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NATHALIA DA SILVA RODRIGUES MENDES

**EVALUATION AND PREDICTION OF INDICATORS OF
BEEF SENSORY QUALITY IN BRAZIL AND FRANCE**

**Avaliação e predição de indicadores de qualidade sensorial de
carne bovina no Brasil e na França**

GOIÂNIA

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Abstract

Brazil and France hold significant positions in the global beef market, despite having different production systems. In compliance with national regulations and international quality standards, both countries aim to ensure the sensory quality of their beef. Australia, another major beef producer and exporter, accomplished this by developing and implementing the Meat Standards Australia (MSA) system. This system, based on critical control points, takes into account various factors such as animal gender, marbling, fat thickness on the carcass, cooking method, and aging time. These data are combined with consumer tests to predict tenderness, flavor, juiciness, and overall satisfaction. The MSA model, using this information, has proven effective not only in Australia but for other production systems around the world as well. The adoption of similar methodologies, such as the Global Guaranteed Grading (3G) system, could enable Brazil to predict and even improve the sensory quality of the beef it produces, especially that from Zebu cattle. Drawing inspiration from Australian and European practices, such as the 3G system recommended by the United Nations Economic Commission for Europe, could provide useful perspectives for Brazil's beef industry. Accordingly, the primary objective of this thesis was to evaluate innovative solutions for predicting beef sensory quality in Brazil and France. The first part (review study) analyzes the development of beef production chains in both countries, and explores the feasibility of implementing MSA protocols in Brazil. The adoption of the MSA by Brazil would ensure or even enhance the taste quality of beef, while creating new opportunities for adding value to traditional products. Non-destructive methods to predict beef taste quality in both countries were also analyzed. The second part presents original research on the potential effects of stress during the transport of cattle from farm to slaughterhouse. In Brazil, 30,230 carcasses of Nellore cattle were studied, and although correlations were observed between carcass weight and ultimate pH (pHu), transport distance had no significant effect on pHu, suggesting low stress during transport. In France, a study on 4,407 Limousin cow carcasses showed that neither the distance traveled, nor the duration of transport affected pHu. The MSA index was also minimally affected by animal transport. The third part examines the use of innovative technologies to measure marbling. In France, the portable Q-FOM™ Beef camera was used to predict MSA/3G marbling scores. The results show that the camera's predictions correspond well with assessments by certified graders, with satisfactory correlation coefficients. Visual carcass grading, both at the slaughterhouse and from on-screen images, also met accreditation criteria. These non-invasive technologies show promise for evaluating marbling in the beef sector in both France and Brazil. In conclusion, this thesis highlights the importance of adapting proven international methodologies, such as the MSA, to enhance the competitiveness of Brazilian beef and better meet consumer expectations. The studies conducted confirm the importance of certain factors on meat quality (such as marbling). Additionally, non-invasive technologies offer opportunities to improve the reliability of the prediction of beef sensory quality, both in France and Brazil.

Keywords: beef carcass traits, animal stress, eating quality, MSA

Resumo

O Brasil e a França ocupam posições significativas no mercado global de carne bovina, apesar de possuírem sistemas de produção distintos. Em conformidade com regulamentações nacionais e padrões internacionais de qualidade, ambos os países buscam garantir a qualidade sensorial da carne bovina. A Austrália, outro grande produtor e exportador de carne bovina, alcançou esse objetivo por meio do desenvolvimento e implementação do sistema Meat Standards Australia (MSA). Esse sistema, baseado em pontos críticos de controle, considera diversos fatores, como sexo do animal, marmoreio, espessura da gordura na carcaça, método de cocção e tempo de maturação. Esses dados são combinados com testes de consumidores para prever maciez, sabor, suculência e satisfação geral. O modelo MSA, utilizando essas informações, demonstrou eficácia não apenas na Austrália, mas também em outros sistemas de produção ao redor do mundo. A adoção de metodologias semelhantes, como o sistema Global Guaranteed Grading (3G), poderia permitir ao Brasil prever e até melhorar a qualidade sensorial da carne bovina que produz, especialmente a proveniente do gado Zebu. Inspirar-se nas práticas australianas e europeias, como o sistema 3G recomendado pela Comissão Econômica das Nações Unidas para a Europa, poderia oferecer perspectivas úteis para a indústria brasileira de carne bovina. Nesse contexto, o principal objetivo desta tese foi avaliar soluções inovadoras para a previsão da qualidade sensorial da carne bovina no Brasil e na França. A primeira parte (estudo de revisão) analisa o desenvolvimento das cadeias de produção de carne bovina em ambos os países e explora a viabilidade da implementação dos protocolos do MSA no Brasil. A adoção do MSA pelo Brasil garantiria ou até aprimoraria a qualidade sensorial da carne, ao mesmo tempo em que criaria novas oportunidades para agregar valor a produtos tradicionais. Também foram analisados métodos não destrutivos para prever a qualidade sensorial da carne bovina nos dois países. A segunda parte apresenta pesquisas originais sobre os possíveis efeitos do estresse durante o transporte do gado da fazenda ao frigorífico. No Brasil, foram estudadas 30.230 carcaças de bovinos Nelore e, embora tenham sido observadas correlações entre o peso da carcaça e o pH final (pHu), a distância do transporte não teve efeito significativo sobre o pHu, sugerindo baixo estresse durante o transporte. Na França, um estudo com 4.407 carcaças de vacas Limousin mostrou que nem a distância percorrida nem a duração do transporte afetaram o pHu. O índice MSA também foi minimamente influenciado pelo transporte dos animais. A terceira parte examina o uso de tecnologias inovadoras para medir o marmoreio. Na França, a câmera portátil Q-FOM™ Beef foi utilizada para prever as pontuações de marmoreio do MSA/3G. Os resultados mostram que as previsões da câmera correspondem bem às avaliações realizadas por certificadores treinados, com coeficientes de correlação satisfatórios. A classificação visual das carcaças, tanto no frigorífico quanto por meio de imagens digitais, também atendeu aos critérios de acreditação. Essas tecnologias não invasivas mostram-se promissoras para a avaliação do marmoreio no setor de carne bovina tanto na França quanto no Brasil. Concluindo, esta tese destaca a importância da adaptação de metodologias internacionais comprovadas, como o MSA, para aumentar a competitividade da carne bovina brasileira e atender melhor às expectativas dos consumidores. Os estudos realizados confirmam a relevância de determinados fatores na qualidade da carne (como o marmoreio). Além disso, as tecnologias não invasivas oferecem oportunidades para aprimorar a confiabilidade da previsão da qualidade sensorial da carne bovina, tanto na França quanto no Brasil.

Palavras-chave: Características da carcaça bovina, estresse animal, qualidade sensorial, MSA

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Neveu A., Pethick D.W., Rombouts T., Nisbet H., Meister M., Marimuthu J., Wang G., Normand J., Anderson F., Corlett, M., Chizzotti M.L., Kombolo-Ngah M., Drachmann F.F, Mata K., Font-i-Furnols M., **Silva Rodrigues Mendes N.**, Cuthbertson H., Hocquette J-F (2023). Classement

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Abbreviations

ABIEC - Associação Brasileira das Indústrias Exportadoras de Carne - Brazilian Association of Meat Exporting Industries

ABCAS - Australian Beef Chiller Assessment System

BBQ - Brazil Beef Quality system startup

CCPs - Critical Control Points

CEPEA - Centro de Estudos Avançados em Economia Aplicada - Center for Advanced Studies on Applied Economics

EUROP - European carcass classification system

Embrapa - Empresa Brasileira de Pesquisa Pecuária - Brazilian Agricultural Research

Corporation INTAQT - Tools for Assessment and Authentication of chicken and beef meat, and dairy products Qualities

MSA - Meat Standards Australia

MAPA - Ministério da Agricultura Pecuária e Abastecimento - Ministry of Agriculture, Livestock and Supply

MLA - Meat and Livestock Australia 3G- Guaranteed Global Grading

PDO - Protected Designation of Origin

PGI - Protected Geographical Indication

TSG - Traditional Specialty Guaranteed

SIF- Federal Inspection Service

SISBOV - Brazilian System for the Identification and Certification of Bovine and Bubaline Origin

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CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 Recent Technological Developments and Future Trends in the Evaluation and Prediction of Beef Sensory Quality in Brazil and France.

