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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
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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; Vavrišínová 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

Animal	Age	Production systems	CW (kg)	Muscle	Factor	Key findings	References
Israel Holstein (male, $n = 205$) vs. Australian Bos indicus × Bos taurus (male, $n = 169$)	~12 mo	Mixed diet (not grazing)	Holstein: 288.8 Bos indicus × Bos taurus: 309.5	*Longissimus dorsi et lumborum*	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)
Slovak Simmental ($n = 16$, male & female, $n = 8$ per sex)	~250 d	In-house rearing from 70 d of age for 180 d	Male: 166.5 Female: 169.1	*Longissimus thoracis et lumborum*	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), and b^* (24 h & 7 d) and lower ultimate pH (24 h), L^* (24 h & 7 d), water, and IMF level.	(Vavrišínová et al., 2021)
Holstein (male, $n = 45$)	NR	Birth weights (<37.5, 37.5–40, and >40 kg) and weaning weights (<90, 90–100, and >100 kg). In-house rearing system.	~79	*Longissimus thoracis et lumborum*	Birth weight Weaning 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)
Minhota calves, 6 mo ($n = 14$ male & 8 female), 9 mo ($n = 11$ male & 8 female)	6, 9 mo	Suckled twice a day and supplemented with farm products	Male (6 mo): 158.9 Male (9 mo): 226.5 Female (6 mo): 127.2 Female (9 mo): 159.0	*Longissimus thoracis*	Sex Slaughter age	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. Male calves at younger ages had lower IMF and higher % n-3 and n-6 FA than female and older calves, with similar protein, ash, moisture, pH, and CLA (18:2 c9t11) regardless of sex and age.	(Araújo et al., 2020)
Hereford × Friesian-Jersey (steers, $n = 60$)	8, 10, 12 mo	Grazing and supplemented with Sharpe Earlywean meal.	NR	*Longissimus lumborum*	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)
Holstein vs. Slovak Simmental ($n = 10$ per breed)	~210 d	Fed with alfalfa hay, feed straw and feed mixture with *ad libitum*	Holstein: 70.16 Slovak Simmental: 71.98	*Longissimus dorsi* *Longissimus thoracis* *Semimembranosus*	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 breed 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., 2019b)
Holstein bull ($n = 12$ [3 per age group])	5, 6, 7, 8 mo	Milk fed for 8 wk, then fed with natural pasture till weaning, followed by roughage & straw	72–109	*Longissimus dorsi*	Slaughter age VP storage (0 ± 1°C for 1/7/10/20/30 d)	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 & Hur, 2019)

Holstein (male, $n = 23$)	NR	Fed with corn silage as roughage and a concentrate commercial pellet	67.9 (140 LW) 87.2 (180 LW) 111.0 (220 LW) 128.6 (260 LW)	*Longissimus lumborum*	Slaughter weight	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.	(Dias et al., 2018)
Limousin suckler calves (male, $n = 18$)	6, 7, 8 mo	Pasture based grazing with dam	6 mo: 141.9; 7 mo: 175.1; 8 mo: 189.7	*Longissimus lumborum*	Slaughter age VP ageing (2°C for 2/5/12 d)	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.	(Florek et al., 2015)
Hanwoo vs. Holstein ($n = 5$ per breed)	8 mo	Milk-fed for 8 wk then fed with natural pasture till weaning, followed by roughage & straw	Hanwoo: 140 Holstein: 141	*Longissimus dorsi* *Semimembranosus*	Breed Muscle VP storage for 1/7/10/20/30 d	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).	(Yim et al., 2015)
Holstein (male and castrated, $n = 132$)	10, 12, 14 mo	In-house concentrate fed	Male: 262, castrated -3 mo: 249; castrated -8 mo: 244; Slaughter 10 mo: 210; 12 mo: 252; 14 mo: 293	*Longissimus*	Slaughter age Castration age	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.	(Marti et al., 2013)
Crossbred Limousin × Mertolenga or Charolais × Mertolenga (Vitela Tradicional do Montado”-PGI veal) vs. Purebred Mertolenga (Mertolenga-PDO bull beef & veal)	PGI veal: 12 mo PDO veal: 15 mo PDO beef: 15–30 mo	Semi-extensive production system: Calves were raised with dam with natural pasture and weaned at 6–9 mo, then fed with concentrate and straw. Bulls were finished with concentrate for 3–5 mo.	PGI veal: 180 PDO veal: 220 PDO young bulls: >220 kg	*Longissimus lumborum*	Combination of breed, age, and production systems	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.	(Monteiro et al., 2013)
Mirandesa ($n = 29$)	~9 mo	Traditional Mirandesa-PDO production system (semi-extensive pasture-based) with weaning at 7 mo and then fed with farm products	NR	*Longissimus lumborum* *Semitendinosus*	Slaughter seasons (late spring or early autumn)	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.	(Pestana et al., 2012)

(*Continued*)

Table 1. (*Continued*)

Animal	Age	Production systems	CW (kg)	Muscle	Factor	Key findings	References
NR ($n = 58$)	NR	NR	Slaughter in spring: 44.0; summer: 40.4; autumn: 37.5	*Longissimus lumborum*	Slaughter season Ageing time (3/7 d)	Slaughter season, ageing time, and their interaction affected pH, meat color, and oxidative stability (TBARS) during storage, with no difference in DL. Spring veal had higher CW, % dressing, harem pigments, CL (7 d), TBARS (3 & 7 d), and pH (45 min & 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 & 7 d PM.	(Florek et al., 2009)
Simmental vs. Holstein vs. Simmental × Holstein ($n = 24$ [8 per breed])	~140 d	In-house feeding with milk replacer, grower concentrate, and ground wheat straw.	NR	*Longissimus thoracis*	Breed	Simmental calves had higher PUFA, PUFA:SFA and n-6/n-3 ratios, but lower SFA and MUFA vs. other breeds. Holstein calves had the lowest PUFA:SFA ratio, and crossbred calves had the lowest n-6:n-3 ratio.	(Kelava et al., 2009)
Barrosã purebred calves ($n = 27$)	Slaughter in autumn: ~7.6 mo; spring: ~7.9 mo	Weaning at 5.5–6.5 mo, then raised on pasture supplemented with cereal grains and forages	NR	*Longissimus dorsi* *Semitendinosus*	Slaughter season Muscle type	Slaughter seasons and muscle types only affected some minor FA and CLA isomers and PUFA/SFA ratio. 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 l*ongissimus*, higher 20:1c11 in *semitendinosus* muscle; lower levels of 18:1c11 in both muscles, 16:0 and 20:2n-6 in s*emitendinosus* and 17:1c9 in l*ongissimus* muscle.	(Alfaia et al., 2007)
Barrosã-PDO calves ($n = 92$, male & female, 46 per sex)	6–9 mo	Suckling and grazing until slaughter. Calves slaughtered in autumn were mainly grass-fed while those slaughtered in spring were mainly grain and forage-fed.	99.4	*Biceps femoris* *Longissimus dorsi* *Supraspinatus*	Sex Slaughter season	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-tocoperol was found regardless of muscles, sex, and slaughter season.	(Costa et al., 2006)
Italian Friesian ($n = 15$)	140/160/190 d	Liquid milk replacer for 1 mo then adding straw into the diet	NR	*Longissimus thoracis*	Slaughter age	Slaughter age did not affect meat color (48 h PM and 6 d storage), shear force, and WHC, while crude protein reduced with age.	(Tarantola et al., 2003)

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

Animal	Age	Production systems	CW (kg)	Muscles	Factors	Key findings	References
Charolaise × Podolica bull (male, $n = 18$)	249–279 d	(A) concentrate only; (B) concentrate + extruded linseed; (C) concentrate + linseed + vitamin E	(A) 299, (B) 307, (C) 262	*Longissimus thoracis*	Adding linseed & vitamin E	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.	(Morittu et al., 2021)
Friesian (male, $n = 48$)	11 mo	(A) concentrate only; (B) concentrate + 10% linseed; (C) concentrate + 2% CLA; (D) concentrate + 10% linseed + 2% CLA	NR	*Longissimus thoracis et lumborum*	Adding linseed & CLA aging (1/7/21 d)	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.	(Barahona et al., 2016)
Holstein (male, $n = 48$)	~322 d	(A) concentrate only; (B) concentrate + 10% linseed; (C) concentrate + 2% CLA; (D) concentrate + 10% linseed + 2% CLA	NR	*Longissimus thoracis*	Adding linseed & CLA	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.	(Gómez et al., 2015)
Pirenaica bull (male, $n = 46$)		(A) concentrate only; (B) concentrate + linseed; (C) concentrate + linseed + vitamin E	NR	*Longissimus dorsi*		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.	(Albertí et al., 2014)
Rubia Gallega (female, $n = 21$)	300 d	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.	(A) 178.7, (B) 156.1, (C) 167.6	*Longissimus dorsi*	Oil source	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.	(González et al., 2014)

