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Grape pomace in diets for Podolian and crossbred young bulls: effects on growth performance, meat quality, and economic analysis of meat production

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The use of local by-products in diets for beef cattle is a useful tool for circular economy; Apulia is the second Italian region for wine making that leads to the production of great amounts of grape pomace (GP), that has a high nutritional potential due to the presence of many bioactive compounds. Forty-eight male calves were used: 16 purebred Podolian, 16 Limousine × Podolian (L×P) and 16 Marchigiana × Podolian (M×P) crossbreeds. Within each genotype, two homogenous groups of eight animals were made and fed a control diet or a diet containing 20% Grape Pomace (GP). Animals were slaughtered at 600 kg. Podolian young bulls needed a longer period to reach the slaughtering weight, with significant differences as compared to the M×P ($p < 0.05$) and to the L×P ($p < 0.01$) bulls. L×P and P young bulls showed a greater GP feed consumption ($p < 0.01$). The carcasses from L×P young bulls were classified as U, while M×P and Podolian were scored as R. The Malondialdehyde (MDA) concentration of meat was lowered ($p < 0.05$) by the dietary inclusion of GP in all the genotypes. Ageing across 3, 9 and 14 days lowered the shear force in raw and cooked meat, that was greater ($p < 0.05$) in P bulls as compared to the other two crossbreeds; the MDA content of meat ($p < 0.05$) increased during storage, irrespective of the diet and genotype. The diet containing GP led to a lower ($p < 0.05$) concentration of palmitic acid, total Saturated Fatty Acids and total Mono Unsaturated Fatty Acids, while increasing ($p < 0.01$) the concentration of Linoleic acid, total Poly Unsaturated Fatty Acids, total n-6 and total CLA ($p < 0.05$), in all the genotypes. For the M×P crossbred bulls, the GP variation rate was negative, while it was positive for the other two genotypes, showing a range of 0.46% in Podolian young bulls to 2.00% in L×P bulls. This preliminary study confirms the usefulness of dietary inclusion of grape pomace in young bulls' diet with benefits in terms of economic circularity, and meat production and quality.

KEYWORDS

Podolian, Marchigiana, Limousine, meat quality, grape pomace

1 Introduction

Beef production has increased rapidly over the last 50 years due to the use of innovative farming and reproductive technologies; however, in some Mediterranean regions, economic analyses show that beef finishing farms usually produce low returns (Trapina et al., 2024). The cost of production inputs and management are amongst the most important factors affecting profit. Nutrition and feeding are essential to ensure satisfactory animal growth and play an important role in improving production efficiency and animal welfare; careful feeding choices are able to lower management costs and promote environmental sustainability.

The use of local agriculture remnants and waste products from the food processing industry in the animal diet may represent a valuable source of nutrients for livestock animals while reducing the reliance on imported feed and conventional feed ingredients, which are often expensive and occasionally difficult to pursue. This practice is at the basis of circular economy, which calls for recycling agro-industrial refuses to create new resources and reduce environmental impact (Chisoro et al., 2023). However, these potential by-products must be characterized for their nutritional properties in order to establish the adequate level of inclusion into the diet (Tozer et al., 2024).

Many by-products have been investigated over time, giving preference to those locally produced by the agro-industry chains (Hofstetter et al., 2014). In particular, the vinification industry produces solid waste products, among which plant remains, grape pomace and wine lees are the most important (Beres et al., 2017). Some of these by-products, such as grape pomace, have garnered increasing interest as food and feed supplements over the last fifteen years (Brunetti et al., 2022). Such waste could easily be harnessed for animal feed production, improving animal welfare and growth as well as meat quality, thanks to the presence of functional ingredients and bioactive constituents (namely polyphenols and dietary fiber) (Ianni and Martino, 2020). The use of secondary biomass obtained from the post-harvest processing of grape crops has been thoroughly explored in ruminant nutrition (Molosse et al., 2024). Grape pomace (GP) includes grape seeds, skins, and stalks, containing high levels of carbohydrates and proteins (Li et al., 2024). This by-product is rich in polyunsaturated fatty acids (PUFAs), contributing to animal health when consumed in moderation, and a rich source of polyphenols, known for their strong antioxidant properties (Blasi et al., 2024; Constantin et al., 2024). With the increasing demand for wine and concerns over the environmental impact of the vineyard traditional treatments, there is a growing need to explore efficient resource utilization strategies for GP (Kafantaris et al., 2018; Muhlack et al., 2018). However, being a by-product, many variables, such as seasonal availability, grape variety, maturity, tannin concentration and wine extraction process are not easily standardized and therefore, may influence the palatability of the matrix and its nutritional efficacy in animal feeding.

In the past, crossbreeding was performed to combine the desired attributes of two or more breeds producing progeny that is more suitable for target markets while maintaining environmental adaptation (Basiel and Felix, 2022). Furthermore, it allows to improve productivity more rapidly in traits that change slowly within a breed, such as environmental adaptation, fertility, and carcass traits, taking advantage of the improvements that result from heterosis (Pulina et al., 2021).

Podolian cattle was historically widespread throughout the Southern Italy regions primarily for work and secondarily for milk. The population has experienced a decrease following the introduction of agricultural technologies which reduced the use of animals for work purposes. This breed boasts excellent adaptability to harsh environmental conditions, efficiency in the use of poor feed resources that otherwise would not be exploited such as woodland pastures, stubbles and shrubs (Tarricone et al., 2019; Karatosidi et al., 2023; Giannico et al., 2024). Milk production exceeding the needs of the calf is used for the production of several traditional agri-food products (TAP), such as the caciocavallo cheese and the manteca (Di Trana et al., 2023).

Since 1986, when the National Association of Italian Beef Cattle Breeders (ANABIC Standard di razza (Italian)) introduced a morphological evaluation which gave a predominant weight to muscle development traits compared to other groups of characters (skeletal conformation and breed characteristics), the selective trend of this breed has become addressed more towards beef production and, to a lesser extent, towards dairy production. Over time, breeders have been experiencing crossbreeding with genotypes characterized by better muscle development, carcass conformation and meat yield. Among the Italian beef cattle breeds used for crossbreeding, the Marchigiana represents an excellent breed for the improvement of meat production; this breed is endowed with great adaptability to different environmental conditions, high capacity for using forage and resistance to diseases and ectoparasites (Sorbolini et al., 2015). Originally, the Marchigiana was considered a dual-purpose breed (meat and work), while currently it is raised only for its meat, with excellent yield and quality, in terms of marbling and tenderness (Mastrangelo et al., 2018; Colombi et al., 2024).

