves at older ages (8 to 12 mo old, vealers) to accelerate the cycle of beef production (Hunt et al., 2019). This is another example to mitigate the animal welfare challenges related to the bobby calf trade. Producing young beef from dairy herds (e.g., Holstein) has been suggested to benefit both dairy and beef industries since it could become an alternative source of income for the dairy sector as well as a way for the industry to improve its social license to operate (Burggraaf et al., 2020; Berry, 2021; Rutherford et al., 2021). This is a standard practice in some European Union countries, such as the Netherlands, Spain, Poland, and other neighboring countries. However, those calves are finished in feedlots with high-energy diets and slaughtered at <12 mo of age. Results from preliminary research on the production of this type of animal in pastoral systems in New Zealand demonstrated the potential to profitably process grass-finished calves at 12 mo old using Prime beef price (Hunt et al., 2019). Comparatively, an 11% to 29% price premium was required to be financially competitive with the current beef system processing Friesian bulls at 18 or 24 mo old (Hunt, 2019). The impact of this system on the environment is expected to be lower than the traditional beef system due to the decreased number of mature animals which are the main contributors to GHG emissions (Murphy et al., 2017). Young cattle less than 1 y are lighter compared to mature animals and potentially could reduce the damage to soils and water quality (e.g., pugging and nitrate leaching) (Sheath & Boom, 1997; Stout, 2003), and utilize the feeds more efficiently due to the lower maintenance energy requirements of this animal category (Rattray et al., 2007). Further, processing animals at a younger age (e.g., 8 to 12 mo) could also increase the working capital for the beef sector (López-Campos et al., 2013; Hunt, 2019).

However, there are challenges to obtaining the value of veal products from pastoral systems similar to the beef from Prime cattle due to the significant differences in composition and meat quality. Understanding the factors affecting the nutritional composition and quality of veal finished on pasture becomes critical to developing strategies for producing high-quality beef from veal. Therefore, this review aims to summarize the factors affecting the nutritional composition and quality characteristics of veal and discuss some promising
strategies to produce high-quality and value-added veal products.

Factors Affecting Nutritional Composition and Quality of Veal

The effects of animal factors and feeding systems on carcass characteristics, nutritional composition, and quality of veal are summarized in Tables 1 and 2, respectively.

Key nutritional composition

Fat, protein, and collagen. Veal is lean meat and is considered as low-fat food for its lower than 3% fat content regardless of genetics, feeding systems, sex, and age/weight of calves at slaughter (Pestana et al., 2012; Domaradzki et al., 2017). On average, the intramuscular fat (IMF) content of veal longissimus muscle is about 1.95% across most studies. Fat content in meat products is of significant interest to both consumers and scientists due to its controversial role in human health where some lipids may be beneficial (e.g., n-3 fatty acids [FA]) while others are detrimental (e.g., saturated fats). On the other hand, fat plays a key role in flavor development and consumer acceptability and liking of meat. A low IMF content of meat is desired by certain consumers as they associate it with a healthier product (Testa et al., 2021). However, the IMF content of veal is below the minimum level of 3% suggested to be required to obtain acceptable palatability (Savell & Cross, 1988). The fat content of veal is mainly associated with on-farm factors (Tables 1–2), and generally, it is affected by animal age and sex, with higher fat levels observed in castrated animals (Marti et al., 2011, 2013), in females than males (Costa et al., 2006; Vavríšínová et al., 2021), and in older than younger calves (Monteiro et al., 2013; Yim & Hur, 2019; Araújo et al., 2020). Other factors such as animal feeding and genetics can also influence the fat content in veal, although the findings are inconsistent and depend on the muscles of interest. It is generally agreed that grazing or grass-fed calves result in leaner veal compared to those raised in feedlots with concentrates and other formulated diets (Miotello et al., 2009; dos Santos et al., 2013). Further, crossbreeding beef with dairy breeds has also been suggested to increase the IMF content of veal (Basiel & Felix, 2022).

Associated with its low IMF content, the FA composition of veal is characterized by a relatively high proportion of polyunsaturated fatty acids (PUFA). As a result, their proportions of saturated (SFA) and monounsaturated fatty acids (MUFA) tend to be slightly lower than in older animals. The high proportion of PUFA in veal meat is reflected in its relatively high PUFA/SFA ratio (∼0.3), which is known to have positive effects on consumers’ cardiovascular health (Chen & Liu, 2020). Although this ratio is still below the suggested minimum dietary level of 0.4, it doubles the ratio of older cattle (Wood et al., 2008). In terms of sensory quality, a higher IMF content in meat is more favorable due to its role in flavor development during cooking; however, the percentage of PUFA and PUFA/SFA ratio decrease with increasing levels of IMF (Scollan et al., 2006). Despite the favorable PUFA/SFA ratio of veal meat, its n-6/n-3 ratio is above the maximum of 4.0 suggested to reduce cardiovascular risk by its anti-inflammatory and anti-oxidative stress effects and by improving the endothelial function (Yang et al., 2016). The high n-6/n-3 ratio could be associated with the use of concentrates as the main component of the diet in most studies (Daley et al., 2010). Different studies (González et al., 2014; Gómez et al., 2015; Morittu et al., 2021) have demonstrated the effectiveness of the incorporation of linseed oil in the concentrate diet of veal to reduce its n-6/n-3 ratio. Such an effect would not be observed in pasture-fed cattle due to the low n-6/n-3 ratio in pasture feed (Pouzo et al., 2015), resulting in lower n-6/n-3 ratios (<4.0) in veal. Further, veal from Simmental calves was found to have higher levels of PUFA, PUFA/SFA, and n-6/n-3 ratios with less SFA and MUFA content compared to Holstein and the crossbred (Simmental × Holstein) (Kelava et al., 2009). The authors have also observed the lowest PUFA/SFA and n-6:n-3 ratios in Holstein and crossbred calves, respectively.

Veal is also an important source of dietary proteins contributing to a similar level of protein (20%–24%) to the meat from older animals. Collagen is a structural protein mainly deposited in connective tissues of the skeletal muscles which has been considered as an important component in maintaining acceptable tenderness and texture of meat. The total amount of collagen and the proportion of its soluble fraction are the key contributors to the variations in collagen-associated toughness. The amount of collagen increases while the solubility of collagen decreases with age, resulting in less tender meat (Monteiro et al., 2013). The collagen content of veal ranged from 0.6% to 1.8%, consisting of a 16.8% to 21.9% soluble fraction (Domaradzki et al., 2017). Genetic factors, growth rate, nutrition of animals, post-mortem processing (e.g., aging), and
Table 1. Effects of animal factors on carcass characteristics, nutritional composition, and quality of veal