This section is the article that was published in *Livestock Science*.

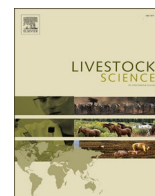
Mendes, N. S. R., Briceno, J. C. C., Mársico, E. T., Ellies-Oury, M. P., Chriki, S., Hocquette, J. F., e Oliveira, T. F. (2024). Recent Technological Developments and Future Trends in the Evaluation and Prediction of Beef Sensory Quality in Brazil and France. *Livestock Science*, 105550. <https://doi.org/10.1016/j.livsci.2024.105550>

1.2 Objectives

In order to meet consumer demand for high quality beef, the accuracy of predictions of the sensory qualities of beef must be improved, and equally important these improvements will need to be implemented in industrial settings, as well as to increase efficiency of production and resource utilization. Consequently, the primary objective of this thesis was to evaluate and predict the feasibility of technological solutions to predict the sensory quality of beef in Brazil and France.

To this end, the experimental work of this thesis has been divided into 2 main parts:

- A study of the effects of potential stress during the transport of cattle from the farm to the slaughterhouse, with a particular focus on the ultimate pH of carcasses in Brazil and France, using private data from commercial slaughterhouses (Chapter 2).
- An assessment of the feasibility of using new technologies in both France and Brazil to assess marbling involving the comparison of marbling assessment by MSA/3G-certified graders with those performed using portable devices (Chapter 3).



Recent technological developments and future trends in the evaluation and prediction of beef sensory quality in Brazil and France

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HIGHLIGHTS

- Brazilian & French production chains require ongoing improvement to stay competitive.
- Implementation of MSA in Brazil would enable reliable predictions of beef quality.
- Such an implementation would be similar to what has already been done in France.
- Cutting edge non-destructive technologies can make such an implementation possible.
- Successful implementations of these would benefit both industry and consumers.

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ABSTRACT

Brazil and France, which are two major beef players, continue to consolidate and strengthen their respective positions on international beef markets. This review summarizes Brazil's and France's recent technological developments in this sector, tracing the recent evolution of their beef markets with attention to indicators of quality, meeting consumer expectations, as well as to future trends in new techniques for predicting beef sensory quality. In addition, this review will focus on the feasibility of implementing the Meat Standards Australia (MSA) grading protocols (known internationally as the Guaranteed Global Grading (3G protocols) by the International Meat Research 3G Foundation. Implementations of the MSA/3G grading scheme as recommended by the United Nations Economic Commission for Europe (UNECE) are particularly attractive because of MSA's proven record of increasing the reliability and accuracy of predictions of the sensory quality of beef through the use of pre- and post-slaughter factors. Additionally, the feasibility of new technologies for assessing the eating quality of beef has been evaluated by comparing the marbling scores of beef given by accredited graders for the MSA/3G method with those obtained using portable devices based on these new technologies. In this way, it is expected that implementation of the MSA/3G methodology and nondestructive techniques to evaluate the quality and safety of

Abbreviations: ABIEC, Associação Brasileira das Indústrias Exportadoras de Carne - Brazilian Association of Meat Exporting Industries; ABCAS, Australian Beef Chiller Assessment System; BBQ, Brazil Beef Quality system startup; CCPs, Critical Control Points; CEPEA, Centro de Estudos Avançados em Economia Aplicada - Center for Advanced Studies on Applied Economics; EUROP, European carcass classification system; Embrapa, Empresa Brasileira de Pesquisa Pecuária - Brazilian Agricultural Research Corporation; INTAQT, Tools for Assessment and Authentication of chicken and beef meat, and dairy products Qualities; MSA, Meat Standards Australia; MAPA, Ministério da Agricultura Pecuária e Abastecimento - Ministry of Agriculture, Livestock and Supply; MLA, Meat and Livestock Australia; 3G, Guaranteed Global Grading; PDO, Protected Designation of Origin; PGI, Protected Geographical Indication; TSG, Traditional Specialty Guaranteed; SIF, Federal Inspection Service; SISBOV, Brazilian System for the Identification and Certification of Bovine and Bubaline Origin.

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beef in Brazil and France will more reliably predict and further improve sensory quality, similar to what has already been implemented elsewhere.

1. Introduction

Brazil and France each have a significant share of the global meat market. According to the Brazilian Association of Meat Exporting Industries (ABIEC), Brazil's beef exports reached a historic milestone in 2023 with the sale of 2.40 million tons to over 150 countries. In 2022, France produced 1.36 million metric tons of beef, making it the leading beef producer in the European Union, as well as among countries with the largest number of cattle in the EU (EUROSTAT, 2022). France and Brazil operate in the global beef market, and both export to various markets although their production systems are considerably different. Both countries adhere to national regulations as well as international market trends and require quality standards. Another major exporter of beef (Australia) has developed efforts to improve the consistency of eating quality of its beef in order to more reliably meet consumer expectations of the beef products available for purchase. This ultimate goal is now shared by other major beef exporters such as France and Brazil. In the case of Brazil, predicting and improving the sensory quality of beef from various breeds should include zebu (*Bos taurus indicus*) breeds, such as Nellore. The increasing demand for high-quality beef puts pressure on farmers and necessitates optimized production systems and breeding programs, which, in turn, requires reliable methods and protocols to consistently predict beef quality. Currently, more than 90 % of beef cattle in Brazil are purebred Nellore or Nellore hybrids (Embrapa, 2023; ABIEC, 2023; Mendes et al., 2022) because of their high productivity, heat tolerance and disease resistance (Mendes et al., 2024). However, zebu beef is typically less tender with less marbling than that of taurine cattle (*Bos taurus*), especially when compared to beef from continental breeds which are very lean (such as the French breeds Limousin, Charolais), or even British breeds such as Angus which are fatter, and other breeds (Andrade et al., 2020; Seideman et al., 1982). Currently, taurine beef has overall superior beef eating quality, but the Brazilian beef industry has initiated genetics-based breeding programs to overcome this difference (Barro et al., 2023; Bonin et al., 2021; Fonseca et al., 2020; Malheiros et al., 2020; Marestone et al., 2022; Santiago et al., 2023).

Research conducted in several countries by the International Meat Research 3G Foundation has demonstrated that in all countries studied (Australia, New Zealand, Japan, South Korea, South Africa, the USA, Poland, France, Ireland, UK), expectations of beef eating quality are similar with only slight differences (Bonny et al., 2017, 2018a). More recent studies are consistent with earlier studies (Hocquette et al., 2023; Liu et al., 2023a; Purslow and Zhang, 2022). For instance, a study conducted in Brazil found that Brazilian consumers, as well as European consumers, demand affordable meat products that are high in organoleptic, sanitary, and nutritional quality, and are ethically produced (Hötzel, and Vandresen, 2022)

As a first attempt to meet the challenge of quality, the Meat Standards Australia (MSA) grading system was developed in 1996 to assess beef palatability under commercial conditions (Watson et al., 2008; MLA and MSA, 2001). This beef quality assurance protocol was based on all Critical Control Points (CCPs) from breeding, considerations of animal welfare, production, pre-slaughter factors, slaughter conditions, and post-slaughter processing to value-added aspects affecting beef quality. These CCP include animal sex, ossification score, carcass hanging method, marbling, fat depth, cooking method, aging time and so on. These measurements were then completed by extensive consumer testing for the determination of scores for tenderness, flavor liking, juiciness and overall liking (Bonny et al., 2018b). Protocols based on MSA have proven effective in predicting beef quality not only in Australia, but also in a variety of production systems and countries

(reviewed by Hocquette et al., 2020).