Another widespread reality in beef finishing farms is crossbreeding with highly specialized foreign breeds, such as the Limousine. Original of France where it represents the second beef meat breed, this genotype is robust, resistant, rustic and very adaptable to different types of climates. The selection was aimed at improving meat production and precocity; in fact, the calves are small at birth but have a very rapid development. For this characteristic, Limousine bulls are widely used in crossbreeding to produce subjects slaughtered at a younger age. Moreover, this breed gives an excellent production of fine-grained meat (Braghieri et al., 2008; Vestergaard et al., 2019; Cosentino et al., 2023; Colombi et al., 2024).

Moreover, the dietary use of a by-product requires a careful analysis of the expected benefits before replacing a conventional diet. Therefore, it is appropriate to identify the main advantages that a diet containing different levels of a by-product may bring, such as increased efficiency, cost reduction, and meat quality improvement. For example, the gross profit and the efficiency, expressed as the ratio of slaughtering weight income to the cost of feed, is becoming an interesting research instrument and a practical decision-support tool. To define efficiency, one of the main used approaches is the structural one that starts from an economic optimization behavior and characterizes inefficiency in terms of deviation from this economic model (Afriat, 1972; Hanoch and Rothschild, 1972; Varian, 1984).

This aim of this study was to investigate the effect of including 20% grape pomace (GP) obtained by the local winemaking industry of “Primitivo” grapes in the diet of purebred Podolian and F1 crossbred young bulls (Limousine×Podolian and Marchigiana×Podolian) on growth performances, carcass quality, and meat quality traits. An economic analysis was carried out in order to estimate the economic advantages of crossbreeding and dietary supplementation with a by-product such as grape pomace in beef production.

2 Materials and methods

2.1 Animal management and diet

Experimental animals were handled according to the European government guidelines (Directive 2010/63/EU, European Council, 2010) in respect of their welfare.

The trial was conducted in a farm located in Mottola (in the province of Taranto, Apulian region, Italy; Latitude: 40.713711, Longitude: 17.059807, 400 m a.s.l.).

For the trial, a total of 48 male calves were used, among which 16 purebred Podolian calves born from parents registered in the relevant herdbooks of the breed, 16 Limousine × purebred Podolian and 16 Marchigiana × purebred Podolian crossbreeds, respectively. According to the traditional farming system, the calves were exclusively milk-fed, suckling from the cows until they reached the age of about 10 ± 0.5 months in February. Afterwards, within each genotype, two groups of eight animals, homogenous for age and weight, were made and subjected to a period of adaptation to the experimental diets (4 weeks). After diet adaptation period, the young bulls were weighed after 12-hour fasting period from both food and water, to determine the initial weight. Each group of bulls was kept in a pen with a straw bedding resting area and had access to an external paddock with a total space allowance of 20 m^2/bull.

During the trial, all subjects were weighed monthly, following a 12-hour fasting period, to determine Average daily gains; young bulls were fed once daily at 07:00, with experimental diets provided at 110% of the previous daily intake (approximately 2% of live body weight/day/bull). Clean, fresh water was always available. During the trial, all the feed offered and the daily refusal were weighed and recorded daily before feeding in the morning in order to calculate the Feed Conversion Ratio.

The animals were slaughtered when they reached a live weight of about 600 kg (± 15.00); this assessment resulted in variations in the age at slaughter among the different genotypes studied.

2.2 Feed preparation

Fresh red grape pomace (GP) (*Vitis vinifera* L., *cultivar* “Primitivo”) was provided by a local wine yard. Immediately after pressing, the GP was spread onto plastic canvas sheets under sunlight. The pomace was turned daily for 7 days to ensure moisture content was below 10% and milled to pass through a 4-mm sieve. Two mixed diets were prepared by a registered commercial feed manufacturer (Specialmangimi Galtieri, Modugno, Bari, Italy): control (no GP) and 20% GP meal, respectively (Table 1). Feed corresponding to approximately 60% of the ration’s dry matter, while hay represents approximately 40% of the ration’s dry matter, calculated in relation to animal requirement. All diets were formulated to be isoenergetic and isonitrogenous (Sauvant et al., 2023).

2.3 Chemical composition of feed

Representative samples of the feeds were taken every 20 days and mixed to obtain a single final pool for each diet, which was analyzed to determine the chemical composition and fatty acid profile (Table 1). Samples were ground in a hammer mill with a 1-mm screen and analyzed using the following Association of Official Agricultural Chemistry procedures (AOAC, 2000): dry matter (method 934.01), ether extract (method 920.39), ash (method 942.05), crude protein (method 954.01), ADF and ADL (method 973.18), and amylase-treated neutral detergent fiber (NDF) (method 2002.04). Total tannin content was measured by the Folin–Ciocalteu colorimetric method (Makkar, 2003). Gallic acid standard curve (0.02–0.10 mg/mL) was used and total tannins were expressed as gram gallic acid equivalent per 100 g DM.

TABLE 1 Ingredients, chemical composition, and fatty acid profile of the diets.

	Dietary Treatment			
Ingredients (%)	**Control**	**Grape pomace**	**Sun-dried grape pomace**	**Hay**
Corn	14.70	11.15		
Wheat middlings	14.50	10.00		
Flaked maize	14.00	10.00		
Soybean meal (45%)	13.50	12.00		
Barley	7.00	5.00		
Soybean seeds	7.00	7.00		
Corn gluten meal	7.00	6.00		
Wheat flour shorts	6.54	4.00		
Alfalfa	3.00	3.00		
Flaked faba bean	3.00	3.00		
Molasses	2.90	2.00		
Sun-dried Grape Pomace	0.00	20.00		
Soybean oil	0.50	–		
Grapeseed oil	–	0.50		
Carob	1.00	1.00		
Bentonite	1.00	1.00		
Calcium carbonate	2.80	2.80		
Dicalcium phosphate	1.00	1.00		
Sodium chloride	0.40	0.40		
Mineral-Vitamin Supplement	0.16	0.16		
Forage Units/Kg DM	1.09	1.01	0.90	0.41
Chemical composition (% on DM basis)				
Moisture	8.80	8.20	9.00	14.77
Crude protein	17.03	17.06	12.76	10.25
Total lipid	4.92	4.73	7.73	1.18
Neutral detergent fiber (NDF)	29.04	28.97	40.74	60.38
Acid detergent fiber (ADF)	15.14	17.08	39.09	37.43
ADL	2.43	2.11	19.87	9.31
Ash	10.44	10.21	9.13	9.05
Total Carbohydrates	10.98	13.87	22.68	34.59
N-free extract	9.20	5.26	–	48.93
Gross Energy (MJ/kg)	10.55	10.67	8.00	11.25
Total phenolics (g of gallic acid equivalent/kg DM)	–	103.99	243.38	
Total tannins (g of gallic acid equivalent/kg DM)	–	61.20	143.04	–
Proanthocyanidins (g of cyaniding chloride equivalent/kg DM)	–	25.70	64.91	–