<table>
<thead>
<tr>
<th>Animal</th>
<th>Age</th>
<th>Production systems</th>
<th>CW (kg)</th>
<th>Muscle Factor</th>
<th>Key findings</th>
<th>References</th>
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<tr>
<td>Israel Holstein (male, n = 205) vs. Australian Bos indicus × Bos taurus (male, n = 169)</td>
<td>~12 mo</td>
<td>Mixed diet (not grazing)</td>
<td>Holstein: 288.8 Bos indicus × Bos taurus: 309.5</td>
<td>Longissimus dorsi et lumbarum</td>
<td>Breed: Australian calves had higher dressing percentage and CW, while veal from Holstein calves had better tenderness, longer sarcomeres, higher pH, a*, b*, IMF, % PUFA, and PUFA:SFA ratio, lower L* and CL, and similar MUFA, SFA, WHC, and collagen content. (Shabtay et al., 2021)</td>
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<td>Slovak Simmental (n = 16, male &amp; female, n = 8 per sex)</td>
<td>~250 d</td>
<td>In-house rearing from 70 d of age for 180 d</td>
<td>Male: 166.5 Female: 169.1</td>
<td>Longissimus thoracis et lumbarum</td>
<td>Sex: Female calves had a higher proportion of meat but lower proportions of bone and separable fat. Female calves had higher internal fat (rumen, intestinal, kidney, pelvic), protein content, a* (24 h), b* (24 h &amp; 7 d) and lower ultimate pH (24 h), L* (24 h &amp; 7 d), water, and IMF level. (Vavrišínová et al., 2021)</td>
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<td>Holstein (male, n = 45)</td>
<td>NR</td>
<td>Birth weights (&lt;37.5, 37.5–40, and &gt;40 kg) and weaning weights (&lt;90, 90–100, and &gt;100 kg).</td>
<td>~79</td>
<td>Longissimus thoracis et lumbarum</td>
<td>Birth weight: Higher birth weight resulted in higher IMF, pH, a* and b* with no difference in DL and shear force. Lower weaning weight only led to lower L* and b*, higher MUFA, and slightly higher protein content. (Vavrišínová et al., 2020)</td>
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<td>Minhota calves, 6 mo (n = 14 male &amp; 8 female), 9 mo (n = 11 male &amp; 8 female)</td>
<td>6, 9 mo</td>
<td>Suckled twice a day and supplemented with farm products</td>
<td>Male (6 mo): 158.9 Male (9 mo): 226.5 Female (6 mo): 127.2 Female (9 mo): 159.0</td>
<td>Longissimus thoracis</td>
<td>Sex: Male calves had higher growth rate, CW, and % dressing regardless of slaughter age; older calves had higher growth rate, LW, and CW and lower trans vaccenic acid (trans C18:1 t11, TVA) regardless of sex. (Araújo et al., 2020)</td>
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<td>Hereford × Friesian-Jersey (steers, n = 60)</td>
<td>8, 10, 12 mo</td>
<td>Grazing and supplemented with Sharpe Earlywean meal.</td>
<td>NR</td>
<td>Longissimus lumbarum</td>
<td>Slaughter age: Differences in meat quality between slaughter ages were small, with lower shear force observed in 10 mo calves, and darker color with increasing age. (Pike et al., 2019)</td>
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<td>Holstein vs. Slovak Simmental (n = 10 per breed)</td>
<td>~210 d</td>
<td>Fed with alfalfa hay, feed straw and feed mixture with ad libitum</td>
<td>Holstein: 70.16 Slovak Simmental: 71.98</td>
<td>Longissimus dorsi et thoracis</td>
<td>Breed: Slovak Simmental had higher kidney fat, head, skin and limb weight with no difference in LW, CW, % dressing, and weight of primal cuts. Slovak Simmental bred had higher initial pH (1 h) but lower ultimate pH (24 h), higher moisture, DL, and WBSF, and similar protein, IMF, electrical conductivity, and CL. (Vavrišínová et al., 2019)</td>
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<td>Holstein bull (n = 12 [3 per age group])</td>
<td>5, 6, 7, 8 mo</td>
<td>Milk fed for 8 wk, then fed with natural pasture till weaning, followed by roughage &amp; straw</td>
<td>72–109</td>
<td>Longissimus dorsi</td>
<td>Slaughter age: The increase in slaughter age led to higher fat, protein, WHC, WBSF, and TBARS and lower CL, with no difference in pH, L* increased with storage with no change in a* and b*, while lower a* and b* were found in veal from older calves. (Yim &amp; Hur, 2019)</td>
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<tr>
<td>Breed and Age</td>
<td>Feeding and Management</td>
<td>Muscle</td>
<td>Slaughter</td>
<td>Comments</td>
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<td>Holstein (male, n = 23)</td>
<td>Fed with corn silage as roughage and a concentrate commercial pellet</td>
<td>Longissimus lumborum</td>
<td>Slaughter weight</td>
<td>The increase in LW led to higher CW, cold carcass yield, subcutaneous fat thickness absolute weight of scraps, crude protein, dry matter, and SFA and lower muscle lipids, UFA, and PUFA, with no difference in marbling level and n-3:n-6 ratio.</td>
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<td>Limousin suckler calves (male, n = 18)</td>
<td>Pasture based grazing with dam</td>
<td>Longissimus lumborum</td>
<td>Slaughter age</td>
<td>Veal from older calves had higher protein, energy value, Mg, Zn, and Fe and lower Cu, CLA, and water:protein ratio, with similar levels of other FA and pH. Veal from younger calves (6 mo) had lighter, less red color with higher DL vs. older animals.</td>
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<td>Hanwoo vs. Holstein (n = 5 per breed)</td>
<td>Milk-fed for 8 wk then fed with natural pasture till weaning, followed by roughage &amp; straw</td>
<td>Longissimus dorsi, Semimembranosus</td>
<td>Breed, Muscle, VP storage for 1/7/10/20/30 d</td>
<td>Both breeds had similar carcass weights. Both muscles from Hanwoo had higher fat, pH, CL, a*, b*, and shear force (longissimus), lower protein content, WHC, and L*. Vacuum-packaged meat from Hanwoo breed was more stable within 10 d of storage at 0°C but less stable afterward (10–30 d).</td>
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<td>Holstein (male and castrated, n = 132)</td>
<td>In-house concentrate fed</td>
<td>Longissimus lumborum</td>
<td>Slaughter age</td>
<td>Castration impaired feed efficiency and reduced CW, muscle pH, and WBSF; early castration increased IMF. Consumption of concentrate and IMF increased with slaughter age, while feed efficiency was reduced.</td>
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<td>Crossbred Limousin × Mertolenga or Charolais × Mertolenga (Vitela Tradicional do Montado)-PGI veal vs. Purebred Mertolenga-PDO bull beef &amp; veal</td>
<td>Semi-extensive production system: Calves were raised with dam on natural pasture and weaned at 6–9 mo, then fed with concentrate and straw. Bulls were finished with concentrate for 3–5 mo.</td>
<td>Longissimus lumborum</td>
<td>Combination of breed, age, and production systems</td>
<td>PGI and PDO veal had lower CW and lighter color (lower pigment content), and were more tender (lower MFI and WBSF) than beef. PGI veal had lower collagen but higher collagen solubility than PGI beef and PDO veal. WBSF decreased with increased IMF in PDO beef, not in both veal samples.</td>
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<td>Mirandesa (n = 29)</td>
<td>Traditional Mirandesa-PDO production system (semi-extensive pasture-based) with weaning at 7 mo and then fed with farm products</td>
<td>NR</td>
<td>Longissimus lumborum, Semitendinosus</td>
<td>Slaughter seasons (late spring or early autumn)</td>
<td>The lipid composition was affected slightly by slaughter seasons (late spring/early autumn) but differed by muscles (higher in longissimus). Grass-fed veal could provide favorable/healthier ratios of n-6/n-3 and levels of n-3 PUFA and α-tocopherol.</td>
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<thead>
<tr>
<th>Animal</th>
<th>Age</th>
<th>Production systems</th>
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<th>Muscle</th>
<th>Factor</th>
<th>Key findings</th>
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<tr>
<td>NR (n = 58)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Longissimus</td>
<td>Slaughter in spring: 44.0;</td>
<td>Slaughter season, ageing time, and their interaction affected pH, meat color,</td>
<td>(Florek et al., 2009)</td>
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<td>Longissimus</td>
<td>summer: 40.4; autumn: 37.5</td>
<td>oxidative stability (TBARS) during storage, with no difference in DL.</td>
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<td>Simmental vs. Holstein vs.</td>
<td>~140 d</td>
<td>In-house feeding with milk replacer, grower</td>
<td>NR</td>
<td>Longissimus</td>
<td>Breed</td>
<td>Spring veal had higher CW, % dressing, harem pigments, CL (7 d), TBARS (3 &amp; 7 d), and pH (45 min &amp; 2 d PM); summer veal had the highest protein and oxidative stability, and the lowest IMF and shear force; autumn veal had higher SF and shear energy at both 3 &amp; 7 d PM.</td>
<td>(Kelava et al., 2009)</td>
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<td>Simmental × Holstein</td>
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<td>concentrate, and ground wheat straw.</td>
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<td>Thoracis</td>
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<td>(n = 24 [8 per breed])</td>
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<td>Semitendinosus</td>
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<td>Barrosã purebred calves</td>
<td>Slaughter in autumn: ~7.6 mo; spring: ~7.9 mo</td>
<td>Weaning at 5.5–6.5 mo, then raised on pasture supplemented with cereal grains and forage-fed</td>
<td>NR</td>
<td>Longissimus</td>
<td>Slaughter season</td>
<td>Slaughter seasons and muscle types only affected some minor FA and CLA isomers and PUFA/SFA ratio.</td>
<td>(Alfaia et al., 2007)</td>
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<td>(n = 27)</td>
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<td>Dorsi</td>
<td>Muscle type</td>
<td>Autumn veal had higher levels of 8:0, 20:3n-6, 20:4n-6, 22:5n-3, and 22:6n-3 in both muscles, higher 10:0 and 20:2n-6 in longissimus, higher 20:1c11 in semitendinosus muscle; lower levels of 18:1c11 in both muscles, 16:0 and 20:2n-6 in semitendinosus and 17:1c9 in longissimus muscle.</td>
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<td>Barroso-PDO calves (n = 92,</td>
<td>6–9 mo</td>
<td>Suckling and grazing until slaughter. Calves</td>
<td>99.4</td>
<td>Biceps</td>
<td>Sex</td>
<td>Female calves generally had higher IMF (biceps femoris only), while male calves had higher total SFA and lower MUFA than female regardless of muscles. Slaughter in autumn had higher IMF and CLA (c9t11) especially in female calves and biceps femoris and supraspinatus. No difference in cholesterol and α-tocopherol was found regardless of muscles, sex, and slaughter season.</td>
<td>(Costa et al., 2006)</td>
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<td>male &amp; female, 46 per sex</td>
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<td>slaughtered in autumn were mainly grass-fed</td>
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<td>Femoris</td>
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<td>while those slaughtered in spring were mainly grain and forage-fed.</td>
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<td>Longissimus</td>
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<td>Supraspinatus</td>
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<td>Italian Friesian (n = 15)</td>
<td>140/160/190 d</td>
<td>Liquid milk replacer for 1 mo then adding straws into the diet</td>
<td>NR</td>
<td>Longissimus</td>
<td>Slaughter age</td>
<td>Slaughter age did not affect meat color (48 h PM and 6 d storage), shear force, and WHC, while crude protein reduced with age.</td>
<td>(Tarantola et al., 2003)</td>
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</table>