(*Continued*)

Table 2. (*Continued*)

Animal	Age	Production systems	CW (kg)	Muscles	Factors	Key findings	References
Holstein bull calves (male, $n = 15$)	90 d	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.	NR	*Longissimus dorsi*	Milk-fed diet	The volatile profile of veal included mainly (>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).	(Wei et al., 2014)
Holstein (male, $n = 43$)	NR	Finished in feedlot fed with concentrate diet vs. grazing with pasture	NR	*Longissimus dorsi*	Finishing system Slaughter weight (140/180/220/260 kg LW)	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.	(dos Santos et al., 2013)
NR ($n = 81$)	9.2/9.4/ 9.7 mo	(A) Normal weaning (7 mo), early weaning (B) <3 mo or (C) <7 mo, followed by different feeding strategies	(A) 229, (B) 221, (C) 227	*Longissimus dorsi*	Weaning strategy	Early weaning resulted in higher IMF content and lower shear force, linolenic acid and n-3 content and n-6/n-3 ratio, with no difference in proximate content, CL, and WHC. Different weaning strategies caused variations in the color and texture profile of veal.	(Pateiro et al., 2013)
Holstein young bulls (male, $n = 12$ [6 for each group])	210 d	Weaning at 60 d, then fed with (A) grain feed and hay (lucerne-grass); (B) hay, grain feed and maize silage, for 150 d.	(A) 75.7, (B) 67.8	*Longissimus dorsi*	Feeding type	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 PUFA with long-chain (EPA, DHA) and lower n-6: n-3 ratio vs. treatment A.	(Vavrišínová et al., 2013)
Parda de Montaña (male, $n = 22$)	NR	GR: grazing suckling calves; SUP: suckling plus supplemented with starter/growing concentrate; FIN: weaned calves finished on concentrates	NR	*Longissimus thoracis*	Feeding type Packaging (overwrapped, MAP, VP storage for 13 d)	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.	(Ripoll et al., 2013)

Holstein-Friesian bull (male, $n = 16$)	90 d	Control: barley; MD: dry maize grain; BMS: 50% barley + 50% ensiled maize grain; MDMS: 50% dry maize + 50% ensiled maize grain	NR	*Longissimus thoracis*	Starch source	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.	(Sosin-Bzducha et al., 2012)
Galician Blond (male, $n = 20$)	240 d	(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	(A) weaned: 175.6, non-weaned: 210.2; (B) weaning: 163.8, non-weaned: 197.0	*Longissimus thoracis*	Weaning age + finishing system	The finishing system hardly affected FA. Veal from non-weaned calves had higher 18:3n-3, 20:5n-3, 22:5n-3, n-3 PUFA, MUFA and conjugated linoleic acid, reduced 18:0, 18:2n-6, and n-6 PUFA, which may be more suitable for human health due to higher levels of anti-atherogenic FA.	(Bispo et al., 2011)
Holstein (steers vs. male, $n = 48$)	11 mo	(A) Concentrate with vitamin A; (B) concentrate with restricted level of vitamin A	Bull: 255 (A), 257 (B); Steer: 232 (A & B)	*Longissimus thoracis*	Vitamin A restriction Castration	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.	(Marti et al., 2011)
Galician Blond (male, $n = 36$)	240 d	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)	Non-weaned: 204.7Weaning at 5 mo: 173.4Weaning at 2 mo: 166.1	*Longissimus thoracis*	Weaning age + finishing system	Non-weaned veal had higher n-3 PUFA, conjugated linoleic acid and 18:1trans-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.	(Bispo et al., 2010b)
Rubia Gallega (male, $n = 36$)	240 d	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)	Non-weaned: 204.7Weaning at 5 mo: 173.4Weaning at 2 mo: 166.1	*Longissimus thoracis*	Weaning age + finishing system	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.	(Bispo et al., 2010a)
Parda de Montaña or Pirenaica (male, $n = 28$, 14 per breed)	10–11 mo	Early weaning at 90 d or normal weaning at 150 d, followed by intensive feedlot feeding with concentrate.	Parda de Montaña: 447; Pirenaica: 451. Early & normal weaned: 449	*Longissimus thoracis*	Weaning age Breed	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.	(Blanco et al., 2009)

(*Continued*)

Table 2. (*Continued*)

Animal	Age	Production systems	CW (kg)	Muscles	Factors	Key findings	References
Simmental (organic $n = 15$, conventional $n = 14$)	~6 mo	Organic: pasture reared with natural suckling; Conventional: milk-replacers and roughage sources.	NR	*Longissimus thoracis*	Organic feeding	Organic veal had lower fat content, L^*, b^* 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.	(Miotello et al., 2009)
Parda de Montaña (male, $n = 46$)	8–10 mo	Early weaning at 90 d or normal weaning at 150 d, with/without supplementation of concentrate pre-weaning	Early weaned: 261–262; Normal weaned: 254–257	*Longissimus dorsi*	Weaning age Pre-weaning supplementation	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.	(Blanco et al., 2008b)
Parda de Montaña (male, $n = 16$)	362 d	Early weaning at 90 d or Normal weaning at 180 d and finished with concentrate	Early weaned: 290; Normal weaned: 270	*Longissimus thoracis*	Weaning age	Early weaned calves had higher % dressing and CW and lower L^* and b^*, with similar LW, fat score, conformation, a^*, meat tenderness, chemical compositions, and FA profile.	(Blanco et al., 2008a)
Holstein bulls (male, $n = 18$)	131 d	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.	NR	*Longissimus thoracis et lumborum*	Adding of Se and vitamin E	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.	(Sk ivanová et al., 2007)
Rubia Gallega (male, $n = 43$)	200–347 d	Non-weaned: suckling and reared on a rotational system vs. Weaned at 3 mo and fed with grass silage *ad libitum* and concentrate.	Non-weaned: 180.8Weaned: 185.6	*Longissimus thoracis*	Weaning status VP storage for 7/14 d.	Weaning status did not affect CW, WHC, and pH. Non-weaned had higher b^* and hue but lower pigment content, while the differences disappeared after longer aging for 14 d.Storage increased a^*, b^*, hue and chroma while reducing pigment content, expressible juice, and toughness.	(Oliete et al., 2006)

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*	Milk intake level 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 (sensory) 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.	(Vieira et al., 2005)
Holstein veal ($n = 48$)	NR	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	*Longissimus thoracis*	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.	(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 *semitendinousus*; however, the difference between other muscles was marginal (Mestre Prates et al., 2006). Similarly, no significant difference was observed between muscles (*longissimus lumborum* and *semitendinousus*) 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 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 development 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 grain-fed (Adams, 1975; Metson et al., 1979). Meat color from calves that grazed with their dams during the last period of rearing was darker than that from calves receiving their dams' milk and concentrate (Ripoll et al., 2013). The use of different chelating (EDTA) and Fe-binding agents has been proposed to reduce iron absorption from the diet to maintain the typical light color of veal (Gariépy et al., 2004; Ngapo & Gariépy, 2006). On the other hand, limiting iron intake from the diet before slaughter (e.g., 60 d) also produced a pale color (Cui et al., 2017). Several other dietary treatments were evaluated, and their effects on meat color were inconsistent (Table 2). A similar color was observed in veal when the calves were fed with milk compared to grain or fed with milk *ad libitum* or in restricted amounts during the first 2.5 mo (Vieira et al., 2005). Color differences were not observed when comparing different proportions of concentrate in finishing veal diets (Cerdeno et al., 2006; Serrano et al., 2007; dos Santos et al et al., 2013). Darker meat color was observed in Holstein than in Australian beef breeds or Tudacana × Charolais than in Limousin calves (Aldai et al., 2012; Shabtay et al., 2021), which was suggested to be associated with the variations in the ultimate pH value.

Slaughter age significantly influences meat color, with a darker meat color (lower L^*, but higher a^* and b^* values) observed with increasing slaughter age/weight (Monteiro et al., 2012; dos Santos et al., 2013; Marti et al., 2013; Albertí et al., 2014; Florek et al., 2015; Pike et al., 2019). In contrast, Yim and Hur (2019) observed that a^* and b^* values decreased in older calves, but that the L^* value was not affected by animal age. On the other hand, the effect of weaning age on color is not conclusive (Table 2); weaning at a younger age could generate darker (3 vs. 7 mo) (Pateiro et al., 2013), lighter (90 vs. 180 d) (Blanco et al., 2008a), or similar meat color (90 vs. 150 d) (Blanco et al., 2008b, 2009). The effect of weaning age on color could be attributed to the change in the type of muscle fibers (Blanco et al., 2008a) with greater proportions of glycolytic fiber in calves weaned at a younger age. Further, weaning of Holstein calves at a lower weight (<90 kg) resulted in lower L^* and b^* relative to those weaned at higher weights (>100 kg) (Vavrišínová et al., 2020).