(Continued)

TABLE 1 Continued

	Dietary Treatment			
Ingredients (%)	Control	Grape pomace	Sun-dried grape pomace	Hay
Fatty acid profile (%FA methyl esters)				
C16:0 (Palmitic)	19.53	16.08	10.03	13.45
C18:0 (Stearic)	2.32	1.91	2.04	3.03
C18:1 n-9 (Oleic)	19.71	17.78	15.39	12.13
C18:2 n-6 (Linoleic)	52.46	59.17	72.14	31.00
C18:3 n-6 (γ-linolenic)	1.41	1.22	0.19	
C18:3 n-3 (α-linolenic)	4.94	2.73	0.22	0.01

Proanthocyanidin content was measured using the procedures of Porter et al. (1986) and results expressed as gram cyaniding chloride equivalent per 100 g DM. All results were averages of four replicates.

2.4 Performances and slaughtering data

In respect to the EU legislation (European Council, 2009), the animals were slaughtered after fasting for 12 h, with free access to water, into a local public slaughterhouse and weighed immediately before slaughtering (slaughter weight). Slaughtering data were collected as described by Giannico et al. (2024). The hot carcasses were visually evaluated for conformation and grade of subcutaneous fat development: the carcass conformation was classified according to the SEUROP system (European Council, 2017); the subcutaneous fat development was evaluated on a scale of 5 classes (Kruk and Ugnivenko, 2024). Carcasses were hung and chilled at 0–4°C (80–82% relative humidity) for 24 h and then re-weighed (ASPA, 1991). The refrigerated carcasses were split into two halves across the mid-line; the right side was divided into different cuts (round, shoulder clod, rib + loin, steaks, neck with bone, belly, brisket) and weighed separately (ASPA, 1996). From each carcass, the rib-eye between the 12th and 13th rib surface of the *Longissimus dorsi* muscle, was measured using a transfer and graph paper as described by Nusri-un et al. (2024) while, the back fat thickness was measured in correspondence of the 12th rib, using a digital caliber.

2.5 Physical parameters and MDA concentration of muscles

The 9–11th rib section of the *Longissimus lumborum* (Ll) muscle was excised from the right half carcass of each young bull in order to assess meat color and tenderness. Then, the Ll muscles were divided into three parts: the first one was analyzed upon arrival to the laboratory, i.e. 72 h post slaughtering (Day 3), while the other two were sealed in polyethylene bags, vacuum-packaged and aged in a dark refrigerated room (0–4°C) for 6 (Day 9) or 11 days (Day 14). At all the three ageing times, meat samples were assessed for pH, color, shear force on raw and cooked meat, cooking loss and lipid oxidation by malondialdehyde (MDA) concentration, while chemical and fatty acid composition were assessed on day 3.

Two pH measurements were assessed on the Ll muscle using a portable instrument (Eutech Instruments XS PH110, Singapore, Singapore) with a Hamilton Double Pored penetrating electrode.

The color features (L* = Lightness, a* = red index, b* = yellow index) were determined using a Hunter Lab MiniscanTM XE Spectrophotometer (Model 4500/L, 45/0 LAV, 3.20 cm diameter aperture, 10° standard observer, focusing at 25 mm, illuminant D65/10; Hunter Associates Laboratory Inc., Reston, VA, USA). Three readings were taken for each sample by placing the instrument on different meat areas. The instrument was normalized to a standard white tile before performing the analysis (Y=92.8, x=0.3162, and y=0.3322). The reflectance measurements were performed after the samples were allowed to oxygenate in the air for at least 30 min, to take stable measurements. Three samples (2.54 cm diameter) of each muscle were tested for tenderness by the Warner-Bratzler Shear (WBS) force system using an Instron 5544 testing machine; samples were assessed in triplicate and sheared perpendicularly to the muscle fiber direction (load cell 50 kg, shearing speed 200 mm/min). Peak force was expressed as kg/cm^2 (ASPA, 1996).

The lipid oxidation was evaluated through the measuring of 2-thiobarbituric acid reactive substances concentration (TBARs) and expressed as mg of Malondialdehyde (MDA)/kg meat (Scarpa et al., 2021).

2.6 Chemical composition and fatty acid profile of *Longissimus lumborum* muscle

Meat samples of the Ll muscle from each young bull were homogenized for the analysis of the chemical composition (AOAC, 2000).

Fat was extracted using a 2:1 chloroform/methanol (v/v) solution to determine the fatty acid profile (Folch et al., 1957). The fatty acids were methylated using a KOH/methanol 2N solution (Christie, 1982) and analyzed by gas chromatography (Shimadzu GC-17A) using a silicone-glass capillary column (70%

Cyanopropyl Polysilphenylene–siloxane BPX 70 by Thermo Scientific, length = 60 m, internal diameter = 0.25 mm, film thickness = 0.25 μm). The starting temperature was 135°C for 7 min, then it was increased by 4°C/min up to 210°C. Fatty acids were expressed as a percentage (wt/wt) of total methylated fatty acids.

The Conjugated Linoleic Acid (CLA) content in young bull's meat was assessed as previously described (Colonna et al., 2020).

The food risk factors of meat were determined by calculating the Atherogenic (AI) and Thrombogenic (TI) Indices (Ulbricht and Southgate, 1991):

$$AI = [(C12:0 + 4 \times C14:0 + C16:0)] \div [\Sigma MUFA + \Sigma n - 6 + \Sigma n - 3];$$

$$TI = [(C14:0 + C16:0 + C18:0)] \div [(0.5 \times \Sigma MUFA + 0.5 \times \Sigma n - 6 + 3 \times \Sigma n - 3 + \Sigma n - 3)/\Sigma n - 6];$$

where MUFA are monounsaturated fatty acids.

2.7 Economic efficiency

Benchmarking enables to compare the efficiency of different production scenarios and to determine the best course of action. To explain the economic advantage following the dietary use of GP for beef production in different genotypes, it is proposed to estimate the gross profit and the efficiency as the ratio of slaughtering weight income to the cost of feed, all other conditions and production factors being equal, which are assumed to be unchanged. We compared the income derived from slaughter weight for each genotype, the duration of the finishing period necessary to achieve the desired slaughter weight, and the overall cost of the feed needed to reach the animal marketable weight.