Study of the adoption and adaptations of the MSA system in these other countries can provide valuable lessons and potential solutions for the Brazilian beef industry (Mendes et al., 2022). The beef industry is encouraged to understand and implement successful practices from Australia and from what has already been developed in Europe, especially in France (Bonny et al., 2018a; Liu et al., 2021; Liu et al., 2023b) through the 3G (Guaranteed Global Grading) scheme that uses the same critical control points and the same methodology and which is recommended by the United Nations Economic Commission for Europe (UNECE). This can also offer insight into addressing challenges related to differences in breed characteristics, farming systems, and post-slaughter processes which may not exist in Australia and may be specific of other countries. As Brazil continues to strive for excellence in its beef production (ABIEC, 2023), careful evaluation of international standards and methodologies can significantly contribute to strategies to meet the growing demands of consumers as well as enhance the overall competitiveness of Brazilian beef in the global market.

The first part of this review is an analysis of the development of the Brazilian and French beef production chains in order to identify challenges and prospects for the Brazilian and French beef sectors. It opens with a discussion of the importance of these countries in the international beef market, while drawing parallels between the production and carcass classification systems; the export markets between Brazil and France; as well as beef consumer expectations.

The second part focuses on the feasibility of implementing MSA protocols in Brazil similarly to what has been developed in France (Ellies-Oury et al., 2020; Liu et al., 2021; Hocquette et al., 2020) by the International Meat Research 3G Foundation under the auspices of UNECE. It is reasonable to expect that the implementation of an MSA-derived methodology will improve beef eating quality, in addition to opportunities for adding value to traditional products for processors and producers based on organoleptic quality potential (Legrand et al., 2013). This review will also assess the feasibility of solutions using non-destructive technologies in Brazil and France to predict beef eating quality. The official Brazilian and French seals and other indicators of quality that guide consumers in their beef purchasing decisions will be described in the fourth part.

2. Beef production in Brazil and France

2.1. Beef production and export

Brazil and France play crucial roles in global meat production (Mendes et al., 2022). However, both countries exhibit distinct differences in their production systems and target markets, including the types of breeds produced, production volume, and production methods (Table 1). While Brazil has focused on technological advancements to increase output and meet export demands, France continues to emphasize product quality and production sustainability (animal welfare, environmental concerns) operating within stringent European Union regulations.

These differences in strategy and context show the diversity found in the global beef market. The "OECD-FAO Agricultural Outlook 2020–2029" report projects that Brazil, along with China, the European Union, and the United States, will collectively produce about 60 % of the world's meat by 2029 (OECD and FAO, 2020). Brazil has made significant technological advancements in its beef production, such as innovations in grazing management, health management, and genetics in order to improve the quality and competitiveness of its beef products on the international market (ABIEC, 2023; Bonin et al., 2021; Fonseca et al.,

Table 1
Comparison of beef production: Brazil and France in 2022.

Aspect	Brazil	France	References
Total Beef Production including meat from calves (2022)	Approximately 10.79 million tons	Approximately 1.48 million tons	(Brazilian Beef Exporters Association (ABIEC) 2023); (MAPA, 2023); (FranceAgriMer, 2022); (EUROSTAT 2022)
Top Beef-Producing Region	Mato Grosso (15.8 %) and São Paulo (11.5 %)	Nouvelle-Aquitaine, Auvergne-Rhône-Alpes, Bourgogne Franche-Comté, Pays de la Loire and Occitanie (69 %)	(MAPA, 2023); FranceAgriMer (2022); (Brazilian Beef Exporters Association (ABIEC) 2023)
Primary Cattle Beef Breed	Nellore (90 %), Angus, and Brahman	Mainly Charolais, Limousin, but also Blonde d'Aquitaine and dairy cattle	(United States Department of Agriculture (USDA) 2021); (Idele, 2023)
Type of Animal	Steer, cow, young bull, heifer	Young bull, steer, heifer, cow	(Brazilian Beef Exporters Association (ABIEC) 2023); EU (2022)
Cattle Ranching System	Predominantly extensive grazing (95 %)	Diverse systems including extensive grazing ones	(Embrapa 2023); (Interbev and Idele, 2023)
Domestic market (CWE - carcass weight equivalent)	7.78 million tons CWE (72.4 %)	1.16 million tons CWE (78.4 %)	(Brazilian Beef Exporters Association (ABIEC) 2023); FAO (2022)
Exports (CWE - carcass weight equivalent)	Major exporter with 3.02 million tons CWE (27.96 %)	Exports around 249 thousand tons CWE	(Brazilian Beef Exporters Association (ABIEC) 2023); (Idele 2023)
Major Export Markets	China (54.7 %), United States (5.9 %), Egypt (4.3 %), Hong Kong (4.2 %) and European Union countries (3.8 %)	Italy (22.7 %), Netherlands (18.9 %), Germany (16.3 %), Greece (13.5 %) and Belgium (9.6 %)	(Brazilian Beef Exporters Association (ABIEC) 2023); (Idele, 2023)
Beef Consumption per Capita (2022)	Approximately 36.7 kg per capita consumption (meat inspected by the federal (SIF), state (SIE) and municipal systems (SIM): 23.5 kg/year	Approximately 23.2 kg per capita	(Brazilian Beef Exporters Association (ABIEC) 2023); FAO (2022)

2020; Santiago et al., 2023; Scapol et al., 2023; Silva et al., 2019a, 2019b). In 2022, Brazil slaughtered 42.31 million head of cattle, with the states of Mato Grosso, Mato Grosso do Sul, and São Paulo each making a significant contribution. The Nellore breed dominates commercial beef herds in Brazil, making up over 90 % of commercial beef herds. Among the reasons for its predominance are its resilience and suitability for Brazil's traditional pasture-based beef production systems (ABIEC, 2023; Mendes et al., 2024).

Total Brazilian beef production amounted to 10.79 million CWE (Carcass Weight Equivalent) with a domestic consumption of 7.78 million CWE. Exports amounted to 3.02 million CWE, or 28.0 % of total production, processed beef to 267.10 thousand CWE or 8.8 % of total production, and edible offal to 164.50 thousand CWE, or 5.5 % of total production. Of total fresh (in natura) exports, China accounts for 62.4 %,

the US 4.5 %, Egypt 4.3 %, Chile 4.0 %, with 120 other countries accounting for 24.8 %. Exports of processed beef products to 116 countries were to the United States with 40.9 %, the United Kingdom 18.1 %, the European Union 12.5 %, Canada 2.4 %, with other countries accounting for the remaining 26.1 %. Edible offal exports were made to 109 countries of these Hong Kong received 35.1 %, Ivory Coast 7.7 %, the EU 7.3 %, Russia 7.2 % with other countries receiving 42.7 % (ABIEC, 2023).

Adoption of intensive and semi-intensive production systems has increased in recent years because of increasing demand for protein, coupled with a decline in available pasture land in Brazil. Brazil has continued to increase its beef exports, especially to China, making it one of China's major trading partners (Mendes et al., 2022). Brazil's livestock sector increased in relative importance to the country's GDP (Gross domestic product), despite a 4.1 % decrease in GDP in 2020, further highlighting its significance to the Brazilian economy (CEPEA, 2021).

On the other hand, France, as a member of the European Union, has stringent regulations governing animal welfare, sanitary production, transportation, and processing in particular for its beef industry. Research and development, as well as extension services, are available to enhance productivity and quality in beef production, with a focus on animal welfare and environmental sustainability (Soler and Thomas, 2020). In 2022, beef production in France amounted to 1.2 million tons CWE (excluding meat from calves) (Interbev and Idele, 2023). France imports and exports beef, with total exports of approximately 249,000 tons of carcass weight equivalent in 2022, mainly to Italy, Germany, Greece, Netherlands and Belgium (Idele, 2023). The French cattle industry includes about 134,000 farms with at least 5 cows, totaling 17.3 million cattle (Interbev and Idele, 2023).