CL = cooking loss; CLA = conjugated linoleic acid; CW = carcass weight; DL = drip loss; FA = fatty acids; IMF = intramuscular fat; LW = live weight; MUFA = monounsaturated fatty acids; NR = not reported; PM = postmortem; PUFA = polyunsaturated fatty acids; SFA = saturated fatty acids; TBARS = thiobarbituric acid reactive substances; VP = vacuum packaged; WBSF = Warner Bratzler shear force; WHC = water-holding capacity.
Table 2. Effects of feeding systems on carcass characteristics, nutritional composition, and quality of veal

<table>
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<tr>
<th>Animal</th>
<th>Age</th>
<th>Production systems</th>
<th>CW (kg)</th>
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<tbody>
<tr>
<td>Charolaise × Podolica bull</td>
<td>249–279 d</td>
<td>(A) concentrate only; (B) concentrate + extruded linseed; (C) concentrate + linseed + vitamin E</td>
<td>(A) 299, (B) 307, (C) 262</td>
<td>Longissimus thoracis</td>
<td>Adding linseed &amp; vitamin E</td>
<td>Adding linseed and vitamin E had lower cholesterol and n-6:n-3 ratio and a higher % PUFA, while adding linseed only reduced a*, b*, and C* in veal vs. control. Adding vitamin E to the diet increases the oxidative stability of lipid.</td>
<td>(Morittu et al., 2021)</td>
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<td>Friesian (male, n = 48)</td>
<td>11 mo</td>
<td>(A) concentrate only; (B) concentrate + 10% linseed; (C) concentrate + 2% CLA; (D) concentrate + 10% linseed + 2% CLA</td>
<td>NR</td>
<td>Longissimus thoracis et lumborum</td>
<td>Adding linseed &amp; CLA aging &amp; (1/7/21 d)</td>
<td>Aging had more significant impacts on the instrumental quality of veal vs. diet. Linseed-enriched diet led to higher DL, IMF, beef and liver flavors, lower a*, b*, hue and fat odor in veal vs. calves fed with CLA.</td>
<td>(Barahona et al., 2016)</td>
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<tr>
<td>Holstein (male, n = 48)</td>
<td>~322 d</td>
<td>(A) concentrate only; (B) concentrate + 10% linseed; (C) concentrate + 2% CLA; (D) concentrate + 10% linseed + 2% CLA</td>
<td>NR</td>
<td>Longissimus thoracis</td>
<td>Adding linseed &amp; CLA</td>
<td>Treatment groups increased the level of rumenic acid and α-linolenic acid, and decreased the n-6:n-3 FA ratio in veal. Adding linseed increased n-3 and CLA in veal; and CLA was further increased by adding 2% CLA in the diet, leading to a healthier n-6:n-3 ratio.</td>
<td>(Gómez et al., 2015)</td>
</tr>
<tr>
<td>Pirenaica bull (male, n = 46)</td>
<td></td>
<td>(A) concentrate only; (B) concentrate + linseed; (C) concentrate + linseed + vitamin E</td>
<td>NR</td>
<td>Longissimus dorsi</td>
<td></td>
<td>Adding linseed increased n-3 FA and α-linolenic acid, and lowered n-6:n-3 ratio, with no impact on carcass characteristics, SFA, MUFA, and PUFA content. Adding vitamin E did not affect meat color stability during storage.</td>
<td>(Alberti et al., 2014)</td>
</tr>
<tr>
<td>Rubia Gallega (female, n = 21)</td>
<td>300 d</td>
<td>Reared with mother on pasture till 7 mo, then penned and fed with three diets for 90 d: grass hay plus concentrate supplemented with oil from (A) linseed, (B) sunflower, or (C) soybean.</td>
<td>(A) 178.7, (B) 156.1, (C) 167.7</td>
<td>Longissimus dorsi</td>
<td>Oil source</td>
<td>Adding 4% of oils to diets had no impacts on animal performance, carcass characteristics, and meat quality, while feeding with linseed oil (A) increased n-3 PUFA in veal meat and fat. Adding linseed (A) and soybean (C) oils could be beneficial for human health, while the challenge is most dietary PUFA were completely bio-hydrogenated.</td>
<td>(González et al., 2014)</td>
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<tr>
<td>Holstein bull calves (male, $n = 15$)</td>
<td>90 d</td>
<td>Milk-fed for 1 mo, then (A) whole milk feeding for 2 mo; (B) whole milk + calf starter diet for 2 mo; (C) whole milk + starter diet for 1 mo then ad libitum for 1 mo.</td>
<td>NR</td>
<td>Longissimus dorsi</td>
<td>Milk-fed diet</td>
<td>The volatile profile of veal included mainly (&gt;50%) aldehydes and alcohols, and the composition differed by different feeding treatments. Different milk-fed diets altered aldehyde content in veal with the highest level in treatment A (whole milk feeding) and the lowest in treatment C (ad libitum + calf starter diet for 60 d).</td>
<td>(Wei et al., 2014)</td>
</tr>
<tr>
<td>Holstein (male, $n = 43$)</td>
<td>NR</td>
<td>Finished in feedlot fed with concentrate diet vs. grazing with pasture</td>
<td>NR</td>
<td>Longissimus dorsi</td>
<td>Finishing system Slaughter weight (140/180/220/260 kg LW)</td>
<td>Feedlot-raised calves had higher fat content and similar carcass characteristics and meat quality vs. pasture. Calves finished on pasture showed improved texture quality with increasing slaughter weights.</td>
<td>(dos Santos et al., 2013)</td>
</tr>
<tr>
<td>NR ($n = 81$)</td>
<td>9.2/9.4/9.7 mo</td>
<td>(A) Normal weaning (7 mo), early weaning (B) &lt;3 mo or (C) &lt;7 mo, followed by different feeding strategies</td>
<td>(A) 229, (B) 221, (C) 227</td>
<td>Longissimus dorsi</td>
<td>Weaning strategy (overwrapped, MAP, VP storage for 13 d)</td>
<td>Veal from FIN and SUP systems produced pale, light and tender meat when aged and had lower DL, while those from GR had healthier FA composition (higher PUFA, lower SFA, n-6/n-3). Packaging types had a greater impact on color than the feeding system, with lower metmyoglobin in VP veal, while MAP had higher $L^*$ and hue and the shortest shelf life due to discoloration.</td>
<td>(Ripoll et al., 2013)</td>
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<tr>
<td>Holstein young bulls (male, $n = 12$ [6 for each group])</td>
<td>210 d</td>
<td>Weaning at 60 d, then fed with (A) grain feed and hay (lucerne-grass); (B) hay, grain feed and maize silage, for 150 d.</td>
<td>(A) 75.7, (B) 67.8</td>
<td>Longissimus dorsi</td>
<td>Feeding type</td>
<td>Treatment A had higher carcass yield, lower ultimate pH (24 h), and similar DL and color properties vs. treatment B. The addition of maize silage led to higher production of n-3 PUFAs with long-chain (EPA, DHA) and lower n-6/n-3 ratio vs. treatment A.</td>
<td>(Vavrišinová et al., 2013)</td>
</tr>
<tr>
<td>Parda de Montaña (male, $n = 22$)</td>
<td>NR</td>
<td>GR: grazing suckling calves; SUP: suckling plus supplemented with starter/growing concentrate; FIN: weaned calves finished on concentrates</td>
<td>NR</td>
<td>Longissimus thoracis</td>
<td>Packaging (overwrapped, MAP, VP storage for 13 d)</td>
<td>Veal from FIN and SUP systems produced pale, light and tender meat when aged and had lower DL, while those from GR had healthier FA composition (higher PUFA, lower SFA, n-6/n-3). Packaging types had a greater impact on color than the feeding system, with lower metmyoglobin in VP veal, while MAP had higher $L^*$ and hue and the shortest shelf life due to discoloration.</td>
<td>(Ripoll et al., 2013)</td>
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<tr>