Gross Profit (GPRO) represents the difference between incomes and costs, while the efficiency (E) considers the relationship between the result obtained and the resources employed, allowing the actual performance to be measured. In a broader sense, efficiency (E) can be measured by the ratio of benefit (B) to cost (C). Efficiency (E) assumes that the benefit obtained from the economic activity is greater than the cost (B > C) and the value of the product is greater than the value of the resources sacrificed in production (Afriat, 1972; Hanoch and Rothschild, 1972). Therefore, the greater the benefit relative to the cost, the greater the efficiency. In the context of this study, both indexes are significant if viewed in a comparative sense concerning the margins and the performances of tested grape pomace feed within the same genotype concerning the control feed.

2.8 Statistical analysis

Data were analyzed using the SAS software 9.1 2004 (SAS, 2004).

The individual young bull was the experimental unit for analysis of all data. Data on animal performance and slaughtering data, chemical composition and fatty acid profile were subjected to ANOVA and analyze according to the following model:

$$Yijk = M + Ai + Bj + (AB)ij + Eijk$$

where:

M represents the overall mean,

Ai is the effect of genotype (i: 1 to 3),

Bj is the effect of diet (j: 1 to 2),

(AB)ij is the interaction between genotype and diet,

Eijk accounts for random error.

The differences among groups were determined using Tukey's test with $p< 0.05$ as the significance level, results are reported as least squares mean and standard error of the mean (SEM).

Meat physical parameters (pH, L*, a*, b*, raw and cooked WBS, cooking loss and MDA) were statistically analyzed using a mixed model for repeated measures. The fixed factors in the model were the genotype, the diet, the time of storage, and their interaction, with the animal as random factor. In Table 2, since the interactions D×G, G×T and D×T were not significant, the interaction D×G×T was not reported. When significant effects were found at $p< 0.05$, means were compared using Student's t test.

3 Results

3.1 Slaughtering and carcass traits of young bulls

Table 2 shows the growth performances and the slaughtering data of young bulls in relation to the diet and genotype. The initial weight was significantly greater in L×P young bulls as compared to the other two genotypes ($p< 0.01$), and also the interaction diet × genotype was significant ($p< 0.05$). The duration of the trial was not influenced by the diet, but it was significantly affected by the genotype ($p< 0.01$) along with the interaction D×G ($p< 0.05$); in particular, pure Podolian young bulls needed a longer period to reach the marketable slaughtering weight, with significant differences as compared to the M×P ($p< 0.05$) and to the L×P ($p< 0.01$) bulls. Despite the diet, the average daily gain was significantly lower for Podolian young bulls in comparison with crossbred Marchigiana ($p< 0.05$) and crossbred Limousine ($p< 0.01$); the interaction D×G was also significant ($p< 0.05$).

The feed intake was significantly affected by the diet ($p< 0.01$) and the genotype ($p< 0.01$), and the interaction of the two effects was also significant ($p< 0.01$). L×P and P young bulls showed a greater consumption of the feed containing grape pomace ($p< 0.01$). On average, the M×P bulls displayed the highest feed intake as compared to other two genotypes; when they were fed the control diet, feed consumption was significantly greater as compared to Podolian ($p< 0.05$) and L×P ($p< 0.01$) young bulls. The consumption of the GP feed was markedly lower in L×P young bulls as compared with the other two genotypes ($p< 0.05$).

The feed conversion rate was significantly affected by the diet ($p< 0.01$) and the genotype ($p< 0.01$), and the interaction of the two effects was also significant ($p< 0.01$). This parameter was significantly higher following the GP diet ($p< 0.01$) for all the genotypes; the Podolian

TABLE 2 Growth performances and slaughtering data of young bulls in relation to the diet (D) and genotype (G).

Diet	Control			Grape pomace			SEM ^{1}	Effects		
Genotype	L×P	M×P	P	L×P	M×P	P		D	G	D × G
Initial weight (kg)	395.50^{C}	360.00^{D}	340.00^{D}	394.00^{C}	361.00^{D}	337.00^{D}	20.951	n.s.	**	*
Duration of the trial (d)	141.00^{D}	218.00^{Cd}	267.00^{Cc}	148.00^{D}	229.00^{Cd}	272.00^{Cc}	6.542	n.s.	**	*
Slaughter weight (kg)	612.50	604.00	608.00	624.50	617.00	615.00	33.471	n.s.	n.s.	n.s.
Average daily gain (g/d)	1539.00^{C}	1119.30^{Dc}	1003.75^{Dd}	1557.43^{C}	1117.90^{Dc}	1022.06^{Dd}	97.656	n.s.	**	*
Feed Intake (kg/d)	8.48^{BD}	11.68^{Cc}	10.88^{Bd}	10.72^{Ad}	11.81^{c}	11.54^{Ac}	0.348	**	**	**
Feed conversion rate	8.65^{Bd}	9.08^{Bcd}	9.79^{Bc}	10.27^{Ad}	11.60^{Acd}	12.00^{Ac}	0.044	**	**	**
Hot carcass weight (kg)	380.55^{C}	357.19^{D}	359.66^{D}	397.71^{C}	361.20^{D}	366.70^{D}	1.254	n.s.	**	**
Cold carcass weight (kg)	371.85^{C}	349.78^{D}	352.40^{D}	388.13^{C}	353.05^{D}	358.91^{D}	1.313	n.s.	**	**
Drip loss (%)	2.29	2.08	2.02	2.41	2.26	2.12	0.040	n.s.	n.s.	n.s.
Hot dressing percentage (%)	62.13^{C}	59.14^{D}	59.15^{D}	63.69^{C}	58.54^{D}	59.63^{D}	1.247	n.s.	**	*
Cold dressing percentage (%)	60.71^{C}	57.91^{D}	57.96^{D}	62.15^{C}	57.22^{D}	58.36^{D}	1.372	n.s.	**	*
Carcass conformation grade	U	R	R	U	R	R	–	n.s.	n.s.	n.s.
Subcutaneous fat development	3	2+	2-	3	2+	2-	–	n.s.	n.s.	n.s.

[1] SEM, standard error of means. Differences between diets within each genotype: A, B, $p < 0.01$. Differences between genotypes within the diet: C, D, $p < 0.01$; C, d: $p < 0.05$. Significance of effects: n.s., not significant; **: $p < 0.01$; *: $p < 0.05$.

young bulls showed a markedly higher feed conversion rate as compared to crossbred Limousine (p< 0.05), regardless of the diet.