Additionally, meat color is also affected by the ultimate pH of the muscle. A darker meat color results from a high ultimate pH (Abril et al., 2001) due to insufficient muscle glycogen content at slaughter, which is mainly associated with diet and pre-slaughter stress (Immonen et al., 2000). On the other hand, a fast pH decline caused by electrical stimulation could lead 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 determining 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 postmortem 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) (Vavrišínová et al., 2019a) and Hanwoo breed (4.39 vs. 7.89 kg) (Yim et al., 2015).

Marbling or IMF level has been suggested to positively 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 mechanism; however, its impacts on tenderness were inconsistent (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 pastures (dos Santos et al., 2013) or reared with milk compared to grain (Vieira et al., 2005). However, direct comparisons of absolute WBSF values across trials should be considered cautiously since they may be subject to unaccounted diverse sources of variation.

Water-holding capacity. The ability of meat to retain its water throughout the supply chain (e.g., production, processing, storage, distribution, and shelf display) 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 et al., 2000; Adzitey & Nurul, 2011). Meat products 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* (Vavrišínová 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 *semimembranosus* 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 findings 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/pasture) (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 welfare, 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, 2007; New Zealand Trade and Enterprise, 2021). Resano et al. (2018) argued that few studies focused on evaluating consumers' demand for veal in general, and more specifically from vealers (e.g., age between 8 and 10 mo). The authors highlighted that regional origin, 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

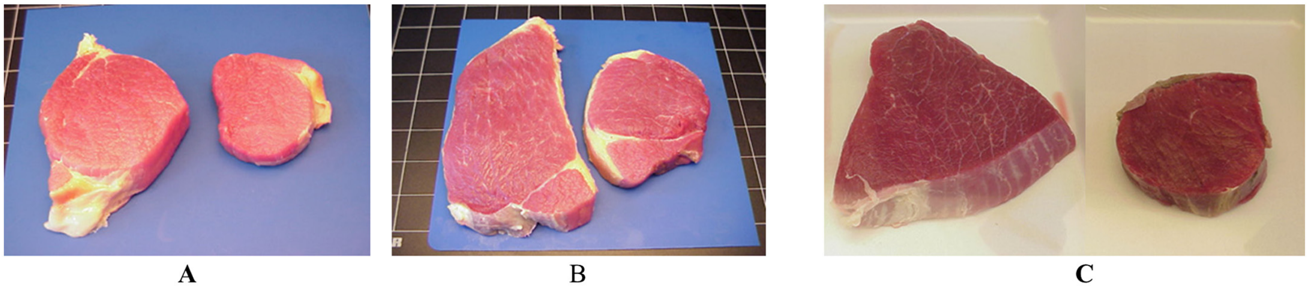

Figure 1. Digital photographs of control (left) and stretched (right) eye of round (A, *semitendinosus*), flat (B, *biceps femoris*), and insides corner cut (C, *semimembranosus*). These muscles were stretched and shaped pre-rigor using a proprietary stretching device.

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, Vavrišínová 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-shorten 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 that veal 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 (Maggiolino et al., 2021) or on adding value to low-value cull cow meat (Barragán-Hernández 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-Hernández 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.

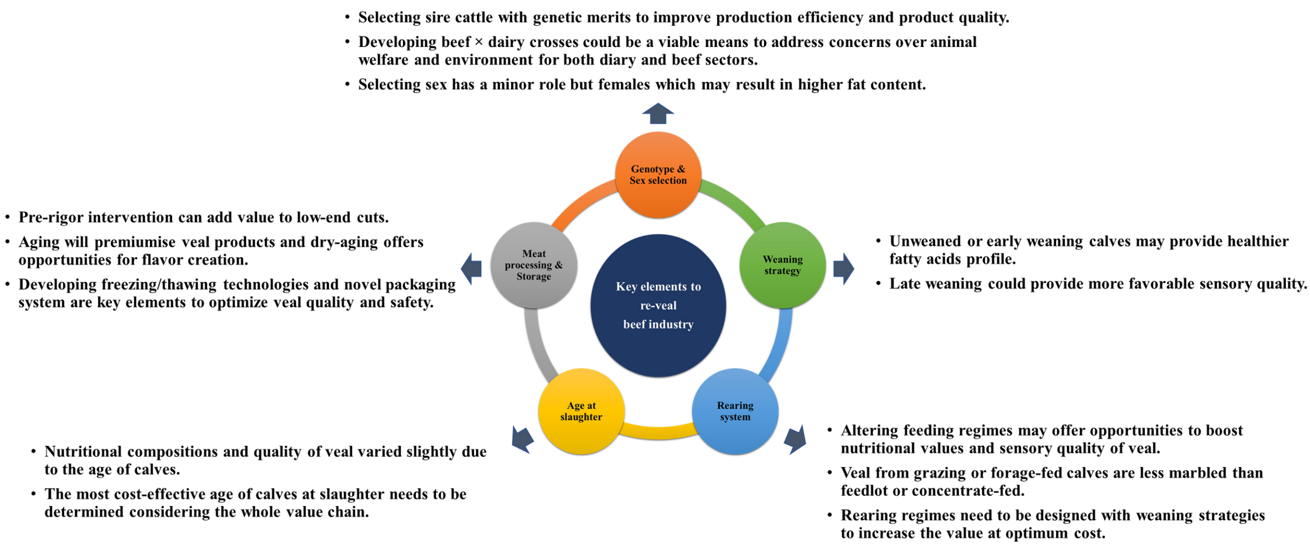

Figure 2. Key elements and suggested strategies to support the growth of the veal industry.

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; Domínguez 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 (Martín 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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Literature Cited

Abril, M., M. M. Campo, A. Onenc, C. Sanudo, P. Alberti, and A. I. Negueruela. 2001. Beef colour evolution as a function of ultimate pH. Meat Sci. 58:69–78. https://doi.org/10.1016/s0309-1740(00)00133-9

Adams, R. S. 1975. Variability in mineral and trace element content of dairy cattle feeds. J. Dairy Sci. 58:1538–1548. https://doi.org/10.3168/jds.S0022-0302(75)84750-3

Adzitey, F., and H. Nurul. 2011. Pale soft exudative (PSE) and dark firm dry (DFD) meats: Causes and measures to reduce these incidences—A mini review. International Food Research Journal 18:11–20.

Albertí, P., M. J. Beriain, G. Ripoll, V. Sarriés, B. Panea, J. A. Mendizabal, J. L. Purroy, C. Olleta, and C. Sañudo. 2014. Effect of including linseed in a concentrate fed to young bulls on intramuscular fatty acids and beef color. Meat Sci. 96:1258–1265. https://doi.org/10.1016/j.meatsci.2013.11.009

Aldai, N., P. Lavín, J. K. G. Kramer, R. Jaroso, and A. R. Mantecón. 2012. Breed effect on quality veal production in mountain areas: emphasis on meat fatty acid composition. Meat Sci. 92:687–696. https://doi.org/10.1016/j.meatsci.2012.06.024

Alfaia, C. M. M., M. L. F. Castro, S. I. V. Martins, A. P. V Portugal, S. P. A. Alves, C. M. G. A. Fontes, R. J. B. Bessa, and J. A. M. Prates. 2007. Effect of slaughter season on fatty acid composition, conjugated linoleic acid isomers and nutritional value of intramuscular fat in Barrosã-PDO veal. Meat Sci. 75:44–52. https://doi.org/10.1016/j.meatsci.2006.06.013

Alonso, M. E., J. R. González-Montaña, and J. M. Lomillos. 2020. Consumers' concerns and perceptions of farm animal welfare. Animals 10:385. https://doi.org/10.3390/ani10030385

Araújo, J. P., P. Pires, J. L. Cerqueira, M. Barros, and T. Moreno. 2020. Intramuscular fatty acid composition of the longissimus muscle of unweaned Minhota breed calves at different slaughter age. Iranian Journal of Applied Animal Science 10:17–24.