<td>Study</td>
<td>Breed</td>
<td>Age</td>
<td>Feeding</td>
<td>Starch Source</td>
<td>Longissimus thoracis</td>
<td>Weaning Age + Finishing System</td>
<td>Breed</td>
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<tr>
<td>Holstein-Friesian bull (male, n = 16)</td>
<td>90 d</td>
<td>Control: barley; MD: dry maize grain; BMS: 50% barley + 50% ensiled maize grain; MDMS: 50% dry maize + 50% ensiled maize grain</td>
<td>NR</td>
<td><strong>Starch source</strong></td>
<td>Veal fed with maize grain (dry or ensiled) had a higher level of some long-chain FA, and lower MUFA:SFA. No impact of starch source on the physicochemical characteristics of veal.</td>
<td>(Sosin-Bzducha et al., 2012)</td>
<td></td>
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<tr>
<td>Galician Blond (male, n = 20)</td>
<td>240 d</td>
<td>(A) Intensive (grazing for 2 mo + feedlot); (B) semi-intensive (grazing for 5–5.5 mo + feedlot) Weaning at 5–5.5 mo vs. non-weaned</td>
<td>(A) weaned: 175.6, non-weaned: 210.2; (B) weaning: 163.8, non-weaned: 197.0</td>
<td><strong>Longissimus thoracis</strong></td>
<td>Weaning age + finishing system</td>
<td>Weaning age + finishing system</td>
<td>(Bispo et al., 2011)</td>
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<tr>
<td>Holstein (steers vs. male, n = 48)</td>
<td>11 mo</td>
<td>(A) Concentrate with vitamin A; (B) concentrate with restricted level of vitamin A</td>
<td>Bull: 255 (A), 257 (B); Steer: 232 (A &amp; B)</td>
<td><strong>Vitamin A restriction</strong></td>
<td>Bulls had lower IMF vs. steers with higher restricted vitamin A treatment. Vitamin A restriction tended to result in better oxidative stability in meat, while it did not improve IMF in meat from bulls.</td>
<td>(Marti et al., 2011)</td>
<td></td>
</tr>
<tr>
<td>Galician Blond (male, n = 36)</td>
<td>240 d</td>
<td>Non-weaned (3 mo pasture + 5 mo indoor) vs. weaning at 5.5 mo old (3 mo pasture + 5 mo indoor) vs. weaning at 2 mo (3 d pasture + 8 mo indoor)</td>
<td>Non-weaned: 204.7Weaning at 5 mo: 173.4Weaning at 2 mo: 166.1</td>
<td><strong>Longissimus thoracis</strong></td>
<td>Weaning age + finishing system</td>
<td>Weaning age + finishing system</td>
<td>Non-weaned veal had higher n-3 PUFA, conjugated linoleic acid and 18:1 trans-11. Early weaning showed the highest levels of n-6 PUFA, 18:1trans-10, and 18:1 trans-6/7/8, while late weaning had intermediate values for trans FA and 18:1 isomers. FA profiles of veal from non-weaned and late-weaning calves were closer to milk.</td>
</tr>
<tr>
<td>Rubia Gallega (male, n = 36)</td>
<td>240 d</td>
<td>Non-weaned (3 mo pasture + 5 mo indoor) vs. weaning at 5.5 mo old (3 mo pasture + 5 mo indoor) vs. fed with artificial lactation until weaning at 2 mo (2 d pasture + 8 mo indoor)</td>
<td>Non-weaned: 204.7Weaning at 5 mo: 173.4Weaning at 2 mo: 166.1</td>
<td><strong>Longissimus thoracis</strong></td>
<td>Weaning age + finishing system</td>
<td>Weaning age + finishing system</td>
<td>Non-weaned veal had the highest CW and had higher a*, b* and Chroma than the early weaning group. Later weaning was more desirable as the early weaning group had a higher rating of shear firmness and a lower rating of elastic, tender, and juicy by trained panelists.</td>
</tr>
<tr>
<td>Parda de Montaña or Pirenaica (male, n = 28, 14 per breed)</td>
<td>10–11 mo</td>
<td>Early weaning at 90 d or normal weaning at 150 d, followed by intensive feedlot feeding with concentrate.</td>
<td></td>
<td><strong>Longissimus thoracis</strong></td>
<td>Weaning age</td>
<td>Weaning age</td>
<td>Weaning strategies did not affect animal performance, carcass characteristics, and meat quality in both breeds. Raising Pirenaica calves would be more profitable due to higher CW at similar costs of feeding.</td>
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<tr>
<td>Simmental (organic $n=15$, conventional $n=14$)</td>
<td>~6 mo</td>
<td>Organic: pasture reared with natural suckling; Conventional: milk-replacers and roughage sources.</td>
<td>NR</td>
<td>Longissimus thoracis</td>
<td>Organic feeding</td>
<td>Organic veal had lower fat content, $L^<em>$, $b^</em>$ and hue, CL, ether extract, and cholesterol content and higher % lean, $a^*$ and red index. Organic veal also had higher n-3 FA, n6/n-3 ratio and conjugated linoleic acid, % SFA, and PUFA and lower MUFA.</td>
<td>(Miotello et al., 2009)</td>
</tr>
<tr>
<td>Parda de Montaña (male, $n=46$)</td>
<td>8–10 mo</td>
<td>Early weaning at 90 d or normal weaning at 150 d, with/without supplementation of concentrate pre-weaning</td>
<td>Early weaned: 261–262; Normal weaned: 254–257</td>
<td>Longissimus dorsi</td>
<td>Weaning age Pre-weaning supplementation</td>
<td>Meat quality was not affected by the treatments, while early weaning increased % dressing and fatness score. Traditional weaning without supplementation was not suggested due to a poorer carcass conformation.</td>
<td>(Blanco et al., 2008b)</td>
</tr>
<tr>
<td>Parda de Montaña (male, $n=16$)</td>
<td>362 d</td>
<td>Early weaning at 90 d or Normal weaning at 180 d and finished with concentrate</td>
<td>Early weaned: 290; Normal weaned: 270</td>
<td>Longissimus thoracis</td>
<td>Weaning age</td>
<td>Early weaned calves had higher % dressing and CW and lower $L^<em>$ and $b^</em>$, with similar LW, fat score, conformation, $a^*$, meat tenderness, chemical compositions, and FA profile.</td>
<td>(Blanco et al., 2008a)</td>
</tr>
<tr>
<td>Holstein bulls (male, $n=18$)</td>
<td>131 d</td>
<td>Milk replacer + starter concentrate for 3–4 wk, then fed with basal diet (control), or supplemented with Se only, or with both Se + vitamin E.</td>
<td>NR</td>
<td>Longissimus thoracis et lumborum</td>
<td>Adding of Se and vitamin E</td>
<td>Supplementation of Se and vitamin E improved lipid stability while having no impact on the growth rate, digestibility of dry matter and Se, the chemical composition of muscle, color and FA profile. Adding Se increased Se content and glutathione peroxidases (GSH-Px) activity in meat.</td>
<td>(Skrivanová et al., 2007)</td>
</tr>
<tr>
<td>Rubia Gallega (male, $n=43$)</td>
<td>200–347 d</td>
<td>Non-weaned: suckling and reared on a rotational system vs. Weaned at 3 mo and fed with grass silage ad libitum and concentrate.</td>
<td>Non-weaned: 180.8 Weaned: 185.6</td>
<td>Longissimus thoracis</td>
<td>Weaning status VP storage for 7/14 d.</td>
<td>Weaning status did not affect CW, WHC, and pH. Non-weaned had higher $b^<em>$ and hue but lower pigment content, while the differences disappeared after longer aging for 14 d. Storage increased $a^</em>$, $b^*$, hue and chroma while reducing pigment content, expressible juice, and toughness.</td>
<td>(Oliete et al., 2006)</td>
</tr>
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</table>
Spanish Brown Swiss (male)  
Trial 1: 147–157 d;  
Trial 2: 210–218 d  
Trial 1: Full milk (*ad libitum*) intake or restricted intake (75%) for first 75 d.  
Trial 2: Milk fed vs. grain fed supplemented with true milk.  