The hot and cold carcass weights, and the hot and cold dressing percentages, were unaffected by the diet and significantly higher in L×P bulls (p< 0.01); for these parameters, the interaction between the diet and genotype was also significant (p< 0.01).

Carcass conformation was unaffected by the diet in all the three genotypes; the carcasses from L×P young bulls were classified as U (very good), while M×P and Podolian were scored as R (good) according to the SEUROP system. The fat subcutaneous development of the L×P carcasses received a score of 3, whereas the M×P and Podolian were judged as 2+ and 2-, respectively.

The dissection data of the right-side carcass of young bulls are presented in Table 3. Podolian young bulls showed the lowest (p< 0.05) incidence of steaks compared to both crossbred genotypes, irrespective of the diet.

The fat thickness measured at the 12th rib fat and the rib-eye area were significantly lower in Podolian young bulls as compared to the crossbred Marchigiana and Limousine animals (p< 0.05), regardless of the diet administered. Despite the different growth rates, no particular difference was found for the proportion of the different commercial meat cuts, except for steaks, that was similar in L×P and M×P young bulls and both greater as compared to Podolian. Furthermore, the effect of genotype was observed also

TABLE 3 Dissection data (%) of the right half carcass of young bulls in relation to the diet (D) and genotype (G).

Diet	Control			Grape pomace			SEM ^{1}	Effects		
Genotype	L × P	M × P	P	L × P	M × P	P		D	G	D × G
Right-side weight (kg)	186.15^{c}	174.64^{d}	176.28^{d}	194.09^{c}	176.46^{d}	179.37^{d}	1.073	n.s.	*	*
Round	30.71	28.77	26.13	32.09	27.87	27.60	0.841	n.s.	n.s.	n.s.
Shoulder clod	11.92	11.21	10.05	11.64	11.28	11.07	0.067	n.s.	n.s.	n.s.
Rib + Loin	8.84	8.95	8.60	8.66	8.65	7.23	0.081	n.s.	n.s.	n.s.
Steaks	15.23^{c}	15.77^{c}	13.47^{d}	14.73^{c}	14.07^{c}	13.65^{d}	0.798	n.s.	*	n.s.
Neck with bone	7.82	7.65	8.55	7.93	7.44	7.04	0.063	n.s.	n.s.	n.s.
Belly	6.33	6.35	6.50	6.55	6.68	6.12	0.071	n.s.	n.s.	n.s.
Brisket	16.06	15.99	16.94	15.33	14.89	15.07	0.056	n.s.	n.s.	n.s.
12th rib fat thickness (cm)	5.6^{c}	4.9^{cd}	3.8^{d}	5.8^{c}	5.0^{cd}	4.1^{d}	0.015	n.s.	*	n.s.
Rib-eye area (cm^2)	54.68^{c}	51.82^{cd}	36.87^{d}	55.37^{c}	52.06^{cd}	38.34^{d}	1.241	n.s.	*	n.s.

[1] SEM, standard error of means. Differences between genotypes within the diet: c, d: $p < 0.05$. Significance of effects: n.s.: not significant; *: $p < 0.05$.

on the 12th rib fat thickness and on the rib-eye area, that were greatest for the L×P crossbred young bulls (Figure 1).

3.2 Physical parameters and MDA concentration of *Longissimus lumborum* muscle of young bulls

The physical characteristics and the MDA concentration of the Ll muscle of young bulls are reported in Table 4. No significant differences were observed for meat pH and b* color index. The grape pomace diet led to a significant (p< 0.05) increase of the L* value of meat in all genotypes; moreover, meat lightness decreased significantly (p< 0.05) from day 3 to 14 in all the groups, regardless of the diet or genotype. The a* index of meat was significantly (p< 0.05) affected only by the storage time that determined an increase of the value from day 3 to 14. Raw and cooked meat from Podolian young bulls showed a significantly (p< 0.05) greater shear force as compared to the other 2 genotypes. In all the groups, ageing for 14 days significantly (p< 0.05) improved raw and cooked meat tenderness. The cooking loss was not affected neither by the diet nor by the genotype and the storage time.

The MDA concentration of meat was significantly (p< 0.05) lowered by the dietary inclusion of grape pomace in all the

TABLE 4 Physical parameters and MDA concentration of *Longissimus lumborum* muscle of young bulls in relation to the diet (D), genotype (G) and storage time (T).

Diet	Day	Control			Grape pomace			SEM [1]	Effects					
Genotype		L × P	M × P	P	L × P	M × P	P		D	G	T	D × G	G x T	D x T
pH	1	6.49	6.48	6.33	6.49	6.59	6.58	0.404	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	9	5.85	5.78	6.03	5.92	5.87	5.79							
	14	5.45	5.39	5.71	5.56	5.39	5.46							
L*	3	28.59 ^{be}	28.70 ^{be}	29.95 ^{be}	32.42 ^{a}	32.31 ^{a}	33.65 ^{a}	2.467	*	n.s.	*	n.s.	n.s.	n.s.
	9	28.06 ^{bef}	28.21 ^{bef}	29.43 ^{bef}	32.04 ^{a}	31.94 ^{a}	33.27 ^{a}							
	14	27.64 ^{bf}	27.72 ^{bf}	29.01 ^{bf}	31.87 ^{a}	31.65 ^{a}	32.81 ^{a}							
a*	3	10.50 ^{f}	11.23	10.69 ^{f}	11.40	10.00	10.95 ^{f}	2.302	n.s.	n.s.	*	n.s.	n.s.	n.s.
	9	11.36 ^{ef}	11.86	11.07 ^{ef}	11.74	10.62	11.57 ^{ef}							
	14	11.98 ^{e}	12.13	11.98 ^{e}	12.34	11.03	12.07 ^{e}							
b*	3	8.10	8.45	7.39	8.35	7.20	7.77	1.146	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	9	8.19	8.67	7.74	8.61	7.58	8.13							
	14	8.41	8.88	8.01	8.97	7.94	8.47							
WBS raw	3	2.50 ^{d}	2.55 ^{d}	3.50 ^{ce}	2.60 ^{d}	2.62 ^{d}	3.05 ^{ce}	0.153	n.s.	*	*	n.s.	n.s.	n.s.
	9	2.22 ^{d}	2.18 ^{d}	3.04 ^{cef}	2.36 ^{d}	2.36 ^{d}	2.67 ^{cef}							
	14	1.98 ^{d}	1.87 ^{d}	2.79 ^{cf}	2.01 ^{cd}	1.89 ^{d}	2.13 ^{cf}							
WBS cooked	3	6.30 ^{de}	6.45 ^{de}	7.70 ^{c}	6.90 ^{d}	6.75 ^{d}	7.75 ^{c}	0.504	n.s.	*	*	n.s.	n.s.	n.s.
	9	5.89 ^{def}	5.97 ^{def}	7.32 ^{c}	6.41 ^{d}	6.01 ^{d}	7.24 ^{c}							
	14	4.74 ^{df}	4.81 ^{df}	6.84 ^{c}	5.97 ^{d}	5.84 ^{d}	6.91 ^{c}							
Cooking loss (%)	3	25.09	26.17	26.70	25.01	26.66	26.95	1.148	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	9	25.00	26.03	26.53	24.78	26.37	26.58							
	14	24.31	25.61	26.45	24.62	26.03	26.34							
MDA (mg/kg of meat)	3	0.14 ^{af}	0.13 ^{af}	0.12 ^{af}	0.09 ^{b}	0.08 ^{b}	0.07 ^{b}	0.203						
	9	0.23 ^{aef}	0.22 ^{aef}	0.22 ^{aef}	0.12 ^{b}	0.11 ^{b}	0.10 ^{b}	*	n.s.	*	n.s.	n.s.	n.s.	
	14	0.39 ^{ae}	0.38 ^{ae}	0.37 ^{ae}	0.19 ^{b}	0.18 ^{b}	0.17 ^{b}							