2.2. Current cattle classification system

The Brazilian system, established in 1989 and subsequently modified in 2004, employs a multifaceted approach that considers gender, age, carcass conformation, fatness, and hot carcass weight. In 2004, carcass conformation and hot carcass weight were removed from this system (Brasil, 2005), leaving only the parameters of gender, age and lean maturity.

The first beef carcass grading system used in Brazil (Brasil, 1989) was based on the following 5 parameters: 1) gender (M- male, C- castrated male and F- female); 2) maturity was determined by dentition: milk teeth (up to 20 months) two teeth, (21 - 24 months) four teeth (25 - 30 months), six teeth (31 - 41 months), and eight teeth (42 months for above); 3) fatness, which was scored visually using a 9-point scale with scores from 1 to 9 (1 - absent fat; 2,3,4, - scarce 5,6,7 medium, 8 uniform, and 9 - excessive fat; and 4) hot carcass weight; 5) carcass conformation (visual assessment of muscle mass). The degree of muscularity of carcasses (conformation) was evaluated by trained assessors after sawing carcasses in half in accordance with the Brazilian System of Carcass Classification. Carcasses were graded in increasing order of muscularity: Convex (C), Sub-convex (Sc), Rectilinear (R), Sub-rectilinear (Sr), or concave (Co) (BRASIL, 1989). A Convex carcass has a more rounded posterior and greater muscularity on top, and is considered to have the best conformation. A Sub-convex carcass tends to present a more rounded/concave portion in the posterior region, but less prominently than the Convex. The Rectilinear conformation is very visible in the posterior region, and is the median grade of carcass muscularity. The Sub-Rectilinear conformation is between Rectilinear and Concave, with less muscle than the Rectilinear, with slight concavity on top. The Concave conformation represents the least muscular development and is, therefore, the least desirable conformation (BRASIL, 1989; Gomide et al., 2014). Because of variations in assessor ability and experience, consistency in predictions of the participation of fat in carcass conformation is elusive (Gomes et al., 2021).

Combining these parameters forms six hierarchical classes (B-R-A-S-

I-L), in which the highest quality carcasses are classified as “B” and the lowest as “L.” Although the Brazilian system has been used for over 30 years to classify beef carcasses, concerns have been voiced over the lack of data for the effectiveness of these parameters in predicting beef eating quality (Duarte et al., 2011).

In hot carcasses, fat has not yet solidified, and muscle tissue is still in the phase preceding *rigor mortis*, so no qualitative evaluation of the meat is performed. Classification into types is done in the chiller. The BRASIL system is, therefore, a typical hot carcass system, similar to those of Argentina, Uruguay, and the European Union (Santos et al., 2021). Felício (2011) criticizes this system for grouping different kinds of carcasses together into types in which parameters such as meat quality should be consistent but are not. Oliveira Silva et al. (2017) described the Brazilian beef cattle industry as consisting of heterogeneous production systems with different systems assigning a different degree of importance to different carcass characteristics, both qualitative and quantitative, which may be affected by genetics and feedlot management. For Martins et al. (2022), in Brazil, the carcass grading scheme is deficient because of the lack of incentives for producers to consistently manage their herds in different parts of the country.

To overcome this deficiency in the Brazilian beef supply chain, it is necessary to identify functional quality and conformity quality. Functional quality consists of the qualities that consumers expect from their purchase, such as visual quality, intramuscular fat, wholesomeness, and palatability. Conformity quality, on the other hand, is the standardization of beef production processes. This includes feeding practices, breed of animal, aging, and packaging, in addition to uniformity of weight and genetic composition, carcass yield and boning of carcasses, as well as any standardized and codified cuts (Felício et al., 2011).

However, for an official grading system for predicting beef eating quality to be successful, its precision, accuracy, and consistency must be demonstrated (Felício et al., 2011). The deficiencies of the BRASIL grading system and the requirements for continued growth of the Brazilian beef industry clearly demonstrate a need for fundamental revision of the BRASIL grading system, or even replacing it with a reliable grading system able to take advantage of modern technologies.

In contrast, the EUROP system, introduced by the European Union in 1981, is characterized by its emphasis on carcass characteristics, including conformation, fatness, in addition to sex categorization. This system employs a five-point scale for both conformation and fatness, allowing for the subdivision of carcasses into 15 subclasses that provide a more detailed description of cattle herds. While the EUROP system is widely utilized for beef trading in Europe, its primary focus is on production yield, and it does not directly address beef eating quality or carcass composition (Tarrés et al., 2011). As shown by Bonny et al. (2016) and Liu et al. (2020), this carcass classification standard does not correlate with meat quality and consumer eating experience in Europe.

The present comparative analysis underscores the inherent differences between these grading systems (Table 2). The BRASIL approach is more multifaceted, encompassing various parameters and hierarchical classes, while the EUROP system simplifies the grading process with fewer parameters. Moreover, the Brazilian system seeks to classify carcasses for quality, whereas the EUROP system is predominantly oriented towards facilitating trade, with limited ability to correlate carcass scores with eating quality (Pabiou et al., 2011).

In the European Union (EU), beef carcass evaluation follows the EUROP system, which assesses carcass conformation (E.U.R.O.P) and assigns scores for external fat, but does not include indicators for marbling. Because studies in France (Legrand et al., 2013; Bonny et al., 2018a; Liu et al., 2021) and other countries (Farmer and Farrell, 2018; Pogorzelski et al., 2022) highlighting the importance of marbling in improving the eating quality of beef, the French National Food Conference recently recommended the inclusion of marbling in the French beef grading system. This proposal, made by Interbev representing the meat sector (Etats Généraux de l’Alimentation EGA, 2018).

Although the Brazilian and European classification systems reflect

Table 2
Current cattle classification systems in Brazil, Europe, and Australia.

Aspect	System in Brazil (BRASIL)	EUROP grid	MSA (Meat Standards Australia)
Parameters	Sex categorization, Age, Conformation, Fatness, Hot Carcass Weight	Conformation, Fatness, Sex categorization	<i>Bos indicus</i> %; hormonal growth promotor implants; carcass weight; sex; hump height; electrical stimulation; hang; marbling; ossification; pH; aging time; cooking method
Hierarchical Classes	6 classes (B to L) for carcasses	15 subclasses for carcasses	Four quality grades for cuts
Objective	Quality Classification	Trade and production yield	Classification for eating quality
Empirical Validation	Lacks empirical evidence of effectiveness	Limited correlation with eating quality	Aiming to directly predict eating quality
Complexity	More parameters and hierarchical classes	Fewer parameters and simplified grading	Many criteria with also consideration of interactions between them
Used	Predominantly used in Brazil	Widely used in European countries because compulsory in the EU	Common in the Australian beef industry

diverse priorities and practices in their specific regions, both exhibit gaps in assessing beef eating quality. Brazil lacks a national carcass grading system based on beef eating quality. Therefore, each slaughterhouse establishes its own metrics to meet the requirements of both domestic and export markets (Nunes et al., 2024). On the other hand, the EUROP system faces other limitations, most importantly its unsuitability for predicting beef eating quality (Bonny et al., 2016; Liu et al., 2020; Pabiou et al., 2011). For these reasons, it is imperative to conduct additional research and to improve these systems to meet the growing demands of the beef industry and the increasingly discerning expectations of consumers. A promising alternative for the future would be the adaptation and then the adoption of an MSA-like grading scheme similar to the one being developed in Europe, namely the Guaranteed Global Grading (3G) system. This would build on valuable knowledge and successful experiences that others have implemented, thus overcoming gaps identified in the Brazilian and European systems and making possible substantial improvements in the quality of beef available to consumers and in meeting market demands.