Trial 1: 142 (full milk) vs. 125 (restricted milk)  
Trial 2: 184

Longissimus thoracis  
Diet composition  
Slaughter weight  

Trial 1: Full milk intake had higher CW and fatness score, lower total collagen content, and similar % dressing, fat and muscle color and proximate composition, collagen solubility, WHC, WBSF, and sensory scores. Restricted milk resulted in higher levels of SFA in IMF, lower MUFA and similar PUFA levels in both subcutaneous fat and IMF.  
Trial 2: Milk fed was more tender (sensor) with higher WHC, while had no impact on carcass characteristics and chemical composition. Milk-fed veal had higher SFA in subcutaneous and IMF, lower PUFA, and similar MUFA levels in IMF.

Holstein veal  
(n = 48)  
Fed with starter (1–5 wk), grower (6–12 wk), finisher concentrate (13 wk to slaughter), and supplemented with EDTA for 8 or 18 wk at 0, 5, 15 mg levels.

NR  
EDTA supplementation  

Neither the dose nor the duration of administration of EDTA had any effect on the initial pH, ultimate pH, drip loss, initial level of lipid oxidation, collagen content and chemical composition of veal. EDTA supplementation resulted in paler meat color particularly at the higher dose and longer duration while increasing shear force and reducing oxidative stability during storage.

Vieira et al., 2005

Gariépy et al., 2004

CL = cooking loss; CW = carcass weight; DHA = docosahexaenoic acid; DL = drip loss; EPA = eicosapentaenoic acid; FA = fatty acids; IMF = intramuscular fat; LW = live weight; MAP = modified atmosphere packaging; MUFA = monounsaturated fatty acids; NR = not reported; PM = postmortem; PUFA = polyunsaturated fatty acids; SFA = saturated fatty acids; VP = vacuum packaged; WBSF = Warner Bratzler shear force; WHC = water-holding capacity.
cooking could also alter the role of collagen in the textural properties of meat. For example, restricting the growth rate of yearling steers may result in tougher meat due to the lower percentage of soluble collagen (Fishell et al., 1985). The tenderization of meat during postmortem aging could be partially explained by the structural changes of collagen due to the proteolytic activities of collagenolytic cathepsins (Weston et al., 2002).

**Cholesterol.** Cholesterol is another component affecting the nutritional quality of meat due to the possible association with the increased risk of chronic diseases like cardiovascular disease (Berger et al., 2015). The concentration of cholesterol was lower in the skeletal muscle of Polish Holstein-Friesian calves compared to heifers, young bulls, and cows (Litwi czuk et al., 2015), suggesting that the age of cattle at slaughter may vary the cholesterol content. However, similar cholesterol levels were observed for veal (10 to 11 mo old) and young bulls (18 mo old) regardless of production systems (PGI or PDO specifications) (Monteiro et al., 2012). There was no effect of the sex of calves and slaughter seasons (autumn or spring) on cholesterol content observed in 3 muscles (biceps femoris, longissimus dorsi, and supraspinatus) of Barrosã-PDO veal 6–9 mo old (Costa et al., 2006). A significantly higher cholesterol content was observed in longissimus thoracis compared to longissimus lumborum and semitendinosus; however, the difference between other muscles was marginal (Mestre Prates et al., 2006). Similarly, no significant difference was observed between muscles (longissimus lumborum and semitendinosus) for Mirandesa calves of 9 mo old, while the calves slaughtered in late spring had significantly lower cholesterol content in longissimus lumborum compared to those processed in early autumn (Pestana et al., 2012). Further, different feeding systems may also vary the cholesterol level in veal with lower cholesterol content in longissimus thoracis of calves (~6 mo old) reared on pasture with natural suckling compared to those fed with milk replacers and roughage (Miotello et al., 2009).

**Vitamins and trace elements.** Micronutrients such as choline and vitamins are of increasing interest to consumers due to their bioactive characteristics which may have significant implications in supporting the functioning of the human body and well-being (Wyness, 2016; Wallace et al., 2018). Previous studies observed similar vitamin E homologs (α- and γ-tocopherol) and β-carotene between longissimus thoracis, longissimus lumborum, and semitendinosus of Barrosã-PDO veal suggesting comparable antioxidant activity between these muscles (Mestre Prates et al., 2006). α-Tocopherol is the dominant type of vitamin E homolog present in meat, and its concentration in muscles has been suggested to vary with feeding systems (Yang et al., 2002; Sk ivanová et al., 2007), geographical locations of farms (Costa et al., 2011), and cooking of meat (Perham et al., 2019). Concentrations of choline and B and D vitamins in veal were less explored in the literature. Feeding systems and muscle types could be the main drivers of variation in their concentrations. Higher levels of B and D vitamins were observed in veal from special-fed calves that received milk (soy/milk products) replacer formula diet until slaughter at 20 to 22 wk compared to commercial beef (recorded in the USDA database) (Perham et al., 2019).

Dietary intake of essential trace elements, such as iron, zinc, and selenium, is considered an important means for maintaining the proper functioning of the human body (Gupta & Gupta, 2014). Similar to other red meats, veal is a significant dietary source of essential trace elements, with the highest content found in zinc (Zn), followed by copper (Cu), selenium (Se), manganese (Mn), chromium, molybdenum, nickel, iron (Fe), and cobalt (Co) (Gálvez et al., 2019). The concentrations of trace elements in meat have been suggested to be associated with genetic factors (e.g., breed) (Miranda et al., 2018) and feeding systems (e.g., rearing methods and diets) (Blanco-Penedo et al., 2009). Significant variations of essential trace elements, especially Fe, Zn, and Cu, have also been observed among 7 veal cuts including shoulder clod, inside round, eye of round, bottom round, heel of round, knuckle, and tenderloin (Gálvez et al., 2019). Significantly higher levels of trace elements were found in tenderloin and shoulder clod, which could become a value-adding advantage to these muscles, especially for shoulder clod. The changes in trace elements between muscles may be due to the varied compositions of fiber types (slow- or fast-twitch fibers) in the different muscles (Pereira et al., 2017). Some essential trace elements (e.g., Co, Cu, Fe, Mn, and Se) were found to have negative relationships with protein contents of 10 commercial veal cuts (about 9-mo-old calves) including rib boneless entrecote, tenderloin, eye round, thick flank, tail of rump, chuck tender, shin, upper chuck, flank, and brisket (Pereira et al., 2017). It could be associated with the accumulation of trace elements in slow-twitch (oxidative) fibers along with increased levels of mitochondrial enzymes, myoglobin, and Fe-containing cytochrome to maintain the aerobic metabolic activities of these fibers (Choi & Kim, 2009). Further, increasing the age of calves at slaughter from 6 to 8 mo could result in higher levels of these elements.
of polyvalent metals (Magnesium [Mg], Zn, and Fe) with reduced Cu content in the loin muscles (Florek et al., 2015). Iron is the essential component for the synthesis of red blood cells, including hemoglobin, myoglobin, and cytochromes, and adequate intake of iron is necessary for the proper functioning and developmental of the human body (Speich et al., 2001).

**Physical quality**

**Color.** Color is one of the most important attributes affecting consumers’ purchasing decisions due to the perceived linkages with freshness and quality of meat. The color properties of meat are influenced by myoglobin content and its oxidation status, and by the ultimate pH of muscle. The value of veal is highly dependent on its color (Hulsegge et al., 2001; Ngapo & Gariépy, 2006). Different studies evaluated the veal color instrumentally using the CIELAB system ($L^*$: lightness, $a^*$: redness, $b^*$: yellowness), generally with $L^*$ ranging from 42 to 51, $a^*$ from 8 to 14, and $b^*$ from 2 to 6 depending on the time postmortem, muscles, and production systems (Hulsegge et al., 2001; Lagoda et al., 2002; Vandoni & Sgoifo Rossi, 2009).

The meat from calves is associated with a pale or light red/pink color since traditionally this type of meat was obtained from young calves only fed on milk resulting in a relatively low level of myoglobin. The myoglobin content varies between muscles (Ngapo & Gariépy, 2006) and is affected by the diet; an increased iron intake may accumulate in muscles and result in a redder color of meat. Veal from grain-fed calves was darker and redder than that from milk-fed calves due to the lower iron content in milk compared to grain (Adams, 1975; Flynn, 1992). Similarly, pasture-fed (e.g., grass and clover) beef also has a darker color compared to paler veal color at 24 h postmortem (Eikelenboom & Smulders, 1986; Warner et al., 2014).