Balan, P., M. M. Farouk, A. D. Stuart, R. Kemp, M. Staincliffe, C. Craige, and Y. H. B. Kim. 2019. Effects of electrical stimulation and pre-rigor conditioning temperature on aging potential of hot-boned beef M. longissimus lumborum. Anim. Sci. J. 90:1050–1059. https://doi.org/10.1111/asj.13217

Baldi, G., S. Ratti, C. E. M. Bernardi, V. Dell'rto, C. Corino, R. Compiani, and C. A. S. Rossi. 2015. Effect of ageing time in vacuum package on veal longissimus dorsi and biceps femoris physical and sensory traits. Ital. J. Food Sci. 27:290–297. https://doi.org/10.14674/1120-1770/ijfs.v271

Barahona, M., J. L. Olleta, C. Sañudo, P. Albertí, B. Panea, M. Pérez-Juan, C. E. Realini, and M. M. Campo. 2016. Effects of whole linseed and rumen-protected conjugated linoleic acid enriched diets on beef quality. Animal 10:709–717. https://doi.org/10.1017/S1751731115002591

Barragán-Hernández, W., P. L. A. Leighton, O. López-Campos, J. Segura, J. L. Aalhus, and N. Prieto. 2022. Effect of in-the-bag dry-ageing on meat palatability and volatile compounds of cull cows and youthful steers. Meat Sci. 188:108800. https://doi.org/10.1016/j.meatsci.2022.108800

Basiel, B. L., and T. L. Felix. 2022. Board Invited Review: Crossbreeding beef × dairy cattle for the modern beef production system. Translational Animal Science 6(2). https://doi.org/10.1093/tas/txac025

Bekhit, A., M. M. Farouk, L. Cassidy, and K. Gilbert. 2007. Effects of rigor temperature and electrical stimulation on venison quality. Meat Sci. 75:564–574.

Berger, S., G. Raman, R. Vishwanathan, P. F. Jacques, and E. J. Johnson. 2015. Dietary cholesterol and cardiovascular disease: A systematic review and meta-analysis. Am. J. Clin. Nutr. 102:276–294. https://doi.org/10.3945/ajcn.114.100305

Berry, D. P. 2021. Invited review: Beef-on-dairy—The generation of crossbred beef × dairy cattle. J. Dairy Sci. 104:3789–3819. https://doi.org/10.3168/jds.2020-19519

Bhargava, N., R. S. Mor, K. Kumar, and V. S. Sharanagat. 2021. Advances in application of ultrasound in food processing: A review. Ultrason. Sonochem. 70. https://doi.org/10.1016/j.ultsonch.2020.105293

Bispo, E., L. Monserrat, L. González, D. Franco, and T. Moreno. 2010a. Effect of weaning status on animal performance and meat quality of Rubia Gallega calves. Meat Sci. 86:832–838. https://doi.org/10.1016/j.meatsci.2010.07.005

Bispo, E., T. Moreno, A. Latorre, L. González, P. G. Herradón, D. Franco, and L. Monserrat. 2010b. Effect of weaning status on lipids of Galician Blond veal: Total fatty acids and 18:1 cis and trans isomers. Meat Sci. 86:357–363. https://doi.org/10.1016/j.meatsci.2010.05.014

Bispo, E., A. Thomas, D. Durand, L. Monserrat, L. Gonzalez, and D. Bauchart. 2011. Effects of weaning and finishing feeding treatment on fatty acids, especially cis and trans C18:1 isomers, in the Longissimus thoracis muscle of Galician Blond calves. Animal 5:802–812. https://doi.org/10.1017/S1751731110002338

Blanco, M., G. Ripoll, P. Albertí, A. Sanz, R. Revilla, D. Villalba, and I. Casasús. 2008a. Effect of early weaning on performance, carcass and meat quality of spring-born bull calves raised in dry mountain areas. Livest. Sci. 115:226–234. https://doi.org/10.1016/j.livsci.2007.07.012

Blanco, M., D. Villalba, G. Ripoll, H. Sauerwein, and I. Casasús. 2008b. Effects of pre-weaning concentrate feeding on calf performance, carcass and meat quality of autumn-born bull calves weaned at 90 or 150 d of age. Animal 2:779–789. https://doi.org/10.1017/S1751731108001808

Blanco, M., D. Villalba, G. Ripoll, H. Sauerwein, and I. Casasús. 2009. Effects of early weaning and breed on calf performance and carcass and meat quality in autumn-born bull calves. Livest. Sci. 120:103–115. https://doi.org/10.1016/j.livsci.2008.05.003

Blanco-Penedo, I., R. Shore, M. Miranda, J. Benedito, and M. López-Alonso. 2009. Factors affecting trace element status in calves in NW Spain. Livest. Sci. 123:198–208. https://doi.org/10.1016/j.livsci.2008.11.011

Bown, M. D., P. D. Muir, and B. C. Thomson. 2016. Dairy and beef breed effects on beef yield, beef quality and profitability: A review. New Zeal. J. Agr. Res. 59:174–184. https://doi.org/10.1080/00288233.2016.1144621

Brscic, M., F. Gottardo, and G. Cozzi. 2013. Citizens' view on veal calves' fattening system in Italy and animal welfare. Agriculturae Conspectus Scientificus 78:249–253.

Burggraaf, V. T., and D. Lineham. 2016. Effect of easy calving beef sires on the birth weight and growth of dairy beef cattle. NZGA: Research and Practice Series 16:329–332.

Burggraaf, V. T., G. M. Lucci, S. F. Ledgard, D. L. Antille, V. O. Snow, and C. A. de Klein. 2020. Application of circular economy principles to New Zealand pastoral farming systems. Journal of New Zealand Grasslands 82:53–59.

Calkins, C. R., and J. M. Hodgen. 2007. A fresh look at meat flavor. Meat Sci. 77:63–80. https://doi.org/10.1016/j.meatsci.2007.04.016

Castejón, D., J. M. García-Segura, R. Escudero, A. Herrera, and M. I. Cambero. 2015. Metabolomics of meat exudate: Its potential to evaluate beef meat conservation and aging. Anal. Chim. Acta. 901:1–11. https://doi.org/10.1016/j.aca.2015.08.032

Cerdeno, A., C. Vieira, E. Serrano, P. Lavin, and A. R. Mantecon. 2006. Effects of feeding strategy during a short finishing period on performance, carcass and meat quality in previously-grazed young bulls. Meat Sci. 72:719–719. https://doi.org/10.1016/j.meatsci.2005.10.002

Chen, J., and H. Liu. 2020. Nutritional indices for assessing fatty acids: A mini-review. Int. J. Mol. Sci. 21:5695. https://doi.org/10.3390/ijms21165695

Choi, Y. M., and B. C. Kim. 2009. Muscle fiber characteristics, myofibrillar protein isoforms, and meat quality. Livest. Sci. 122:105–118. https://doi.org/10.1016/j.livsci.2008.08.015

Choi, Y. S., S. K. Ku, J. Y. Jeong, K. H. Jeon, and Y. H. B. Kim. 2015. Changes in ultrastructure and sensory characteristics on electro-magnetic and air blast freezing of beef during frozen storage. Korean J. Food Sci. An. 35:27. https://doi.org/10.5851/kosfa.2015.35.1.27

Claus, J. R., H. Wang, and N. G. Marriott. 1997. Prerigor carcass muscle stretching effects on tenderness of grain-fed beef under commercial conditions. J. Food Sci. 62:1231–1234. https://doi.org/10.1111/j.1365-2621.1997.tb12251.x

Coombs, C. E., B. W. Holman, M. A. Friend, and D. L. Hopkins. 2017. Long-term red meat preservation using chilled and frozen storage combinations: A review. Meat Sci. 125:84–94. https://doi.org/10.1016/j.meatsci.2016.11.025

Costa, P., A. F. Costa, P. A. Lopes, C. M. Alfaia, R. J. B. Bessa, L. C. Roseiro, and J. A. M. Prates. 2011. Fatty acid composition, cholesterol and α-tocopherol of Barrosã-PDO veal produced in farms located in lowlands, ridges and mountains. J. Food Compos. Anal. 24:987–994. https://doi.org/10.1016/j.jfca.2010.11.008

Costa, P., L. C. Roseiro, A. Partidário, V. Alves, R. J. B. Bessa, C. R. Calkins, and C. Santos. 2006. Influence of slaughter season and sex on fatty acid composition, cholesterol and α-tocopherol contents on different muscles of Barrosã-PDO veal. Meat Sci. 72:130–139. https://doi.org/10.1016/j.meatsci.2005.06.011

Cui, K., Y. Tu, Y. C. Wang, N. F. Zhang, T. Ma, and Q. Y. Diao. 2017. Effects of a limited period of iron supplementation on the growth performance and meat colour of dairy bull calves for veal production. Anim. Prod. Sci. 57:778–784. https://doi.org/10.1071/AN15388

Daley, C., A. Abbott, P. Doyle, G. Nader, and S. Larson. 2010. A review of fatty acid profiles and antioxidant content in grass-fed and grain-fed beef. Nutr. J. 9:10. https://doi.org/10.1186/1475-2891-9-10

De Palo, P., A. Maggiolino, P. Centoducati, and A. Tateo. 2013. Effects of two different packaging materials on veal calf meat quality and shelf life. J. Anim. Sci. 91:2920–2930. https://doi.org/10.2527/jas.2012-5292

De Palo, P., A. Maggiolino, A. Tateo, and P. Centoducati. 2014. Influence of gas mixture on quality and shelf life of veal calf meat. Ital. J. Anim. Sci. 13:226–233. https://doi.org/10.4081/ijas.2014.3129

den Hertog-Meischke, M., R. Van Laack, and F. Smulders. 1997. The water-holding capacity of fresh meat. Vet. Quart. 19:175–181.