3. Current management of beef quality in Brazil and France

3.1. Quality development programs in Brazil and France

To fulfill the requirements for traceability in the bovine production chain in Brazil, in 2002, the Ministry of Agriculture, Livestock and Supply (MAPA) created the Brazilian System for the Identification and Certification of Bovine and Bubaline Origin (SISBOV) to track cattle from birth to slaughter. Animals registered in SISBOV must have an identity document with the farm of origin, gender, date of birth, feeding and breeding system, sanitary data along with other data. In addition, there are several programs to certify beef quality: “Rebanho Xingu” (Amazônia biome), “Alianza del Pastizal” (Pampa biome), “Carne de Mato Grosso” (Amazônia/Cerrado biomes) and “Carne Sustentável do Pantanal” (Pantanal biome). In 2015, the Brazilian Agricultural Research Corporation (Embrapa) jointly with MAPA developed certification for “Carbon Neutral Brazilian Beef”. This certification is a new

concept for sustainable beef cattle production using integrated systems and has a mandatory forestry component (Embrapa, 2023).

In order to reach these goals, the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA) has proposed the Low Carbon Agriculture Program or “ABC Program”, with the aim of transferring new mitigation technologies, especially the recovery of degraded pastures, to large numbers of farmers. Accordingly, the objective of this program is to assess animal growth, muscle development and meat quality of beef cattle raised in grazing systems with three levels of intensification (use of nitrogen fertilizer; use of more productive grass species; and irrigation) and in a degraded pasture system in the Atlantic Forest biome (Embrapa, 2023; Mendes et al., 2022).

An important part of the development of the Brazilian livestock industry has occurred on the farms themselves, with different segments of society seeking productivity, quality and sustainability of production. These included scientific and technical institutions, education, industry, producers’ associations, non-governmental organizations, among others. The initiatives taken have greatly contributed to increased quality in the beef production chain. Improvements in meat quality are continually sought by both industry and government initiatives to meet market and consumer demands. Different programs such as Pacto Sinal Verde “The Green Sign Pact”, Programa de Novilho Precoce “Early Beef” and Selo Carne Carbono Neutro “The Carbon Neutral Meat Seal” are examples of efforts in this direction. The benefits of this type of initiative are multiple. In addition to valuing producers who produce better, they aim to increase the quality of beef for the consumer, in addition to addressing environmental and economic aspects (Embrapa, 2023; Mendes et al., 2022).

The Green Sign Pact aims to completely classify beef carcasses using standards of undesirable, tolerable and desirable; to assess the quality of farm management; to provide a mapping of production processes; to promote sustainable production; to strengthen consumer loyalty; and to develop new markets. This initiative would enable an assessment of the beef production chain, including road conditions, and encourage improvements in herd health. The Early Beef program provides tax incentives to producers who successfully produce young animals with good fatness. This has helped reduce the slaughter age of animals from an average of 48 to 36 months, as well as improve pasture quality, genetics, nutrition, reproduction, health, and herd management practices (Embrapa, 2023; Mendes et al., 2022).

“Carbon Neutral Meat” is a concept brand, customizable and verifiable, which aims to certify beef produced in integrated silvo-pastoral or agro-silvo-pastoral systems through the use of specific certification protocols. Its main objective is to guarantee compensation for enteric methane emissions (Embrapa, 2023).

The Brazilian beef cattle supply chain has undergone a technological modernization of its production systems, which has resulted in improvements in productivity, meat quality and competitiveness. This technological evolution is the result of new management practices, genetic improvement of the animals, advances in nutrition and grazing methods, awareness of environmental and sanitary responsibilities, but also of the commercial barriers faced by the sector’s developments. In practice, new tools (electronic scales, electronic collars and chips, weather stations, and livestock monitoring by drones) are increasingly being used (Malafaia et al., 2020a; Malafaia et al., 2020b).

The study by Malafaia et al. (2021b) identified trends in the Brazilian beef supply chain, projected to 2040, using the Delphi method to identify challenges. This method allows the collection of expert opinions and leads to robust analyses of complex survey topics (Landeta, 2006; Rikonen et al., 2006). As a result, scenarios were developed and ten priorities were identified: 1) biological progress in waste management; 2) biotechnological transformation of cattle farming; 3) improved pasture management to reduce grazing while simultaneously increasing meat yield; 4) animal welfare; 5) consolidated cattle farming with key stakeholders; 6) more natural and efficient slaughterhouses; 7) meat with designation of origin; 8) digital technology transforming the entire

supply chain; 9) availability of skilled labor; 10) Brazil as a major exporter of meat and genetics. According to these researchers, internationally, Brazil could be a major exporter of meat and (probably) of specialized and value-added animal genetics (Malafaia et al., 2021b). Global advances in the supply chain will come from highly technical, professional, and competitive animal production, taking full advantage of technological advances.

In contrast, France, as a part of the European Union, uses various EU certified quality labels for beef products. These labels, including Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), Traditional Specialty Guaranteed (TSG), and the EU Organic logo labels, are designed to emphasize the geographical origin and specific qualities of beef products. PDO and PGI labels, for example, recognize products traditionally associated with a particular region and regulate the sourcing of ingredients and production processes within that region. PDO and PGI labels differ in how much of a product’s raw ingredients must originate from the region of production and how much of the manufacturing process must take place in that region. In addition, the PGI label also indicates specific production methods and techniques. The TSG label emphasizes traditional production methods and ingredients without the requirement of origination from a specific region (European Commission, 2023). TSG labels highlight traditional production methods and ingredients, while the EU Organic logo signifies products fully compliant with EU organic regulations (Bonny et al., 2017).

3.2. Labels and brands of quality used in France and Brazil

Brazil and France have thus taken distinct approaches to ensure the quality and sustainability of their beef production. Brazil has developed a comprehensive traceability system and multiple certification programs, emphasizing sustainability and technological modernization. In contrast, France relies on EU certified labels to highlight the regional and traditional characteristics of beef products, ensuring their authenticity and quality in alignment with European standards. France has also developed one specific label focused on eating quality (Label rouge). These efforts in both countries reflect the commitment to meet market demands with the aim to continuously improve the quality of beef production.

The quality of meat is a critical factor for consumers and producers worldwide. Both in France and Brazil, systems of quality labels play a pivotal role in ensuring the origin, quality, and safety of beef. In this section, we present a comparative analysis of the quality labels used in both countries to understand the similarities and differences in their approaches (Table 3).

The comparative analysis reveals some notable differences in quality labels between the two countries. While France emphasizes geographic origin with PDO and PGI labels, Brazil focuses on aspects like traceability and animal welfare standards. Furthermore, France places a clear emphasis on meat eating quality, exemplified by the Label Rouge seal, which promotes excellence in flavor and texture.




Conversely, Brazil places a high value on identifying cattle breeds, as seen in specific seals like the “*Certificado de Carne Angus*”. Additionally, sustainable production programs and organic certifications are emphasized to meet quality and sustainability demands. In 2022, Brazil set a record for exports of certified Angus beef. The volume of exports reached 1,880,000 tons, representing a significant increase of 102 % compared to the 934.01 tons exported in 2021. These figures were released by the Brazilian Angus Association, which represents breeders based on establishments associated with the Certified Angus Beef program (Associação Brasileira de Angus, 2024).

It is essential to note that Brazil also strives to guarantee food safety through the Federal Inspection Service (SIF). In Brazil, there are several important meat brands, recognized for their quality and reputation. Those brands are in addition to the food safety inspections required by the SIF. Here are some of the most important brands, along with their concepts and certifications.

Table 3
Labels and examples of brands used in France and Brazil to indicate high quality grades to consumers.