**Texture/tenderness.** Tenderness is an important sensory attribute that contributes to the consumer satisfaction of beef. The tenderness of meat can be determined using sensory and instrumental analyses. Shear force, especially Warner-Bratzler shear force (WBSF) is a widely accepted measure for determining the tenderness of meat, which may provide relatively comparable results to sensory analysis (Otremba et al., 1999). Veal is characterized by being more tender (lower WBSF) than commercial beef (Monteiro et al., 2013; Domaradzki et al., 2017). This characteristic of veal could be attributed to its low content of total collagen and high content of soluble collagen compared to older.
animals as discussed earlier (Warner et al., 2021). The
genotype of calves seemed to play a key role in deter-
mining the tenderness of veal (Table 1). Veal from the
Limousin sired had lower tenderness (higher WBSF)
than Charolais sired (Revilla & Vivar-Quintana, 2006;
Severiano-Pérez et al., 2006) after 7 d of the post-
mortem aging (5.05/4.79 kg vs. 2.67/3.93 kg, young
bulls/heifers from Limousin vs. Charolais). Holstein
breed could produce more tender veal (lower WBSF)
compared to the Slovak Simmental breed (3.99 vs.
10.81 kg.cm⁻² for loin muscle) (Vavrišinová et al.,
2019a) and Hanwoo breed (4.39 vs. 7.89 kg) (Yim
et al., 2015).

Marbling or IMF level has been suggested to pos-
itively affect the tenderness of meat (Nishimura et al.,
1999), while such an impact seems to be more evident
in older cattle than in veal, which could be due to its
lean nature. Although the age at slaughter and sex could
affect the fat content (as described earlier), the slight
change in fat content in veal may not translate into
an improvement in tenderness. Similar WBSF was
observed in veal regardless of the sex and age of
the calves (Revilla & Vivar-Quintana, 2006; Monteiro
et al., 2013; Florek et al., 2015). The feeding system
is another factor associated with the marbling mechan-
ism; however, its impacts on tenderness were incon-
sistent (Table 2). Lower WBSF values were found in
veal from grazing suckler calves compared to suckler
calves supplemented with concentrate (Florek et al.,
2013), while the opposite trend was also reported
(Ripoll et al., 2013). No significant differences in
WBSF values were observed in veal from calves reared
with milk replacer plus roughage compared to those
following an organic feeding system (Miotello et al.,
2009) from calves reared on feedlot compared to past-
tures (dos Santos et al., 2013) or reared with milk com-
pared to grain (Vieira et al., 2005). However, direct
comparisons of absolute WBSF values across trials
should be considered cautiously since they may be sub-
ject to unaccounted diverse sources of variation.

Water-holding capacity. The ability of meat to
retain its water throughout the supply chain (e.g., pro-
duction, processing, storage, distribution, and shelf dis-
play) and during cooking is referred to as water-holding
capacity (WHC). WHC is a key quality attribute
closely related to saleable value of meat (Castejón et al.,
2015), microbial safety (den Hertog-Meischke et al.,
1997), juiciness, and consumer liking of meat (Torley
with poor WHC commonly lead to increased weight
losses from drip/purge (i.e., drip/purge loss) and during
the cooking process (i.e., cook loss). Breed and age of
the calves at slaughter have been suggested to cause
variations in the WHC of veal, although results
were inconsistent (Table 1). Veal from the Slovak
Simmental breed had higher drip loss (2.31% vs.
1.54%) and similar cook loss compared to Holstein
in longissimus thoracis (Vavrišinová et al., 2019b).
Higher cook losses and lower WHC of veal from the
Hanwoo breed were observed compared to Holstein
in the longissimus dorsi (% cook loss: 32.28 vs.
16.83; % WHC: 41.50 vs. 60.93) and semimembrano-
sus muscles (% cook loss: 35.85 vs. 20.83; % WHC:
39.26 vs. 58.72) (Yim et al., 2015). However, a similar
cook loss in veal meat was obtained regardless of the
breed and sex (Severiano-Pérez et al., 2006). In terms
of age, veal from older animals (8 mo old) had better
WHC with lower cook loss compared to younger
calves (5 to 7 mo old) (Yim & Hur, 2019). However,
a lower cook loss was found when veal (12 mo old)
was compared to beef from mature animals (15 to
30 mo old) (Monteiro et al., 2013). Inconsistent find-
ings were also reported with higher drip losses and
lower cook losses observed in 6-mo-old compared to
8-mo-old calves (Florek et al., 2015). No difference
in cook loss and drip loss was found between ages
(140, 160, and 190 d) (Tarantola et al., 2003) and
weights at slaughter (Mandell et al., 2001). Generally,
weaning strategies (e.g., weaned/non-weaned and
weaning age) (Oliete et al., 2006; Bispo et al., 2010a;
Pateiro et al., 2013) and feeding system (feedlot/past-
ture) (dos Santos et al., 2013) had minimal impacts
on the WHC (cook loss and drip loss) of veal; only
in one study the WHC of milk-fed veal was found to
be higher than that of grain-fed veal (Vieira et al.,
2005).

Consumer perception and sensory quality

Consumer quality perception of beef including
veal is complex, dynamic, and increasingly influenced
by extrinsic attributes such as price, origin, animal wel-
fare, and environmental impact of meat production
among others. However, sensory characteristics of
food including meat remain the main purchase and
repeat purchase consumer criteria (Calkins & Hodgen,
Resano et al. (2018) argued that few studies focused
on evaluating consumers’ demand for veal in general,
and more specifically from dealers (e.g., age between 8
and 10 mo). The authors highlighted that regional ori-
gin, empowered by local breed, and health information
were more important than tenderness in Europe for
experienced consumers, while younger consumers
valued “tenderness guarantee.” The high variability in meat quality results in consumer difficulties in forming clear quality expectations. However, an “experience guarantee” label in consistently tender products would in part contribute to enhancing the factors that influence consumers’ purchasing decisions (Resano et al., 2018). Severiano-Pérez et al. (2006) evaluated the parameters affecting consumers’ choice of veal, indicating the light color of raw meat and odor, taste, tenderness, and juiciness of cooked veal as main attributes. Since color preferences for raw meat commonly vary between countries and by regions within the same country (Grunert, 1997), gaining an understanding of consumer perception and preferences in target markets for the color of veal from pasture-finished animals would be recommended.

Consumers perceive differences in overall liking of meat and meat products mainly through the assessment of juiciness, tenderness, and flavor (Grunert et al., 2004; Miller, 2020). For beef, consumer research before the 1990s showed that tenderness was the main driver of liking, while more recent research has shown that if tenderness and juiciness are at acceptable levels, the flavor becomes the main driver of beef consumer liking (Miller, 2020). Veal is expected to be tender and juicy and the flavor is significantly milder than beef from older animals. Different authors evaluated the relationships between muscle characteristics and meat quality, including sensory attributes. Serra et al. (2004) evaluated the eating quality of meat from yearling bulls and reported that meat odor and flavor were slightly positively correlated with carcass fatness and IMF, while overall tenderness and juiciness were positively correlated and negatively affected by the cooking loss. Furthermore, beef from forage-based systems tends to be higher in lean-type flavors, such as beef identity, bloody/serumy, metallic, and liver-like, and lower in lipid-derived flavors, such as fat-like and cardboardy (Sitz et al., 2005; Calkins & Hodgen, 2007; Miller, 2020). Miller (2020) indicated that consumers responded similarly to the differences in tenderness, but the flavor is more affected by cultural and environmentally learned behaviors in some countries. Thus, understanding consumer flavor preferences for grass-fed veal would be critical to meeting those preferences. The limited published data regarding the eating quality of veal produced from grazing systems highlight the need to evaluate those sensory attributes by domestic and target international consumers and their segments. More specifically, what are consumer preferences and the relative importance of credence (e.g., country of origin, animal welfare, environmental outcomes, and pastoral farming), search (e.g., overall appearance and color), and experience (e.g., tenderness and taste) attributes of veal from pastoral systems for domestic and international markets? For instance, are consumers willing to preferentially purchase veal from pastoral systems with a darker color and potentially a different taste than traditional European, Asian, or North American veal? Moreover, labeling and/or certification schemes can support signaling credence attributes to veal consumers.