Dias, A. M. O., L. F. G. de Menezes, W. Paris, F. L. M. de Paula, G. R. Schmitz, S. S. e Souza, A. M. Umezaki, and J. A. F. Filho. 2018. Performance and fatty acid profile of Holstein calves slaughtered at different weights. Rev. Bras. Zootecn. 47. https://doi.org/10.1590/rbz4720170208

Domaradzki, P., P. Stanek, Z. Litwi czuk, P. Skałecki, and M. Florek. 2017. Slaughter value and meat quality of suckler calves: A review. Meat Sci. 134:135–149. https://doi.org/10.1016/j.meatsci.2017.07.026

Domínguez, R., F. J. Barba, B. Gómez, P. Putnik, D. B. Kova ević, M. Pateiro, E. M. Santos, and J. M. Lorenzo. 2018. Active packaging films with natural antioxidants to be used in meat industry: A review. Food Res. Int. 113:93–101.

dos Santos, P. V., W. Paris, L. F. G. De Menezes, D. Von, M. F. da Silveira, and J. Tubin. 2013. Carcass physical composition and meat quality of holstein calves, terminated in different finishing systems and slaughter weights. Ciênc. Agrotec. 37:443–450. https://doi.org/10.1590/S1413-70542013000500008

Eikelenboom, G., and F. J. M. Smulders. 1986. Effect of electrical stimulation on veal quality. Meat Sci. 16:103–112. https://doi.org/10.1016/0309-1740(86)90069-0

Farouk, M., and J. Swan. 1998. Effect of rigor temperature and frozen storage on functional properties of hot-boned manufacturing beef. Meat Sci. 49:233–247.

Farouk, M., E. Wiklund, and K. Rosenvold. 2009a. Carcass interventions and meat tenderness. In: J. P. Kerry and D. Ledward, editors, Improving the sensory and nutritional quality of fresh meat. Woodhead Publishing. p. 561–584.

Farouk, M., E. Wiklund, A. Stuart, and P. Dobbie. 2009b. Ageing prior to freezeng improves the colour of frozen-thawed beef and venison. Congress Proceedings, 55th Intl. Congress Meat Sci. Technol., Copenhagen, Denmark 16–21 August.

Farouk, M., E. Wiklund, A. Stuart, and P. Dobbie. 2009c. Ageing prior to freezing improves waterholding capacity in beef and venison. Congress Proceedings, 55th Intl. Congress Meat Sci. Technol., Copenhagen, Denmark 16–21 August.

Fishell, V. K., E. D. Aberle, M. D. Judge, and T. W. Perry. 1985. Palatability and muscle properties of beef as influenced by preslaughter growth rate. J. Anim. Sci. 61:151–157. https://doi.org/10.2527/jas1985.611151x

Florek, M., P. Domaradzki, P. Stanek, Z. Litwi czuk, and P. Skałecki. 2015. Longissimus lumborum quality of Limousin suckler beef in relation to age and postmortem vacuum ageing. Ann. Anim. Sci. 15:785–798. https://doi.org/10.1515/aoas-2015-0019

Florek, M., Z. Litwi czuk, and P. Skałecki. 2009. Influence of slaughter season of calves and ageing time on meat quality. Pol. J. Food Nutr. Sci. 59:309–314.

Florek, M., P. Stanek, Z. Litwi czuk, and P. Zòłkiewski. 2013. Effect of concentrate supplement on slaughter value and meat quality of Limousin suckler beef reared on pasture until the age of 8 months. Bulg. J. Agric. Sci. 19:1112–1119.

Flynn, A. 1992. Minerals and trace elements in milk. In: J. E. Kinsella, editor, Advances in food and nutrition research. Academic Press. p. 209–252.

Gálvez, F., M. López-Alonso, C. Herrero-Latorre, M. Miranda, D. Franco, and J. M. Lorenzo. 2019. Chemometric characterization of the trace element profile of raw meat from Rubia Gallega × Holstein Friesian calves from an intensive system. Meat Sci. 149:63–69. https://doi.org/10.1016/j.meatsci.2018.11.010

Gariépy, C., A. Ghodratnama, and S. L. Scott. 2004. Effect of iron bioavailability on muscle fibre types and on quality and oxidative stability of grain-fed veal. Can. J. Anim. Sci. 84:651–659. https://doi.org/10.4141/a03-100

Ghvanidze, S., N. Velikova, T. H. Dodd, and W. Oldewage-Theron. 2016. Consumers' environmental and ethical consciousness and the use of the related food products information: The role of perceived consumer effectiveness. Appetite 107:311–322. https://doi.org/10.1016/j.appet.2016.08.097

Gira Consultancy and Research. 2020. Global veal market outlook. https://www.mla.com.au/contentassets/660c5e58bb514b5d83b1af29d7257472/v.gvm.0001_final_report.pdf. (Accessed 26 March 2015.).

Gómez, I., J. A. Mendizabal, M. V. Sarriés, K. Insausti, P. Albertí, C. E. Realini, M. Pérez-Juan, A. Oliver, A. Purroy, and M. J. Beriain. 2015. Fatty acid composition of young Holstein bulls fed whole linseed and rumen-protected conjugated linoleic acid enriched diets. Livest. Sci. 180:106–112. https://doi.org/10.1016/j.livsci.2015.07.023

González, L., T. Moreno, E. Bispo, M. E. R. Dugan, and D. Franco. 2014. Effect of supplementing different oils: Linseed, sunflower and soybean, on animal performance, carcass characteristics, meat quality and fatty acid profile of veal from "Rubia Gallega" calves. Meat Sci. 96:829–836. https://doi.org/10.1016/j.meatsci.2013.09.027

Grunert, K. G. 1997. What's in a steak? A cross-cultural study on the quality perception of beef. Food Qual. Prefer. 8:157–174. https://doi.org/10.1016/S0950-3293(96)00038-9

Grunert, K. G., L. Bredahl, and K. Brunsø. 2004. Consumer perception of meat quality and implications for product development in the meat sector—A review. Meat Sci. 66:259–272. https://doi.org/10.1016/S0309-1740(03)00130-X

Gupta, U. C., and S. C. Gupta,2014. Sources and deficiency diseases of mineral nutrients in human health and nutrition: A review. Pedosphere 24:13–38. https://doi.org/10.1016/S1002-0160(13)60077-6

Hulsegge, B., B. Engel, W. Buist, G. S. M. Merkus, and R. E. Klont. 2001. Instrumental colour classification of veal carcasses. Meat Sci. 57:191–195. https://doi.org/10.1016/S0309-1740(00)00093-0

Hunt, J. J. 2019. Viability of dairy-origin calves for a new beef production enterprise in New Zealand. M.S. thesis, Massey University, Palmerston North, New Zealand.

Hunt, J. J., P. Tozer, P. Kenyon, N. Schreurs. S. Pike, R. Hickson, H. Blair, and D. Garrick. 2019. Brief communication: Relative cost of producing carcasses from dairy-origin steers slaughtered at 8–12 months of age in New Zealand. New Zealand Journal of Animal Science and Production 79:153–155.