Labels / Examples of brands	Quality Labels / Certification Programs	Description
<i>France</i>		
	PDO (Protected Designation of Origin)	Indicates geographic origin and specific characteristics.
	PGI (Protected Geographical Indication)	Similar to PDO but may have less stringent requirements.
	TSG (Traditional Specialty Guaranteed)	Certifies traditional products with an emphasis on traditional production methods.
	EU Organic logo	Used for organic products meeting EU standards.
	Label Rouge [Red Label]	Certifies premium products with an emphasis on meat quality and taste.
	(Brand with Certification Program) Charal	A meat brand focusing on quality, traceability, and food safety.
	(Brand with Certification Program) Or Rouge [Red Gold]	Limousin beef brand focusing on meat quality and marbling.
<i>Brazil</i>		
	SISBOV	A voluntary traceability system ensures the origin and quality of Brazilian beef, often used for exports.
	Animal Welfare Certifications	Ensures humane treatment of animals before slaughter.
	Organic Certifications	Seals guaranteeing that products are organic and meet specific standards.
	Geographical Indication	Certifies the geographic origin and quality of specific products in Brazil.
	SIF (Federal Inspection Service)	A food safety standard present in all legally commercialized beef products.
	Breed-Specific Quality Certifications	Certifications related to specific cattle breeds, Ex: "Certificado de Carne Angus" for Angus beef.

Table 3 (continued)

Labels / Examples of brands	Quality Labels / Certification Programs	Description
	Sustainable Production Programs	Programs promoting sustainable beef production and environmental conservation.
	(Brand with Certification Program) Or Rouge [Red Gold]	Angus x Nellore beef brand focusing on meat quality and marbling.
	(Brand with Certification Program) 1953 Friboi	Taurine beef brand focusing on quality, traceability, and food safety

In France, beef produced for quality programs is between 5 and 10 % of total production. Interbev, The French Interprofessional Livestock and Meat Association, seeks to expand this to 40 % (INAO, 2022; Interbev, 2023).

Products of animal origin for sale in other states in Brazil or internationally, under the purview of the Ministry of Agriculture, Livestock and Supply, are registered and approved by the Federal Inspection Service (SIF) in order to guarantee sanitary and technological certification in compliance with applicable national and international legislation. In 2022, percentages of beef production in Brazil by type of inspection was 57 % by the SIF, 26.1 % not inspected, 3.5 % by the SIM (Municipal Inspection Service), 13.4 % by the State Inspection Service (SIE) (IBGE, 2024).

Certifying organizations register with SISBOV, in order to collaborate with the Brazilian government and carry out inspections of rural properties. Brazil has 10 certifying organizations accredited by MAPA, which are responsible for farm inspections and for verifying compliance with all applicable rules and regulations before goods may be exported to the European Union. Although traceability certification is a requirement of some markets for exported beef, the participation of producers in the traceability system is not mandatory (Andrade et al., 2020; Nunes et al., 2024).

4. Perspective for managing quality in France and Brazil: implementation of the MSA/3G grading system

Before the 1990s, Australia faced a significant decline in beef consumption, largely due to consumer difficulties in finding reliable beef products at reasonable prices. This uncertainty stemmed from the industry's failure to deliver a consistent consumer experience. To reverse this trend, it is imperative that the industry prioritize delivery of a consistent consumer experience. This would include measures such as standardized quality, predictable pricing, improved marketing to educate consumers, and investments in technologies and practices to ensure consistency throughout the beef supply chain. These steps would enable the industry to rebuild consumer confidence and stimulate demand for beef products in Australia (Polkinghorne et al., 2008). Industry failure to provide a consistent experience to consumers left consumers unable to reliably choose beef products at an appropriate price point. Beef production faces significant challenges from the variability of beef eating quality and the consequent lack of guarantees for a consistent consumer experience (MLA and MSA, 2001, 2018, 2023). Consumer sensory evaluation has evolved to become an essential tool in meat quality research making it possible to base research on beef palatability on empirically verified consumer experiences and preferences (Miller, 2017). For this reason, determination of beef eating quality requires consumer input and participation (Watson et al., 2008). Similar

expectations were expressed by European consumers (Verbeke et al., 2010).

Development of the MSA grading scheme was initiated to address industry failure to provide consumers with a consistent product experience by using extensive research on consumer taste preferences and beef eating quality. MSA incorporates evaluations of animal pre-slaughter, of carcasses post-slaughter in the chiller and of meat post-chiller (Bonny et al., 2018b). MSA was developed to address these challenges. It has proven to be a useful tool for the beef industry to assess beef palatability since the 1990s not only in Australia (Watson et al., 2008) but also in other countries (Hocquette et al., 2020).

Unlike methods for grading beef, MSA provides a more consistent eating experience for consumers than do other methods. MSA is distinct from other grading methods because (1) standards for eating quality are based on responses from untrained consumers; and (2) beef quality is graded using individual MSA cuts, rather than being carcass-based (Bonny et al., 2018b). Incorporation of these two facets into the MSA database makes a wealth of detailed information about the relationships between the physical characteristics of beef and the consumer experience of beef products.

The MSA database contains detailed information on animals, carcasses, and meat cuts. The large amount of data available allows not only for statistically robust correlations between various parameters and beef eating quality, but also makes possible a deep understanding of variability in beef quality using various criteria (breed, age, sex, pH, marbling, carcass hanging method, cooking method, fat depth and so on) (Bonny et al., 2018a; Farmer and Farrell, 2018; Liu et al., 2021). In addition to the detailed information about carcass traits, the MSA database contains results from over 1.7 million consumer taste tests of different methods for preparing different cuts of meat by more than 250,000 consumers from 13 countries (MLA, 2023).

Sophisticated statistical analyses allow this large database to be successfully utilized to identify critical control points for palatability, according to aging times, and specific methods of preparation for each muscle (Watson et al., 2008). MSA research and development continued in 2021–22 with the goal of having all meat from cattle and sheep be eligible for MSA; and focused on new technologies and methods in order to guarantee a consistent consumer experience. Ongoing R&D projects include genetic, nutrition, management research, and beef eating quality of diverse breeds, including dairy breeds. These all show promising results (MLA, 2023). Certification training is conducted using *AUS-MEAT's methodology* (2018), with additional required training courses at least every six months in order to maintain certification as an MSA certified grader (MLA and MSA, 2001, 2018; MLA, 2023). Such training sessions were conducted several times in Europe (France, Spain) and one Brazilian technician followed one training session in Australia.

The International Meat Research Guaranteed Global Grading Foundation (3G) is actively involved in improving beef quality by implementing its system, which is based on the same principles as MSA. This initiative has been approved by the United Nations Economic Commission for Europe (UNECE). UNECE support can lead to greater standardization of beef quality, strengthening the sector's competitiveness in the global market. The results of the ProSafeBeef and ProOptiBeef projects, both funded by the European Union, as well as by other national projects, demonstrate the potential for developing an international classification system similar to MSA for the supply chain in the EU, despite the diversity and the complexity of beef production systems in Member States (Bonny et al., 2018b). As reviewed by Hocquette et al. (2011), these studies were developed in 2008 when these projects started and were conducted by French research institutes, such as the French Livestock Institute (Institut de l'Élevage) and INRAE Theix. FranceAgriMer requested both institutes to evaluate the MSA grading scheme (Hocquette et al., 2011).

In both Brazil and France, initiatives related to MSA were primarily led by researchers conducting studies evaluating beef carcasses using MSA. They established or helped to establish startups, such as Brazil Beef

Quality or the 3G grading scheme, which were associated with universities, to implement protocols based on MSA principles. These startups, in conjunction with smaller organizations and private enterprises (such as Beauvallet which has slaughterhouses in both France and Brazil), have a limited but increasingly significant impact throughout the entire beef supply chain. There is a paucity of evidence indicating that the government is involved in the adoption of these standards. In general, the Brazilian and French governments participate in quality management systems for exports by engaging external auditors to validate beef quality for different markets. This sometimes intersects with MSA principles. In brief, the same academic research on beef quality may be implemented in both countries which have differently organized beef supply chains.