### Strategies to Produce High-Quality Beef From Veal

#### Tailoring meat quality through farm management

As discussed in the previous section, the impacts of breed on veal quality are mainly on carcass characteristics, color, and tenderness, with minor effects on other traits such as pH, WHC, and some nutritional components (e.g., protein, moisture, fat, and trace elements). Feeding systems and weaning strategies also affected carcass characteristics and color of veal, but they have a significant effect on its nutritional composition as well, especially the FA profile. Further, the sex and age of calves at slaughter play a minor role in determining the quality of veal, with marginal changes observed mainly in color, fat content, and FA composition. These on-farm factors affect different aspects of veal quality, which may render opportunities to tailor certain quality attributes through applying different farm management systems and practices in response to the demands from different markets. For instance, selecting beef sires with genetic merits for improved growth, higher levels of marbling, and higher dressing percentages could result in larger and heavier cuts with improved quality. The right feeding system needs to be considered with the genotype since suckler calves (with the dam) were found to have lower weight gain than those fed with concentrate and hay regardless of the breeds (Bispo et al., 2010a; Ripoll et al., 2013). Lower marbling has been linked with grazing calves and forage-fed compared to feedlots or concentrate-fed (dos Santos et al., 2013).

Manipulation of feeding regime and weaning strategies are also relevant if the production goal is to boost the nutritional value of veal. For example, veal from grass-fed animals has been suggested to provide a more favorable n-6/n-3 ratio and level of n-3 PUFA and α-tocopherol compared to calves finished with farm
products (e.g., hay, straws, oats, barley, or wheat) (Pestana et al., 2012). In concentrate-based diets, supplementation with linseed increased C18:3 n-3, conjugated linoleic acids (CLA) c-9, t-11, and other n-3 PUFA (Albertí et al., 2014; Gómez et al., 2015; Barahona et al., 2016; Morittu et al., 2021), and CLA supplementation further increased its proportion in the FA profile (Gómez et al., 2015; Barahona et al., 2016). The supplementation with maize in both dry and moist ensiled form led to a beneficial effect on the FA profile by increasing the proportions of MUFA and PUFA at the expense of SFA in veal (Sosin-Bzducha et al., 2012). However, adding linseed oil (4%) into the feed could increase n-3 PUFA content in veal meat and fat (González et al., 2014). Similarly, Vavrišnová et al. (2013) also observed that adding maize silage to a concentrate diet resulted in higher levels of n-3 PUFA, especially long-chain PUFA (eicosapentaenoic acid and docosahexaenoic acid, i.e., 20:5 n-3 and C22:6 n-3, respectively), and reduced n-6/n-3 ratio in veal. On the other hand, weaning practice and different weaning ages/weights could affect the FA composition, especially PUFA, although the results were conflicting. Based on the findings, nonweaned or early-weaned animals may provide a more favorable FA profile in veal with higher levels of MUFA and PUFA and lower SFA compared to late-weaned calves (Bispo et al., 2010b; Bispo et al., 2011).

**Pre-rigor biochemical and biophysical interventions**

The unique features of veal such as the lighter weight of the carcass, the resultant smaller sizes of the primal and subprimal cuts, and the relative leanness and tenderness of the meat compared to meat from older animals should be considered in any applied intervention to improve the quality or add value to the carcass.

Biochemical interventions revolve around the manipulation of the temperature and pH of muscles at rigor. The rates of temperature and pH decline are affected by various pre-rigor environments (e.g., application of electrical stimulation and carcass chilling rates) which determine the rate at which muscles attain rigor and convert to meat (Balan et al., 2019; Rhee & Kim, 2001). Muscles tend to cold-shrink when they enter rigor at temperatures below 10°C, resulting in tough meat, while muscle proteins denature at high rigor temperatures, resulting in faster deterioration in the quality attributes of meat such as color and WHC (Farouk & Swan, 1998; Bekhit et al., 2007). Calf carcasses have a relatively thin fat cover, which is prone to be cooled down faster than mature animals, thus caution should be paid to the chilling rate of calf carcasses to prevent cold-shortening of muscles. The pH/temperature window for the optimum meat quality for the smaller and leaner carcasses from yearling calves of 10 to 12 mo is unknown. However, based on the outcomes of previous studies, an early postmortem intervention that limits the pre-slaughter and immediate post-slaughter electrical inputs to those associated with stunning and immobilization should be sufficient when combined with rigor temperatures between 12°C and 15°C to optimize the eating quality and processing attributes of vealers (Farouk & Swan, 1998; Bekhit et al., 2007).

Biophysical interventions involve the physical manipulation of the muscle pre-rigor, including the way carcasses are hung while the muscles are undergoing rigor and the physical manipulation of the individual muscles using various restructuring methods. It has long been established that pre-rigor muscles can enter rigor with different degrees of contraction and meat from relaxed muscles are more tender relative to those from shortened or contracted muscles (Locker, 1960). This understanding has led to the development of many techniques to prevent pre-rigor muscles from...
contracting or to stretch these muscles to obtain relaxed ones during their conversion to meat (Sørheim & Hildrum, 2002). Some of these techniques include the suspension of carcasses from the Achilles tendon (the common industry practice) and its variants including the Tenderstretch and Tendercut processes. The former method involves the suspension of the carcass from the aitch bone (Obsturator foramen) instead of the traditional Achilles tendon, while the latter involves the severance at the 12th thoracic vertebrae in beef carcass perpendicular to the vertebral column, ensuring the skin, adipose tissue, intercostal muscle, and connective tissue are all severed, leaving only the longissimus muscle to be maximally stretched (Wang et al., 1994; Claus et al., 1997; Farouk et al., 2009a).

The lower value cuts of veal such as the primal and subprimal from the fore- and hindquarters of a veal carcass can be hot-boned pre-rigor and manipulated to add value. Hot-boned muscles, because they are in a pre-rigor state, can be physically stretched to alter sarcomere length and tenderness in a manner analogous to the on-carcass Tenderstretch system of pelvic suspension. Manipulating hot-boned meat also offers some unique advantages such as portion control (Figure 1, unpublished data), which allows otherwise irregular muscle shapes to be manipulated to produce a regular (usually cylindrical) shape of the product. When muscle stretching is applied in conjunction with the optimal pre-rigor temperature/pH conditions, improved meat appearance and eating quality benefits may be realized.

Postmortem aging

Postmortem aging is a well-known processing technique to improve the tenderness and flavor of meat. There are 2 types of aging in general including wet- and dry-aging. Extensive studies were performed on wet-aging and mostly using beef from cattle over 18 to 24 mo of age. Based on the limited research performed on young cattle, veal of different ages (5, 6, 7, and 8 mo), genotype, and sex showed similar tenderization rates (Florek et al., 2015; Yim & Hur, 2019), whereas veal from young calves (e.g., ≤5 mo) had better initial tenderness (Ngapo & Gariépy, 2006; Domaradzki et al., 2017), suggesting different aging strategies would be needed for veal slaughtered at different ages to achieve favorable tenderness levels. The muscle of interest is also an important factor affecting the implementation of aging strategies. A minimum period of 4 d for loin muscle and 8 d for silverside of milk-fed Holstein calves (~160 kg carcass weight) was recommended to obtain a perceivable tenderizing effect (Baldi et al., 2015). A minimum of 10 to 14 d of aging was suggested for veal raised on milk-based diets (Aldai et al., 2012; Ripoll et al., 2013; Florek et al., 2015). However, longer aging times seemed to be more favorable for producing veal with more homogeneous quality and minimizing variations due to other on-farm factors such as genetics (Monsón et al., 2004; Sañudo et al., 2004) and weaning strategies (Oliete et al., 2006). Aging could also increase color attributes ($L^*$, $a^*$, $b^*$, and hue) of veal, resulting in intense color with a more pink hue (Oliete et al., 2006; Florek et al., 2009; Ripoll et al., 2013; Florek et al., 2015).