[1] SEM, standard error of means. L*, Lightness; a*, redness; b* yellowness; WBS, Warner–Bratzler shear force; MDA, malondialdehyde. Differences between diets within each genotype: a, b, $p < 0.05$; differences between genotypes within the diet: c, d: $p < 0.05$; differences between storage times: e, f: $p < 0.05$. Significance of effects: n.s., not significant; *: $p < 0.05$.

FIGURE 1
From left to right: 12th rib steak from Podolian, Podolian x Marchigiana and Podolian x Limousine young bulls.

genotypes. Ageing markedly ($p < 0.05$) increased the MDA content of meat, irrespective of the diet and genotype.

3.3 Chemical composition and fatty acids profile of *Longissimus lumborum* of young bulls

The chemical composition of meat from the Ll muscle was unaffected by the diet and by the genotype, as shown in Table 5.

Table 6 shows the fatty acid profile of the Ll muscle of young bulls in relation to the diet and the genotype. The diet containing grape pomace led to a significantly ($p < 0.05$) lower concentration of palmitic acid, total Saturated Fatty Acids (SFAs) and total Mono Unsaturated Fatty Acids (MUFAs). On the contrary, this diet increased the concentration of Linoleic acid ($p < 0.01$), total Poly Unsaturated Fatty Acids (PUFAs; $p < 0.01$), total n-6 ($p < 0.01$) and total CLA ($p < 0.05$) in meat from all the genotypes. The GP diet also determined a significant ($p < 0.01$) increase of the n-6/n-3 ratio.

3.4 Economic efficiency of young bulls

The results concerning the feeding costs necessary for the finishing period and the economic performances of the young bulls in relation to the genotype and diet are shown in Table 7. The account analysis conducted to compare the diets started from the definition of the costs of feeds administered and the selling price of the animal live weight. The unit costs are €4.00 per kg of live animal, €0.412 per kg of base feed and €0.035 per kg of grape pomace.

The feeding cost ranged from a minimum of €502.50 for the L×P group fed the control feed to a maximum of €1098.66 for Podolian bulls fed with the diet containing grape pomace. The variation was widely affected by the duration of the finishing period and by the total feed administered per day. The former parameter ranged from a minimum of 141 days for the L×P group fed the control feed to a maximum of 272 days for Podolian bulls fed the grape pomace diet. The latter parameter varied between 8.65 kg and 12 kg per day within the same group.

As for the economic performances, Gross Profit and Efficiency are presented in absolute terms for all the groups. GP varied for the

TABLE 5 Chemical composition of *Longissimus lumborum* muscle of young bulls in relation to the diet (D) and genotype (G).

Diet	Control			Grape pomace			SEM [1]	Effects		
Genotype	L × P	M × P	P	L × P	M × P	P		D	G	D × G
Moisture	72.28	72.67	71.35	72.04	71.10	70.05	0.977	n.s.	n.s.	n.s.
Protein	23.40	23.83	22.60	22.75	23.90	23.62	0.991	n.s.	n.s.	n.s.
Fat	2.86	2.21	3.23	3.79	3.06	3.50	1.386	n.s.	n.s.	n.s.
Ash	1.06	0.90	1.44	1.02	0.97	0.93	0.110	n.s.	n.s.	n.s.
N-free extract	0.40	0.39	1.38	0.40	0.97	1.90	0.530	n.s.	n.s.	n.s.

[1] SEM, standard error of means. Significance of effects: n.s., not significant.

TABLE 6 Fatty acids composition of *Longissimus lumborum* muscle of young bulls in relation to the diet (D) and genotype (G).