4.1. Protocol for evaluating consumer preferences

Consumer testing of food products serves two purposes: 1) to determine consumer perceptions of a given product's acceptability along with nuanced aspects such as liking and preference; and 2) to ascertain purchase intent, which is made up of elements such as willingness to buy and willingness to pay more for quality. Furthermore, establishing connections between the sensory profile and consumer data enables food producers to discern which attributes of their product resonate positively or negatively with consumers (Torricco et al., 2018). It should be noted that consumer evaluation assumes an essential role in both the development and launch phases of any novel food or meat product. The MSA grading scheme requires that the prediction of MQ4 scores (composite eating quality scores combining tenderness, juiciness, flavor and overall liking) be aligned with MSA quality grades (MLA, 2023).

Watson et al. (2008) designed the consumer testing protocol still currently used by Meat Livestock Australia for the implementation of the MSA grading scheme. Each cut is subdivided into 10 samples, and a distinct consumer evaluates each sample. The consumers evaluate seven samples, with the first coming from either the strip loin or rump muscle to ensure an average level of eating quality. The remaining six samples originate from different muscle cuts and are served to consumers following a 6×6 Latin square design. This design aims to provide consumers with a diverse range of eating quality experiences while mitigating potential biases such as halo effects or serving order influences.

Consumer assessment of beef palatability traits encompasses four sensory attributes: tenderness, juiciness, flavor liking, and overall liking. Consumers marked their evaluations on 100-mm line scales, where 0 indicated low intensity/liking and 100 indicated high intensity/liking. Subsequently, consumers are prompted to rate each tasted sample as one of the following categories: unsatisfactory (2 stars), good everyday (3 stars), better than everyday (4 stars), or premium (5 stars) (Watson et al., 2008).

4.2. Assessment of meat quality: scoring and grading

Using the MSA grading scheme, it is possible to calculate and predict the potential eating quality of muscle cuts and carcasses. The scores obtained from consumer testing, which encompass tenderness, flavor liking, juiciness, and overall liking, are presently weighted as follows: 0.3, 0.3, 0.1, and 0.3, respectively. Linear discriminant analysis is employed to determine these weights, which have been modified from 0.4, 0.2, 0.1, and 0.3 in previous analyses. Subsequently, these scores are combined to form a composite eating quality score referred to as the meat quality (MQ4) score. The MQ4 score, as assessed by consumers, represents the cumulative eating experience associated with a particular muscle cut (Watson et al., 2008; reviewed by Liu et al., 2022).

Additionally, untrained consumers categorize beef samples into unsatisfactory (2 stars), good everyday (3 stars), better than everyday (4 stars), and premium quality (5 stars). These categories can be correlated

with the MQ4 score, allowing for the classification of muscle cuts into four quality grades. Discriminant analysis is employed to determine the boundaries between each quality grade. Currently, the boundaries are defined as follows: 45.5 for the ungraded/2-star and 3-star categories, 63.5 for the 3-star and 4-star categories, and 76.5 for the 4-star and 5-star categories (Watson et al., 2008) but these boundaries may slightly vary according to consumer groups or countries (Bonny et al., 2018b; Hocquette et al., 2020), making the MSA grading scheme adaptable to different conditions.

4.3. Predictive models for meat quality assessment

The prediction of beef quality is especially important for consumers, along with the definition and description of eating quality. Initial stages of the MSA revealed that carcass grading based solely on carcass parameters fails to accurately predict the eating quality of a given carcass originating from diverse production systems. Moreover, eating quality varies across different muscle cuts within carcasses and is influenced by multiple factors (Bonny et al., 2016). Consequently, the MSA prediction model incorporates the Critical Control Points (CCPs) previously described throughout the supply chain, encompassing breeding, production, pre-slaughter, processing, and value-adding stages, to account for their impact on eating quality and consumer preference. These CCPs were identified through extensive consumer testing (Bonny et al., 2018b).

The prediction model incorporates these various CCPs based on input factors, including animal type and production characteristics (such as *Bos indicus* content, hormone growth promotants, milk-fed vealer classification, sex, sale yard, and selling method), carcass characteristics (carcass weight, ossification score, hump height, USDA marbling score, rib fat depth, and ultimate pH), post-slaughter factors (hanging method and aging time), and predictive factors related to outputs, such as the predicted grade by MSA muscle cuts and cooking method. By utilizing multiple regression analysis with these inputs, prediction models are developed to estimate the MQ4 score for specific muscle cuts (a total of 39 cuts) across a defined aging period and one of eight different cooking methods (reviewed by Liu et al., 2022).

In addition to the factors incorporated in the prediction model, *postmortem* measurements of meat color, fat color, and loin temperature of the carcass play a crucial role in excluding carcasses that have undergone dark cutting, heat-shortening, and/or cold-shortening processes (Watson et al., 2008).

Consumer testing is regularly run as described above to check the accuracy of the predictive model. This regular checking allows any evolution for the MSA grading scheme. For instance, as indicated above, relative weights of tenderness, flavor liking, juiciness, and overall liking have changed over years from 0.4 to 0.3 for tenderness and from 0.2 to 0.3 for flavor liking (Watson et al., 2008). Furthermore, boundaries between quality classes may be also calculated for specific consumer groups.

In addition, the MSA system predicts the eating quality of an entire carcass, which is known as the MSA Index. The MSA Index is determined by summing the weighted MQ4 scores of all 39 MSA muscles. The weight assigned to each cut is derived from the percentage of the total weight of MSA cuts in the carcass. The MSA Index provides feedback to producers, enabling them to assess the potential eating quality of beef carcasses as well as to monitor the effects of genetic, breeding, and management practices on the eating quality of individual carcasses (McGilchrist et al., 2019; MSA, 2018).

5. Non-destructive methods for measuring and predicting beef quality

Innovative non-destructive methods and decision tools have been developed to meet contemporary consumer demands for high-quality, safe, nutritious, and healthy red meat products. These advances

effectively assess, regulate, and enhance the quality of red meat, as well as investigating biological mechanisms underlying its technological and sensory traits. Industry stakeholders are confidently pursuing sustainable and innovative strategies to improve all aspects of red meat quality because of its economic significance and in recognition of the importance of consumer satisfaction (Gagaoua et al., 2022). Beef quality can be reliably predicted using emerging technologies without any sample use. This can be achieved by directly predicting eating quality from animal, carcass or beef characteristics using the MSA/3G grading scheme, or by indirectly predicting quality-related parameters such as meat color, pH, intramuscular fat (IMF) content, and marbling, which impact overall meat quality (Farmer and Farrell, 2018; Sanchez et al., 2022).

5.1. The international meat research 3G foundation

As highlighted in the previous sections, different grading schemes exist to assess beef quality, each with its own set of standards. Furthermore, the evaluation of quality is influenced by various factors such as rearing and feeding systems, environmental conditions, animal types and breeds, and processing practices, resulting in variability across countries. To facilitate scientific research on meat quality evaluation and its practical applications in areas such as international beef trading and marketing, it is essential to develop and/or establish a set of generic principles and an international database containing a substantial number of assessments on beef quality traits from different countries (Hocquette et al., 2020).

MSA protocol has been consistently regarded as providing a reliable, rigorous and complete assessment of beef carcasses and of untrained consumer evaluation of beef palatability. Since 2002, the MSA protocol has been designed for scientific research on sensory evaluation and consumer tests has been studied in numerous countries: Ireland (Brandon et al., 2006), the United States (Polkinghorne, 2007), South Korea (Thompson et al., 2008), Northern Ireland (Farmer et al., 2010), Japan (Polkinghorne et al., 2011), France (Legrand et al., 2013), Poland (Guzek et al., 2015; Pogorzelski et al., 2020), South Africa (Strydom et al., 2019), and China (O'Reilly et al., 2020). In Brazil, the study conducted by Baldassini et al. (2023) performed a sensory analysis with untrained consumers who assigned scores ranging from 0 to 100 on unstructured hedonic scales using the Sensory Meat v. software (Brazil Beef Quality Ltd., Piracicaba, São Paulo, Brazil) for the following meat quality traits: tenderness, flavor liking, juiciness, and overall liking. This assessment was performed using the MSA consumer test protocol, as described by Watson et al. (2008).