Dry-aging is another aging technique being developed for adding value to meat products by creating characteristic flavor profiles (Zhang et al., 2022). Dry-aging is traditionally performed without any packaging to encourage aerobic maturation and dehydration, which are the key contributors toward characteristic dry-aged meat flavors (Zhang et al., 2022). Although dry-aged meat is still a niche product, the intense roasted, nutty, sweet, and umami flavors of dry-aged meat command a premium price in the marketplace (Kim et al., 2018; Zhang et al., 2021b). Dry-aged meat flavors can be tailored by adopting different aging regimes and strategies (e.g., age-n-dry) based on the meat types and flavor characteristics of interest (Zhang et al., 2022; Zhang et al., 2023a; Zhang et al., 2023c). Given the fact thatveal is generally more tender but leaner and with a milder flavor than standard commercial beef, developing a unique flavor profile using the dry-aging technique may increase the consumer acceptability of veal products for niche markets. The flavor profile of dry-aged veal is expected to be distinctive from Prime beef due to its low-fat content. Dry-aging of lean beef has been suggested to produce value-added beef with acceptable quality and oxidative stability during frozen storage (Zhang et al., 2019, 2021a). So far, limited studies have applied dry-aging on meat from young cattle, especially calves within 1 y of age. However, these studies focused either on the impacts of dietary supplements (Maggjolino et al., 2021) or on adding value to low-value cull cow meat (Barragán-Hemández et al., 2022). Dry-aging of striploin from Angus × Simmental cull cows (~12 mo old) improved salty taste and sour-dairy flavor with reduced livery flavor compared to the wet-aged (Barragán-Hemández et al., 2022). However, whether dry-aging of veal could be a viable strategy to improve the quality and develop a desirable flavor preferred by consumers warrants future research.
Chilled and frozen storage

Chilled and frozen storage are common practices in the meat industry to maintain a sustainable supply of safe meat products locally and satisfy the demands from overseas markets throughout the year. However, preserving the fresh quality of meat is always challenging since the rich nutrient composition and high moisture level of meat make it susceptible to quality deterioration during storage. The storage life (chilled/frozen) of veal products has not been well studied. Veal has a relatively lower fat content compared to commercial beef, suggesting a lower oxidation potential with a possibly longer shelf life. However, storage could have significant impacts on the color properties of meat, which is the key indicator of freshness to consumers, despite the lower concentration of myoglobin and the pale color of veal. The use of different packaging formats such as vacuum packaging, modified atmosphere packaging (MAP), and film overwrapping during shelf display was suggested to have greater effects on the quality of veal compared to feeding systems, especially on the color properties (Ripoll et al., 2013). A MAP with high oxygen composition (80%) resulted in a shorter storage life (<1 wk) compared to vacuum packaging and overwrapping since the significant decrease of redness and chroma resulted in an increased hue angle. The color of the veal packaged with film overwrapping changed similarly compared to vacuum packaging. However, vacuum-packaged veal had lower metmyoglobin content and the highest redness following 13 d of storage, which implies that veal packaged in vacuum experienced a lower degree of discoloration. Decreasing the oxygen level of MAP to 46% resulted in similar color properties during 14 d of shelf storage, while reducing lipid and protein oxidation compared to 70% oxygen (De Palo et al., 2014). The quality deterioration could be further slowed down by using packaging materials with a lower oxygen transmission rate (De Palo et al., 2013). More advanced packaging systems such as active and intelligent packaging (Realini & Marcos, 2014; Dominguez et al., 2018; Li et al., 2022) could be considered for extending the shelf life of veal. For instance, oxidation and microbial spoilage are 2 key factors resulting in quality deterioration during storage; thus, developing an antimicrobial and antioxidant dual-functions active packaging system could be advantageous to both chilled and frozen veal products with improved storage life. Similarly, intelligent packaging systems such as indicators and sensors of time-temperature, integrity and freshness of packaged veal can monitor and inform the condition of the product during storage (Realini & Marcos, 2014).

Freezing is an effective means of being widely used for preserving the quality of meat. Although freezing meat can provide a much longer shelf life compared to chilling, frozen meat is always perceived as an inferior quality product by consumers with lower prices on the market (Zhang et al., 2023b). The issue of frozen meat is mainly with the crystallization of water in meat which results in some quality changes when meat is thawed, such as discoloration and drip loss (Leygonie et al., 2012), while the impacts of freezing on the quality of veal products have not been well-defined. Many studies have been conducted to elucidate the factors responsible for the quality deterioration of thawed meat.
and to develop technologies and processing regimes to improve the thawed meat quality to be as good as fresh (Lu et al., 2022). There is a regime involving aging and freezing as an integrated process (aging before freezing or aging after freezing) being developed, which demonstrated the potential to improve the quality of thawed meat and produce frozen meat with comparable quality to fresh-never-frozen meat (Farouk et al., 2009b, 2009c; Kim et al., 2011; Coombs et al., 2017). Such a regime can be tailored to suit different types of meat, muscles, and ultimate quality of interest through altering aging methods, conditions, and the sequence of aging and freezing/thawing (Zhang et al., 2023b). A regime involving a short aging (3 d at 4°C) before or after frozen storage (5 wk at −20°C) compared to aging only for 5 d was tested on veal (~10 mo old), and a higher drip loss was observed (Moreno et al., 2007). Such outcomes suggested that different strategies may be needed for freezing lean meat like veal. For example, aging conditions (time and temperature) for veal before/after freezing need to be optimized to obtain the most favorable effects of this regime. Further, novel freezing and thawing technologies such as magnetic field and ultrasound have demonstrated the ability to improve the quality of thawed meat (Choi et al., 2015; Bhargava et al., 2021). However, the viability of using these technologies to produce thawed veal with high quality warrants future research.

**Perspectives**

A summary of key elements and suggested strategies to support the growth of the veal industry is illustrated in Figure 2. In addition to the strategies outlined and discussed in the previous section and summarized in Figure 2, a strong integration between the dairy and beef industries becomes imperative to support the growth of the veal industry. Some breeds from the dairy industry like Jersey generally have poor growth performance and carcass yield, despite the high levels of IMF, which prevent the uptake by the meat industry due to the low profitability. Improvements through sire selection with genetic merits (e.g., milk production and easy calving) to benefit both the dairy and beef industries could be the first step to breaking new ground (Burggraaf & Lineham, 2016). The development of beef × dairy crossbred with genetic merits is proposed as a viable path towards the new generation of beef production systems involving the selection of appropriate genetics of beef bulls for mating to dairy cows to develop herd matrices with genetic advantages such as improved growth performance, production yield, and meat quality (Martin et al., 2020; Berry, 2021).

The integration of dairy and beef production systems through promoting the use of calves from dairy surplus to replace the breeding cow/calf component of traditional sheep and beef production systems could be another solution to reduce the costs required for raising breeding cows (Burggraaf et al., 2020). This strategy may further contribute to the dairy sector by improving its social license to operate and adding value to the dairy surplus products (i.e., veal) (Burggraaf et al., 2020). On the other hand, such a strategy has also been suggested to reduce the impacts of maintaining breeding cows on the environment, such as GHG emissions, use of fresh water, and pollution (Berry, 2021; van Selm et al., 2021). For example, the replacement of traditional beef with dairy-derived calves was suggested to reduce 20% to 30% of GHG emissions for the New Zealand beef industry (van Selm et al., 2021). However, achieving this goal is also challenging due to that beef of dairy origin is usually believed to have inferior quality compared to beef from traditional cattle breeds (McGee et al., 2005; Bown et al., 2016). The critical challenge for the success of this strategy is to bring together the relevant parties and satisfy all their needs. For instance, the new system needs to generate enough margin for dairy farmers, calf transporters, calf rearers and finishers, and meat processors to compensate for their investments in the knowledge, technologies, and infrastructural capability developed for the success of such a system. The key motivation of their cooperation requires the markets to be established with growing demands from consumers for these types of veal products. Hence, research into processing innovations, product development, and value-adding is necessary to improve consumer acceptability and ultimately facilitate market development and growth. Further, the finite land area available for farming brings in another challenge once the markets start to grow, which necessitates the innovation of farm management systems to accommodate the large numbers of calves for both breeding and meat production.

**Conclusions**

Based on information revised from the literature, veal from young cattle within 12 mo of age is perceived as lean, juicy, and tender with a characteristic light red color and comparable to or with a better nutrient profile than meat from mature animals. Factors affecting the nutritional composition and quality of veal are rather
complex, and results were inconsistent. The quality of veal may be tailored by designing new farm production systems involving strategies such as cross-breeding and genetic selection to obtain breeding cattle with genetic merits, optimized weaning and finishing age/weight, and feeding management practices. A new farm management strategy should not overlook its impacts on animal welfare and the environment, which will affect consumer acceptability of veal products and the long-term growth of the veal industry. Further, adding value to veal products and developing new flavors can be achieved by pre-rigor interventions (e.g., hot-boned and restructured) and optimized aging, particularly dry-aging. Advancements in the optimization of packaging systems (e.g., active and intelligent packaging) and freezing/thawing techniques are also necessary to preserve premium quality throughout the value chain, reduce meat waste, and improve sustainability. Finally, an improved understanding of consumer preference for pasture-fed veal and its products is critical to meeting those demands and gaining a recognized presence in the domestic and international markets. Beyond the technical aspects to guarantee a premium quality product, a major challenge to support the development and subsequent growth of the veal industry is the collaboration between relevant stakeholders throughout the value chain to assess the viability of new production systems, which warrants further work.

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