Immonen, K., M. Ruusunen, K. Hissa, and E. Puolanne. 2000. Bovine muscle glycogen concentration in relation to finishing diet, slaughter and ultimate pH. Meat Sci. 55:25–31. https://doi.org/10.1016/s0309-1740(99)00121-7

Kelava, N., M. Konja ić, A. Ivanković, J. Ramljak, and I. Kos. 2009. Veal fatty acid composition of different breeds. Ital. J. Anim. Sci. 8:261–263. https://doi.org/10.4081/ijas.2009.s3.261

Kim, Y. H. B., M. Frandsen, and K. Rosenvold. 2011. Effect of ageing prior to freezing on colour stability of ovine longissimus muscle. Meat Sci. 88:332–337. https://doi.org/10.1016/j.meatsci.2010.12.020

Kim, Y. H. B., D. Ma, D. Setyabrata, M. M. Farouk, S. M. Lonergan, E. Huff-Lonergan, and M. C. Hunt. 2018. Understanding postmortem biochemical processes and post-harvest aging factors to develop novel smart-aging strategies. Meat Sci. 144:74–90. https://doi.org/10.1016/j.meatsci.2018.04.031

Lagoda, H. L., L. L. Wilson, W. R. Henning, S. L. Flowers, and E. W. Mills. 2002. Subjective and objective evaluation of veal lean color. J. Anim. Sci. 80:1911–1916. https://doi.org/10.2527/2002.8071911x

Leahy, S. C., L. Kearney, A. Reisinger, and H. Clark. 2019. Mitigating greenhouse gas emissions from New Zealand pasture-based livestock farm systems. Journal of New Zealand Grasslands 81:101–110. https://doi.org/10.33584/jnzg.2019.81.417

Leygonie, C., T. J. Britz, and L. C. Hoffman. 2012. Impact of freezing and thawing on the quality of meat: Review. Meat Sci. 91:93–98. https://doi.org/10.1016/j.meatsci.2012.01.013

Li, X., R. Zhang, M. M. Hassan, Z. Cheng, J. Mills, C. Hou, C. E. Realini, L. Chen, L. Day, X. Zheng, D. Zhang, and T. M. Hicks. 2022. Active packaging for the extended shelf-life of meat: perspectives from consumption habits, market requirements and packaging practices in China and New Zealand. Foods 11:2903. https://doi.org/10.3390/foods11182903

Litwi czuk, Z., P. Domaradzki, T. Grodzicki, A. Litwi czuk, and M. Florek. 2015. The relationship of fatty acid composition and cholesterol content with intramuscular fat content and marbling in the meat of Polish Holstein-Friesian cattle from semi-intensive farming. Anim. Sci. P. 33:119–128.

Liu, J., S. Chriki, M. Kombolo, M. Santinello, S. B. Pflanzer, É. Hocquette, M.-P. Ellies-Oury, and J.-F. Hocquette. 2023. Consumer perception of the challenges facing livestock production and meat consumption. Meat Sci. 200:109144. https://doi.org/10.1016/j.meatsci.2023.109144

Locker, R. 1960. Degree of muscular contraction as a factor in tenderness of beef. J. Food Sci. 25:304–307.

López-Campos, Ó., J. L. Aalhus, E. K. Okine, V. S. Baron, and J. A. Basarab. 2013. Effects of calf-and yearling-fed beef production systems and growth promotants on production and profitability. Can. J. Anim. Sci. 93:171–184. https://doi.org/10.4141/cjas2012-035

Lu, N., J. Ma, and D.-W. Sun. 2022. Enhancing physical and chemical quality attributes of frozen meat and meat products: Mechanisms, techniques and applications. Trends Food Sci. Tech. 124:63–85. https://doi.org/10.1016/j.tifs.2022.04.004

Maggiolino, A., M. F. Sgarro, G. Natrella, J. M. Lorenzo, A. Colucci, M. Faccia, and P. De Palo. 2021. Dry-aged beef steaks: Effect of dietary supplementation with Pinus taeda hydrolyzed lignin on sensory profile, colorimetric and oxidative stability. Foods 10:1080. https://doi.org/10.3390/foods10051080

Mandell, I. B., T. Maclaurin, and S. Buttenhan. 2001. Effects of carcass weight class and postmortem aging on carcass characteristics and sensory attributes in grain-fed veal. J. Food Sci. 66:762–769. https://doi.org/10.1111/j.1365-2621.2001.tb04635.x

Marti, S., C. E. Realini, A. Bach, M. Pérez-Juan, and M. Devant. 2011. Effect of vitamin A restriction on performance and meat quality in finishing Holstein bulls and steers. Meat Sci. 89:412–418. https://doi.org/10.1016/j.meatsci.2011.05.003

Marti, S., C. E. Realini, A. Bach, M. Pérez-Juan, and M. Devant. 2013. Effect of castration and slaughter age on performance, carcass, and meat quality traits of Holstein calves fed a high-concentrate diet. J. Anim. Sci. 91:1129–1140. https://doi.org/10.2527/jas.2012-5717

Martín, N., N. Schreurs, S. Morris, N. López-Villalobos, J. McDade, and R. Hickson. 2020. Sire effects on post-weaning growth of beef-cross-dairy cattle: A case study in New Zealand. Animals 10:2313. https://doi.org/10.3390/ani10122313

McGee, M., M. G. Keane, R. Neilan, A. P. Moloney, and P. J. Caffrey. 2005. Production and carcass traits of high dairy genetic merit Holstein, standard dairy genetic merit Friesian and Charolais × Holstein-Friesian male cattle. Irish J. Agr. Food Res. 44:215–231.

Mestre Prates, J. A., M. A. Gonçalves Quaresma, R. J. Branquinho Bessa, C. M. G. Andrade Fontes, and C. M. P. Mateus Alfaia. 2006. Simultaneous HPLC quantification of total cholesterol, tocopherols and β-carotene in Barrosã-PDO veal. Food Chem. 94:469–477. https://doi.org/10.1016/j.foodchem.2005.01.021

Metson, A. J., E. J. Gibson, J. L. Hunt, and W. M. H. Saunders. 1979. Seasonal variations in chemical composition of pasture. New Zeal. J. Agr. Res. 22:309–318. https://doi.org/10.1080/00288233.1979.10430752

Miller, R. 2020. Drivers of consumer liking for beef, pork, and lamb: A review. Foods, 9:428. https://doi.org/10.3390/foods9040428

Miotello, S., V. Bondesan, F. Tagliapietra, S. Schiavon, and L. Bailoni. 2009. Meat quality of calves obtained from organic and conventional farming. Ital. J. Anim. Sci. 8:213–215. https://doi.org/10.4081/ijas.2009.s3.213

Miranda, M., V. Pereira, P. Carbajales, and M. López-Alonso. 2018. Importance of breed aptitude (beef or dairy) in determining trace element concentrations in bovine muscles. Meat Sci. 145:101–106. https://doi.org/10.1016/j.meatsci.2018.06.005

Monsón, F., C. Sañudo, and I. Sierra. 2004. Influence of cattle breed and ageing time on textural meat quality. Meat Sci. 68:595–602. https://doi.org/10.1016/j.meatsci.2004.05.011

Monteiro, A. C. G., M. A. Fontes, R. J. B. Bessa, J. A. M. Prates, and J. P. C. Lemos. 2012. Intramuscular lipids of Mertolenga-PDO beef, Mertolenga-PDO veal and "Vitela Tradicional do Montado"-PGI veal. Food Chem. 132:1486–1494. https://doi.org/10.1016/j.foodchem.2011.12.008

Monteiro, A. C. G., E. Gomes, A. S. Barreto, M. F. Silva, M. A. Fontes, R. J. B. Bessa, and J. P. C. Lemos. 2013. Eating quality of "Vitela Tradicional do Montado"-PGI veal and Mertolenga-PDO veal and beef. Meat Sci. 94:63–68. https://doi.org/10.1016/j.meatsci.2012.12.011

Moreno, T., N. Pérez, B. Oliete, J. A. Carballo, D. Franco, and L. Monserrat. 2007. Effects on quality attributes of commercial veal pieces under different ageing treatments. Int. J. Food Sci. Tech. 42:373–379. https://doi.org/10.1111/j.1365-2621.2006.01453.x

Morittu, V. M., A. A. Spina, P. Iommelli, A. Poerio, F. V. Oliverio, D. Britti, and R. Tudisco. 2021. Effect of integration of linseed and vitamin E in Charolaise × Podolica Bulls' diet on fatty acids profile, beef color and lipid stability. Agriculture 11:1032. https://doi.org/10.3390/agriculture11111032

Murphy, B., P. Crosson, A. K. Kelly, and R. Prendiville. 2017. An economic and greenhouse gas emissions evaluation of pasture-based dairy calf-to-beef production systems. Agr. Syst. 154:124–132. https://doi.org/10.1016/j.agsy.2017.03.007

New Zealand Trade and Enterprise. 2021. What drives F&B purchases in NZ's major export markets. https://www.fbtech.co.nz/2021/07/21/what-drives-fb-purchases-in-nzs-major-export-markets/. (Accessed 28 September 2023).