Diet	Control			Grape pomace			SEM [1]	Effects		
Genotype	L × P	M × P	P	L × P	M × P	P		D	G	D × G
C14:0 (Myristic)	5.75	5.20	5.70	4.55	4.40	4.65	0.329	n.s.	n.s.	n.s.
C15:0 (Pentadecylic)	0.65	0.70	0.70	0.65	0.55	0.60	0.062	n.s.	n.s.	n.s.
C16:0 (Palmitic)	29.65 ^{a}	28.95 ^{a}	28.45 ^{a}	25.95 ^{b}	26.00 ^{b}	26.00 ^{b}	0.707	*	n.s.	n.s.
C17:0	1.40	1.10	1.45	1.20	1.00	1.05	0.173	n.s.	n.s.	n.s.
C18:0 (Stearic)	15.50	15.95	15.1	16.95	16.05	15.75	1.054	n.s.	n.s.	n.s.
C20:0	0.30	0.30	0.40	0.30	0.35	0.25	0.062	n.s.	n.s.	n.s.
C22:0	0.55	0.60	0.50	0.40	0.50	0.55	0.041	n.s.	n.s.	n.s.
Total SFA[2]	53.80 ^{a}	52.80 ^{a}	52.30 ^{a}	50.00 ^{b}	48.85 ^{b}	48.85 ^{b}	0.496	*	n.s.	n.s.
C 14:1	1.00	1.15	1.35	1.07	1.43	1.35	0.187	n.s.	n.s.	n.s.
C 15:1	0.25	0.30	0.30	0.25	0.25	0.35	0.047	n.s.	n.s.	n.s.
C 16:1	4.40	4.30	4.40	4.05	4.05	4.25	0.855	n.s.	n.s.	n.s.
C 17:1	1.30	1.25	1.40	1.37	1.43	1.40	0.135	n.s.	n.s.	n.s.
C18:1 n-7 (cis-vaccenic acid)	1.45	1.40	1.75	1.35	1.65	1.60	0.211	n.s.	n.s.	n.s.
C18:l n-9 (Oleic)	25.3	26.41	26.95	25.55	25.8	25.6	1.202	n.s.	n.s.	n.s.
C20:l n-9 (Eicosanoic)	0.05	0.15	0.10	0.10	0.10	0.15	0.041	n.s.	n.s.	n.s.
C 22:1 n-9	0.25	0.05	0.10	0.15	0.10	0.20	0.078	n.s.	n.s.	n.s.
Total MUFA[3]	34.00 ^{a}	35.01 ^{a}	36.35 ^{a}	33.89 ^{b}	34.81 ^{b}	34.90 ^{b}	0.502	*	n.s.	n.s.
Total CLA	1.70 ^{b}	1.75 ^{b}	1.65 ^{b}	2.60 ^{a}	2.95 ^{a}	3.05 ^{a}	0.249	*	n.s.	n.s.
C18:2 n-6 (linoleic)	9.40 ^{B}	9.95 ^{B}	9.40 ^{B}	14.05 ^{A}	13.80 ^{A}	13.70 ^{A}	0.252	**	n.s.	*
C18:3 n-3 (α-linolenic)	0.45	0.39	0.48	0.51	0.65	0.48	0.041	n.s.	n.s.	n.s.
C18:3 n-6 (γ -linolenic)	0.15	0.15	0.15	0.10	0.10	0.10	0.041	n.s.	n.s.	n.s.
C20:2 n-6	0.25	0.20	0.30	0.3	0.25	0.35	0.041	n.s.	n.s.	n.s.
C 20:3n-6	0.35	0.20	0.15	0.15	0.20	0.35	0.183	n.s.	n.s.	n.s.
C20:4 n-6 ARA	0.20	0.25	0.10	0.20	0.10	0.25	0.033	n.s.	n.s.	n.s.
C22:5 n-3 (docosapentaenoic, DPA)	0.10	0.10	0.10	0.10	0.05	0.10	0.024	n.s.	n.s.	n.s.
Total PUFA[4]	11.60 ^{B}	11.79 ^{B}	11.33 ^{B}	15.91 ^{A}	16.00 ^{A}	16.18 ^{A}	0.365	**	n.s.	*
Total n-6[5]	10.15 ^{B}	10.50 ^{B}	10.00 ^{B}	14.60 ^{A}	14.35 ^{A}	14.50 ^{A}	0.271	**	n.s.	*
Total n-3[6]	0.75	0.74	0.68	0.81	0.80	0.83	0.033	n.s.	n.s.	n.s.
n-6/n-3	13.53 ^{B}	14.19 ^{B}	14.71 ^{B}	18.02 ^{A}	17.94 ^{A}	17.47 ^{A}	8.593	**	n.s.	*
AI (Atherogenic Index)	0.97	0.95	0.95	1.06	0.87	0.97	0.047	n.s.	n.s.	n.s.
TI (Thrombogenic Index)	1.87	1.81	1.75	2.24	1.83	1.70	0.042	n.s.	n.s.	n.s.

[1] SEM, standard error of means. Differences between diets within each genotype: A, B, $p < 0.01$; a, b: $p < 0.05$. Significance of effects: n.s., not significant; **: $p < 0.01$; *: $p < 0.05$.

control diet from a minimum of €1.355,06 for Podolian to a maximum of €1947.50 for L×P, while E for the grape pomace diet was maximum for L×P (€4.883) and minimum for Podolian (€2.239).

The GPRO variation rate showed varying effects of different diet among genotypes. For the M×P crossbred bulls, the GPRO variation rate was negative for animals fed with grape pomace, while it was positive for the other two genotypes, showing an improvement of 0.46% in Podolian young bulls and 2.00% in L×P bulls. Moreover, the grape pomace diet led to a negative efficiency index variation rate for P and M×P bulls (respectively -0.85% and -6.83%), whereas a positive value was recorded for the L×P genotype (0.14%).

TABLE 7 Feeding costs and economic performances.

Diet	Control			Grape pomace		
Genotype	L × P	M × P	P	L × P	M × P	P
Duration of the finishing period (days)	141	218	267	148	229	272
Feed Intake (kg/d/animal)	8.48	11.68	10.88	10.72	11.81	11.54
Total feed ingested (kg/animal)	1195.68	2546.24	2904.96	1586.56	2704.49	3138.88
Cost of the feed ingested (Cb) (€)	492.62	1049.05	1196.84	653.66	1114.25	1293.22
Grape pomace per day (kg/d/animal)	–	–	–	2.05	2.32	2.40
Total grape pomace (kg/animal)	–	–	–	303.99	531.28	652.80
Cost of grape pomace (Cp) (€)	–		–	10.64	18.59	22.85
Total feed cost (C = Cb+Cp) (€)	492.62	1049.05	1196.84	664.30	1132.84	1316.07
Slaughter weight (kg)	612.50	604.00	608.00	624.50	617.00	615.00
Income (B) (€)	2450.00	2416.00	2432.00	2498.00	2468.00	2460.00
Gross Profit (GPRO=B-C) (€)	1957.38	1366.95	1235.16	1833.70	1335.16	1143.93
Gross Profit variation rate (%)	–	–	–	2.00%	-1.66%	0.46%
Efficiency (E=B/C)	4.876	2.962	2.258	4.883	2.760	2.239
Efficiency variation rate on genotype basis (%)	–	–	–	0.14%	-6.83%	-0.85%

4 Discussion

The dietary inclusion of grape pomace led to a greater feed intake in all genotypes, probably due to a better palatability of the feed, as also found by Tayengwa et al. (2020) in steers fed a diet containing 15% dried grape pomace. However, despite the greater feed intake, the grape pomace diet worsened the feed conversion rate. This result is in contrast with previous studies conducted in lambs (Zhao et al., 2018) in which supplementation with 10% grape pomace was tested. Therefore, it may be hypothesized that a 20% inclusion, as carried out in our study, may have been high, thus reducing feed efficiency.

Previous research reported that crossbreeding has a significant role in enhancing the growth performance of cattle (Thirawong et al., 2025). In this study, the growth performances and slaughtering traits were greatly affected by the genotype. Podolian young bulls showed a lower growth rate as compared to both crossbreed genotypes and needed a longer period to reach the desired marketable slaughter weight. This result is in general agreement with the findings reported by Braghieri et al. (2005), who found higher live pre-slaughter and carcass weights in L×P bulls as compared to pure Podolian. The breed may affect the maturity level of animals that has a substantial impact on the adult size and conformation of the carcass (Thirawong et al., 2025). The effects of breed and animal performances, slaughter and carcass characteristics have been extensively described by other authors (Cuvelier et al., 2006). A study carried out on different cattle breeds by Nusri-un et al. (2024) showed that Holstein Friesian crossbreeds (93.19% Holstein Friesian × 6.81% native Thai) require more feed and energy intake than Charolais crossbreeds (75% Charolais × 25% native Thai) providing a lower carcass yield. In this study, we found a better carcass conformation and subcutaneous fat development in MxP and especially in L×P young bulls as compared to pure Podolian subjects, thus confirming that crossbreeding may capture carcass premium in the beef supply chain, especially from a carcass and meat quality perspective. Complex mechanisms may affect the interaction between genetic factors and extra genetic ones, among which feeding. Previous researches investigated the interaction between genotype and environment on feed efficiency traits in cattle populations, especially in herds raised in countries with large variations in soil, climate, or other sources of heterogeneity in production environments. In such conditions, it has been reported that the nutrition level and quality may restrict the expression of the full genetic potential of an animal, and this is even more pronounced in extensive production systems or in environmental or feeding systems that may create suboptimal conditions for the animals (Silva Neto et al., 2024). Thus, it is crucial to study how the production system and the diet may enable the animals to express their full genetic potential.

The area and depth of the loin eye are important quality traits since they are related with beef technological properties. It has been reported that the rib-eye area and carcass weight are strongly associated between each other and that they are important indicators in grading beef carcasses (Uddin et al., 2019). Steaks from L×P bulls showed a greater rib-eye area along with a better visual appearance of the marbling grade; these two quality traits are important factors able to orient consumers' preferences, because they are related to the eating quality of beef. In fact, in this study, steaks from the two crossbreed genotypes showed a lower WBS value as compared to those obtained from Podolian young bulls. Other authors reported that high marbling scores are related to more tender, juicy and flavorful meats in contrast to cuts with low levels of marbling (Uddin et al., 2019).

In this study, the dietary inclusion of grape pomace affected meat brightness (L*), that decreased during storage, while it showed no effect on the other meat color attributes (a* and b*). This result is similar to previous findings obtained following the inclusion of pomace residue from grapes in sheep (Chikwanha et al., 2019; Bennato et al., 2023) and cattle (Ianni et al., 2019) and grape seed in sheep (Jerónimo et al., 2012). The a* index showed an increase over the days of storage. Lipid oxidation and myoglobin degradation are known to be closely linked, thus the oxidation products, such as aldehydes, could actively promote meat color degradation (Luciano et al., 2009). The antioxidant effect exerted by dietary grape pomace is confirmed also in our study, since feeding grape pomace lowered the MDA concentration in meat in all genotypes. The inclusion of grape residue in the bulls' diet influenced the fatty acid profile of meat, regardless of the genotype. In particular, the grape pomace diet lowered the concentration of palmitic acid and total SFA in turn of an increase of linoleic acid and total PUFAs, with benefits for human health (Arend et al., 2022). Also Molosse et al. (2024) found a lower concentration of total SFA in the meat from steers fed with a diet containing grape pomace silage at 10%. The authors hypothesized that the large amounts of polyphenols in the grape residue may reduce ruminal lipolysis and impair PUFA biohydrogenation, protecting unsaturated fatty acids from microbes or their enzymes (Vasta et al., 2019; Vahmani et al., 2020). Arend et al. (2022) reported an increase of the PUFA content in meat from steers fed a diet containing 58% grape pomace, in terms of the concentration of linoleic and rumenic acid, and total conjugated linoleic acids (CLAs). However, these authors stated that a high amount of GP could limit growth performance in cattle, even if an enhancement of the sensory quality and FA profile of meat increased consumer acceptability.

The economic performance, measured by Gross Profit (GPRO) and Efficiency Index (E), highlighted remarkable differences across genotypes and diets. Several studies used the Gross Profit (GPRO), the benefit-cost ratio, and the efficiency (E) to analyze the economic performances of different parameters regarding feeding, genotype and farming systems (Hofstetter et al., 2014; Tozer et al., 2024; Trapina et al., 2024). The results of the present study showed that crossbred animals displayed better growth rates and feed conversion efficiency compared to pure Podolian bulls. The crossbred bulls overall presented better productive performances, proving to be able to use efficiently by-products like grape pomace as a cost-effective nutrient source without compromising animal growth or carcass quality (Kenny et al., 2018). Chacko Kaitholil et al. (2024) reported that feed efficiency is greatly affected by genotype and environmental factors, including the composition of the diet. Indeed, selecting animals with higher feed efficiency can lead to lower feed costs and improved production outcomes without compromising animal performance. The composition of the diet is also pivotal; diets that optimize nutrient absorption can enhance feed efficiency and contribute to better growth rates and meat quality (Terry et al., 2021). Furthermore, to enhance management and feeding strategies for crossbred Podolian bulls, precision livestock farming (PLF) techniques can be implemented. The PLF approach aligns with the need for tailored feeding strategies that consider the unique requirements of crossbred Podolian bulls (Karatosidi et al., 2023), as well as contributing in improving productivity by supporting sustainable and economically viable farming practices (Morrone et al., 2022).

In conclusion, the identification of an optimal management approach, given by the interaction between the choice of the animal breed and the diet, leads to the best ratio between carcass and meat quality traits, including tenderness, desirable fatty acid composition and shelf-life. The use of a by-product such as grape pomace is worth of further investigation since it didn't affect meat production and quality, while reducing feeding costs of beef farming and improving the environmental sustainability of the wine making industry. In terms of profitability, crossbreeding between the Podolian and Limousine breeds provided the best results as for meat yield and quality.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author/s.

Ethics statement

Ethical approval was not required for the studies involving animals in accordance with the local legislation and institutional requirements because Experimental animals were handled according to the European government guide-lines (Directive 2010/63/EU) in respect of their welfare. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

FG: Writing – original draft, Writing – review & editing. AP: Writing – original draft, Writing – review & editing. FB: Writing – original draft, Writing – review & editing. DK: Writing – original draft, Writing – review & editing. MS: Writing – original draft, Writing – review & editing. CC: Writing – original draft, Writing – review & editing. ST: Writing – original draft, Writing – review &

editing. MR: Writing – original draft, Writing – review & editing. MC: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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