Ngapo, T. M., and C. Gariépy. 2006. Factors affecting the meat quality of veal. J. Sci. Food Agr. 86:1412–1431. https://doi.org/10.1002/jsfa.2507

Nishimura, T., A. Hattori, and K. Takahashi. 1999. Structural changes in intramuscular connective tissue during the fattening of Japanese black cattle: Effect of marbling on beef tenderization. J. Anim. Sci. 77:93–104. https://doi.org/10.2527/1999.77193x

Oliete, B., J. A. Carballo, A. Varela, T. Moreno, L. Monserrat, and L. Sánchez. 2006. Effect of weaning status and storage time under vacuum upon physical characteristics of meat of the Rubia Gallega breed. Meat Sci. 73:102–108. https://doi.org/10.1016/j.meatsci.2005.11.004

Otremba, M. M., M. E. Dikeman, G. A. Milliken, S. L. Stroda, J. A. Unruh, and E. Chambers IV. 1999. Interrelationships among evaluations of beef longissimus and semitendinosus muscle tenderness by Warner-Bratzler shear force, a descriptive-texture profile sensory panel, and a descriptive attribute sensory panel. J. Anim. Sci. 77:865–873. https://doi.org/10.2527/1999.774865x

Pateiro, M., J. M. Lorenzo, S. Diaz, J. A. Gende, M. Fernandez, J. Gonzalez, L. García, F. Rial, and D. Franco. 2013. Meat quality of veal: Discriminatory ability of weaning status. Span. J. Agric. Res. 11:1044–1056. https://doi.org/10.5424/sjar/2013114-4363

Pereira, V., M. López-Alonso, M. Miranda, J. L. Benedito, and M. García-Vaquero. 2017. Relationship between the essential and toxic element concentrations and the proximate composition of different commercial and internal cuts of young beef. Eur. Food Res. Technol. 243:1869–1873. https://doi.org/10.1007/s00217-017-2888-0

Perham, C. C., C. L. Gifford, D. R. Woerner, T. E. Engle, K. S. Sellins, R. J. Acheson, L. W. Douglass, J. D. Tatum, R. J. Delmore, A. Cifelli, S. H. McNeill, and K. E. Belk. 2019. Special-fed veal: Separable components, proximate composition, and nutrient analysis of selected raw and cooked, wholesale and retail cuts. Meat Sci. 148:19–31. https://doi.org/10.1016/j.meatsci.2018.09.016

Pestana, J. M., A. S. H. Costa, S. P. Alves, S. V. Martins, C. M. R. J. B. Alfaia,Bessa, and J. A. M. Prates. 2012. Seasonal changes and muscle type effect on the nutritional quality of intramuscular fat in Mirandesa-PDO veal. Meat Sci. 90:819–827. https://doi.org/10.1016/j.meatsci.2011.11.023

Pike, S., N. Schreurs, R. Hickson, J. Hunt, P. Kenyon, D. Garrick, H. T. Blair, and S. Morris. 2019. Brief communication: Meat quality of light-weight, yearling steers of dairy origin. New Zealand Journal of Animal Science and Production 79:156–158.

Pouzo, L., N. Fanego, F. J. Santini, A. Descalzo, and E. Pavan. 2015. Animal performance, carcass characteristics and beef fatty acid profile of grazing steers supplemented with corn grain and increasing amounts of flaxseed at two animal weights during finishing. Livest. Sci. 178:140–149. https://doi.org/10.1016/j.livsci.2015.05.034

Rattray, P. V., I. Brooks, and A. M. Nicol, editors. 2007. Pasture and supplements for grazing animals. New Zealand Society of Animal Production No. 14.

Realini, C. E., and B. Marcos. 2014. Active and intelligent packaging systems for a modern society. Meat Sci. 98:404–419. https://doi.org/10.1016/j.meatsci.2014.06.031

Realini, C. E., G. Ares, L. Antúnez, G. Brito, S. Luzardo, M. del Campo, C. Saunders, M. M. Farouk, and F. M. Montossi. 2022. Meat insights: Uruguayan consumers´ mental associations and motives underlying consumption changes. Meat Sci. 192:108901. https://doi.org/10.1016/j.meatsci.2022.108901

Realini, C. E., T. Driver, R. Zhang, M. Guenther, S. Duff, C. R. Craigie, C. Saunders, and M. M. Farouk. 2023. Survey of New Zealand consumer attitudes to consumption of meat and meat alternatives. Meat Sci. 203:109232. https://doi.org/10.1016/j.meatsci.2023.109232

Resano, H., A. M. Olaizola, and M. Dominguez-Torreiro. 2018. Exploring the influence of consumer characteristics on veal credence and experience guarantee purchasing motivators. Meat Sci. 141:1–8. https://doi.org/10.1016/j.meatsci.2018.03.001

Revilla, I., and A. M. Vivar-Quintana. 2006. Effect of breed and ageing time on meat quality and sensory attributes of veal calves of the "Ternera de Aliste" quality label. Meat Sci. 73:189–195. https://doi.org/10.1016/j.meatsci.2005.11.009

Rhee, M.-S., and B.-C. Kim. 2001. Effect of low voltage electrical stimulation and temperature conditioning on postmortem changes in glycolysis and calpains activities of Korean native cattle (Hanwoo). Meat Sci. 58:231–237. https://doi.org/10.1016/S0309-1740(00)00155-8

Ripoll, G., P. Albertí, I. Casasús, and M. Blanco. 2013. Instrumental meat quality of veal calves reared under three management systems and color evolution of meat stored in three packaging systems. Meat Sci. 93:336–343. https://doi.org/10.1016/j.meatsci.2012.09.012

Rutherford, N. H., F. O. Lively, and G. Arnott. 2021. A review of beef production systems for the sustainable use of surplus male dairy-origin calves within the UK. Frontiers in Veterinary Science 8. https://doi.org/10.3389/fvets.2021.635497

Sañudo, C., E. S. Macie, J. L. Olleta, M. Villarroel, B. Panea, and P. Albertí. 2004. The effects of slaughter weight, breed type and ageing time on beef meat quality using two different texture devices. Meat Sci. 66:925–932. https://doi.org/10.1016/j.meatsci.2003.08.005

Savell, J. W., and H. R. Cross. 1988. The role of fat in the palatability of beef, pork, and lamb. In: National Research Council (US) Committee on Technological Options to Improve the Nutritional Attributes of Animal Products, editor, Designing foods: Animal product options in the marketplace. National Academies Press, Washington. p. 345–355.

Scollan, N., J.-F. Hocquette, K. Nuernberg, D. Dannenberger, I. Richardson, and A. Moloney. 2006. Innovations in beef production systems that enhance the nutritional and health value of beef lipids and their relationship with meat quality. Meat Sci. 74:17–33. https://doi.org/10.1016/j.meatsci.2006.05.002

Serra, X., M. Gil, M. Gispert, L. Guerrero, M. A. Oliver, C. Sañudo, M. M. Campo, B. Panea, J. L. Olleta, R. Quintanilla, and J. Piedrafita. 2004. Characterisation of young bulls of the Bruna dels Pirineus cattle breed (selected from old Brown Swiss) in relation to carcass, meat quality and biochemical traits. Meat Sci. 66:425–436. https://doi.org/10.1016/S0309-1740(03)00131-1

Serrano, E., P. Pradel, R. Jailler, H. Dubroeucq, D. Bauchart, J. F. Hocquette, A. Listrat, J. Agabriel, and D. Micol. 2007. Young Salers suckled bull production: Effect of diet on performance, carcass and muscle characteristics and meat quality. Animal 1:1068–1079. https://doi.org/10.1017/S1751731107000225

Severiano-Pérez, P., A. M. Vivar-Quintana, and I. Revilla. 2006. Determination and evaluation of the parameters affecting the choice of veal meat of the "Ternera de Aliste" quality appellation. Meat Sci. 73:491–497. https://doi.org/10.1016/j.meatsci.2006.01.008

Shabtay, A., E. Shor-Shimoni, A. Orlov, R. Agmon, O. Trofimyuk, O. Tal, and M. Cohen-Zinder. 2021. The meat quality characteristics of Holstein calves: The story of Israeli 'dairy beef'. Foods 10(10). https://doi.org/10.3390/foods10102308

Sheath, G., and C. Boom. 1997. Impact of beef cattle grazing systems on treading damage and forage supply. Pr. N. Z. Grassl. Assoc. 59:87–92. https://doi.org/10.33584/jnzg.1997.59.2271

Sitz, B. M., C. R. Calkins, D. M. Feuz, W. J. Umberger, and K. M. Eskridge. 2005. Consumer sensory acceptance and value of domestic, Canadian, and Australian grass-fed beef steaks. J. Anim. Sci. 83:2863–2868. https://doi.org/10.2527/2005.83122863x

Sk ivanová, E., M. Marounek, S. De Smet, and K. Raes. 2007. Influence of dietary selenium and vitamin E on quality of veal. Meat Sci. 76:495–500. https://doi.org/10.1016/j.meatsci.2007.01.003

Sørheim, O., and K. I. Hildrum. 2002. Muscle stretching techniques for improving meat tenderness. Trends Food Sci. Tech. 13:127–135. https://doi.org/10.1016/S0924-2244(02)00069-9

Sosin-Bzducha, E. M., J. A. Strzetelski, and G. Skrzy ski. 2012. The effect of starch source on physicochemical and sensory quality of veal meat. J. Anim. Feed Sci. 21:436–446. https://doi.org/10.22358/jafs/66111/2012

Speich, M., A. Pineau, and F. Ballereau. 2001. Minerals, trace elements and related biological variables in athletes and during physical activity. Clin. Chim. Acta. 312:1–11. https://doi.org/10.1016/S0009-8981(01)00598-8

Stout, W. 2003. Effect of urine volume on nitrate leaching in the northeast USA. Nutr. Cycl. Agroecosys. 67:197–203.

Tarantola, M., A. Schiavone, G. Preziuso, C. Russo, and D. Bergero. 2003. Effect of slaughter age on meat qualitative traits of veal calves. Ital. J. Anim. Sci. 2:343–345. https://doi.org/10.4081/ijas.2003.11676006

Testa, M. L., G. Grigioni, B. Panea, and E. Pavan. 2021. Color and marbling as predictors of meat quality perception of Argentinian consumers. Foods 10(7). https://doi.org/10.3390/foods10071465

Torley, P. J., B. R. D'Arcy, and G. R. Trout. 2000. The effect of ionic strength, polyphosphates type, pH, cooking temperature and preblending on the functional properties of normal and pale, soft, exudative (PSE) pork. Meat Sci. 55:451–462. https://doi.org/10.1016/S0309-1740(00)00004-8

van Selm, B., I. J. M. de Boer, S. F. Ledgard, and C. E. van Middelaar. 2021. Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production. Agr. Syst. 186. https://doi.org/10.1016/j.agsy.2020.102936

Vandoni, S., and C. A. Sgoifo Rossi. 2009. Instrumental objective measurement of veal calves carcass colour at slaughterhouse. Ital. J. Anim. Sci. 8:552–554. https://doi.org/10.4081/ijas.2009.s2.552

Vavrišínová, K., K. Hozáková, O. Bu ko, P. Haš ík, and P. Juhás. 2019a. The effect of the slaughter weight on carcass composition, body measurements and veal quality of holstein calves. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 67:1235–1243. https://doi.org/10.11118/actaun201967051235

Vavrišínová, K., K. Hozáková, O. Bu ko, J. Tká ová, and M. Bobko. 2019b. Slaughter characteristics and physical technological parameters of veal from male calves of Holstein and Slovak simmental breeds. Journal of Microbiology, Biotechnology and Food Sciences 9:634–638. https://doi.org/10.15414/jmbfs.2019/20.9.3.634-638

Vavrišínová, K., K. Hozáková, M. Margetín, M. Janí ek, and J. Dóbi. 2020. Influence of birth weight and weaning weight on performance and veal quality. Acta Fytotechnica et Zootechnica 23:116–123. https://doi.org/10.15414/afz.2020.23.mi-fpap.116-123

Vavrišínová, K., M. Janí ek, J. Dóbi, M. Margetín, and P. Juhás. 2021. The veal quality of Slovak Simmental breed in relation to sex. Acta Fytotechnica et Zootechnica 24:118–121. https://doi.org/10.15414/AFZ.2021.24.MI-PRAP.118-121

Vavrišínová, K., S. Prívara, J. ubo , P. Haš ík, and V. Foltys. 2013. Veal quality and fatty acids content in holstein calves at different diets. Veterinarija ir Zootechnika 61:89–95.

Vieira, C., M. D. García, A. Cerdeño, and A. R. Mantecón. 2005. Effect of diet composition and slaughter weight on animal performance, carcass and meat quality, and fatty acid composition in veal calves. Livest. Prod. Sci. 93:263–275. https://doi.org/10.1016/j.livprodsci.2004.11.020

Wallace, T. C., J. K. Blusztajn, M. A. Caudill, K. C. Klatt, E. Natker, S. Zeisel, and K. M. Zelman. 2018. Choline: The underconsumed and underappreciated essential nutrient. Nutr. Today 53:240–253. https://doi.org/10.1097/NT.0000000000000302

Wang, H., J. Claus, and N. Marriott. 1994. Selected skeletal alterations to improve tenderness of beef round muscles. J. Muscle Foods 5:137–147. https://doi.org/10.1111/j.1745-4573.1994.tb00526.x

Warner, R., F. R. Dunshea, D. Gutzke, J. Lau, and G. Kearney. 2014. Factors influencing the incidence of high rigor temperature in beef carcasses in Australia. Anim. Prod. Sci. 54:363–374. https://doi.org/10.1071/AN13455

Warner, R., R. Miller, M. Ha, T. Wheeler, F. R. Dunshea, X. Li, R. Vaskoska, and P. Purslow. 2021. Meat tenderness: Underlying mechanisms, instrumental measurement, and sensory assessment. Meat Muscle Biol. 4:1–25. https://doi.org/10.22175/mmb.10489

Wei, J., K. Wan, Y. Luo, and L. Zhang. 2014. The global volatile signature of veal via solid-phase microextraction and gas chromatography-mass spectrometry. Korean J. Food Sci. An. 34:700–708. https://doi.org/10.5851/kosfa.2014.34.5.700

Weston, A., R. Rogers, and T. G. Althen. 2002. The role of collagen in meat tenderness. The Professional Animal Scientist 18:107–111. https://doi.org/10.15232/S1080-7446(15)31497-2

Wood, J. D., M. Enser, A. V. Fisher, G. R. Nute, P. R. Sheard, R. I. Richardson, S. I. Hughes, and F. M. Whittington. 2008. Fat deposition, fatty acid composition and meat quality: A review. Meat Sci. 78:343–358. https://doi.org/10.1016/j.meatsci.2007.07.019

Wyness, L. 2016. The role of red meat in the diet: Nutrition and health benefits. P. Nutr. Soc. 75:227–232. https://doi.org/10.1017/S0029665115004267

Yang, A., M. Brewster, M. Lanari, and R. Tume. 2002. Effect of vitamin E supplementation on α-tocopherol and β-carotene concentrations in tissues from pasture-and grain-fed cattle. Meat Sci. 60:35–40. https://doi.org/10.1016/S0309-1740(01)00102-4

Yang, L. G., Z. X. Song, H. Yin, Y. Y. Wang, G. F. Shu, H. X. Lu, S. K. Wang, and G. J. Sun. 2016. Low n-6/n-3 PUFA ratio improves lipid metabolism, inflammation, oxidative stress and endothelial function in rats using plant oils as n-3 fatty acid source. Lipids 51:49–59. https://doi.org/10.1007/s11745-015-4091-z

Yim, D., and S. Hur. 2019. Effects of slaughter age and storage period on quality parameters of loin veal from Korean Holstein bulls. Anim. Prod. Sci. 59:395–400. https://doi.org/10.1071/AN16207

Yim, D., E. Chung, and K. Chung. 2015. Meat quality of loin and top round muscles from the Hanwoo and Holstein veal calves. Korean J. Food Sci. An. 35:731–737. https://doi.org/10.5851/kosfa.2015.35.6.731

Zhang, R., P. Chawla, C. Samarakoon, and M. M. Farouk. 2023a. Effects of sex, sire and in-bag dry-ageing on the physicochemical and microbial properties, colour and fatty acids stability of lamb. Food Chem. 403:134356. https://doi.org/10.1016/j.foodchem.2022.134356

Zhang, R., C. E. Realini, Y. H. B. Kim, and M. M. Farouk. 2023b. Challenges and processing strategies to produce high quality frozen meat. Meat Sci. 205:109311. https://doi.org/10.1016/j.meatsci.2023.109311

Zhang, R., A. B. Ross, N. Jacob, M. Agnew, M. Staincliffe, and M. M. Farouk. 2023c. Rapid Evaporative Ionisation Mass Spectrometry fingerprinting can discriminate lamb meat due to different ageing methods and levels of dehydration. J. Proteomics 272:104771. https://doi.org/10.1016/j.jprot.2022.104771

Zhang, R., M. J. Y. Yoo, and M. M. Farouk. 2019. Quality and acceptability of fresh and long-term frozen in-bag dry-aged lean bull beef. J. Food Quality 2019:1975264. https://doi.org/10.1155/2019/1975264

Zhang, R., M. J. Y. Yoo, and M. M. Farouk. 2021a. Oxidative stability, proteolysis, and in vitro digestibility of fresh and long-term frozen stored in-bag dry-aged lean beef. Food Chem. 344:128601. https://doi.org/10.1016/j.foodchem.2020.128601

Zhang, R., M. J. Yoo, C. E. Realini, M. Staincliffe, and M. M. Farouk. 2021b. In-bag dry- vs. wet-aged lamb: Quality, consumer acceptability, oxidative stability and in vitro digestibility. Foods 10(1). https://doi.org/10.3390/foods10010041

Zhang, R., M. J. Y. Yoo, A. B. Ross, and M. M. Farouk. 2022. Mechanisms and strategies to tailor dry-aged meat flavour. Trends Food Sci. Tech. 119:400–411. https://doi.org/10.1016/j.tifs.2021.12.023