Over the past two decades, independent and collaborative studies have consistently concluded that this consumer-focused quality grading scheme, based on cooking and specific cuts, is applicable to these countries. Consequently, the establishment of a platform for data pooling and comprehensive analysis would enhance research efficiency and benefit the global beef industry (Hocquette et al., 2020).

The International Meat Research 3G Foundation, a collaborative, non-profit, and independent organization, was established to address these needs. Its primary objective is to increase consumer satisfaction with beef quality through promotion of worldwide collaborative research throughout the beef supply chain. To achieve this goal, the 3G Foundation established a platform to coordinate and support global scientific research on beef quality evaluation and prediction. This is done through the collection of large amounts of data based on the standardized MSA methodology for data sharing, modeling, and comprehensive investigations of beef quality prediction. Through collaborative international research, quality assessment tools (e.g., protocols, tools, software) are made more widely available, improvements to beef grading systems are made through widespread use of consumer input for evaluating sensory qualities. In addition, commercial descriptions and beef trading are enhanced. The foundation is affiliated with the United Nations Economic Commission for Europe

(UNECE), which encourages development of specifications, regulations, technical cooperation, and exchange of information (reviewed by Liu et al., 2022).

The Innovative Tools for Assessment and Authentication of chicken, beef, and dairy products Qualities (INTAQT) project is an EU-funded research initiative made up of 21 partner organizations from 10 countries (INTAQT - The Innovative Tools for Assessment and Authentication of chicken and beef meat, and dairy products Qualities 2024). Its main goal is to develop innovative tools for assessing and authenticating the qualities of chicken, beef, and dairy products. INTAQT aims to measure various consumer production metrics, with a focus on comparisons of small-scale intensive and non-intensive livestock systems. The INTAQT project promotes the adoption of MSA/3G throughout Europe in the beef sector.

The primary mission of the 3G Foundation is to provide informative and technological support for scientific research by collecting standardized data on animal characteristics and consumer evaluations of beef palatability using the Meat Standards Australia methodology. The foundation comprises three departments with distinct roles to ensure smooth operation. The council, consisting of six members, makes decisions, monitors activities, and evaluates the foundation's work. The scientific reference group is composed of representatives from different countries and organizations, such as scientists from INRAE (France National Research Institute for Agriculture, Food and Environment), IDELE (The French Livestock Institute) and AFBI (Agri-Food and Biosciences Institute) (3G Global Guaranteed Grading, 2023).

The International Meat Research 3G Foundation has designed a European predictive model called 3G similar to the MSA models in its principles but based on European data for bovine characteristics and consumer preferences.

Regular consumer testing has described some of the specifics highlighted above. Liu et al. (2020) and O'Quinn et al. (2018) agreed on the relative importance of flavor, tenderness, and juiciness as traits influencing overall liking. Liu et al., found in their investigation in Europe with untrained consumer ratings, using MSA/3G protocols, that for European consumers, flavor liking emerged as the predominant factor (39 %) in beef overall liking, followed by tenderness (31 %) and juiciness (24 %) ($P < 0.05$; $R^2 > 0.94$). O'Quinn et al., concurred with Liu et al. on the relative importance of these three factors for overall liking: (49.4 %), tenderness (43.4 %), and juiciness (7.4 %) ($P < 0.05$; $R^2 > 0.99$).

Using MSA methodology, Liu et al. (2023b) demonstrated that French consumers are able to perceive significant differences in eating quality traits across different muscle cuts of grass-fed Angus x Salers beef. They evaluated various factors including muscle cuts, ageing times (5 and 14 days), and muscle slicing and grilling methods. Their results indicated that consumers could distinguish between muscle cuts in terms of eating quality, but not between ageing times or between methods used to slice the muscle. Moreover, the study assessed whether the MSA model could accurately predict the eating quality of meat produced by these lean crossbred animals. It was found that the accuracy of the MSA-assigned eating quality score (MQ4) was 64.5 %. Despite the lack of MSA data on these specific lean crossbred animals, the study suggested that the MSA sensory testing protocol, MQ4 calculation, and MSA quality grades can be used to create a consumer-based quality grading system in France.

Because of the large amount of international research, the International Meat Research 3G Foundation is poised to provide tools to predict beef eating quality from animal, carcass, and beef traits without further analysis. Non-destructive methods based on modeling have been studied successfully by many countries as previously indicated.

5.2. Perspectives of the MSA grading scheme in Brazil

According to OECD/FAO (2020), beef consumption will increase over the next ten years and will make up 16 % of the total increase in

meat consumption. In all developing countries, consumption remains generally lower, at about one third of the volume consumed per capita in developed countries. Asia is the only region where an increase in per capita consumption is expected. Several countries with high beef consumption will see their beef consumption decrease, due to replacement by less expensive meats, such as pork and poultry.

Further, the COVID-19 pandemic caused a decrease of beef consumption in the average Brazilian diet (Mendes et al., 2022). The most important factors affecting demand for beef are economic: per capita income, the price of beef, and prices of alternative sources of protein (Malafaia et al., 2021a). In Brazil, domestic beef consumption accounts for 79.6 % of total production and is decreasing. The pandemic has led to changes in consumption resulting from the adoption of preventive sanitary measures. Restaurant sales decreased by 65 %, but in small, medium and large retailers, there was a reverse trend. Consumers began to buy more in supermarkets and local markets. This increase in out-of-home consumption declined and this had an impact on retail sales, leading to reduced demand for premium cuts, with smaller effects on lower-priced cuts (Malafaia et al., 2021a; Bizinoto et al., 2020).

Brazil is a significant player in the international beef market, with more than 90 % of beef cattle being Nellore or Nellore hybrids (ABIEC, 2023). Improving the quality of *Bos indicus* beef is essential to supporting global demand. Use of *Bos indicus* genetics in a more sustainable manner represents a promising avenue for enhancing the industry's ability to meet consumer demands. Refinements in production systems and processing techniques are necessary to bridge the gap between consumer expectations and the characteristics of *Bos indicus* beef. Enhancing tenderness in zebu cattle depends on selecting animals with favorable genotypes, using tools like ultrasonography and molecular markers for accurate evaluation. Techniques such as carcass suspension by the aitch bone or pelvic suspension (tender stretch) and electrical stimulation can improve tenderness and palatability. The integration of *Bos indicus* cattle into modern production schemes, such as the MSA, while addressing the underlying mechanisms that influence beef tenderness, offers a promising pathway for increasing demand through the production of superior-quality beef (Ramos et al., 2024). The genetic composition of *Bos indicus* cattle is a crucial factor in the MSA grading scheme, and is evaluated by measuring hump height. In addition, the proportion of *Bos indicus* genetics is available from declarations provided by producers (AUS-MEAT, 2018).

However, beef consumption is expected to increase in the near future. According to Embrapa Gado de Corte, increases in income will keep growth in demand steady. The trend towards "premiumization" (to move an existing product or service upmarket due in part to a perception of increased health benefits, quality, or prestige) will also be strong in beef, generating opportunities for quality meat projects and brand concepts (Malafaia et al., 2021a; Bizinoto et al., 2020). Despite ongoing efforts of the industry to control beef quality, high variability in palatability remains a problem and is an important source of consumer dissatisfaction (Liu et al., 2022).

Growing demand for quality beef with sensory attributes meeting consumer expectations led to the development of MSA in Australia in 1996 (Watson et al., 2008; MLA and MSA, 2001), and is now well known in the scientific literature in Brazil. Baldassini et al. (2023) compared the effects of pelvic suspension (PS) and suspension by the Achilles tendon (AS) with two groups of 10 Brangus heifers and 10 Nellore bulls on eating quality with protocols based on MSA consumer testing. All animals were feedlot-finished. The suspension method was randomly assigned. A positive statistically significant improvement in sensory tenderness was observed for both groups with carcasses aged for both 5 days and 15 days compared to AS. Hanging method (PS) and length of aging (5 days) increased flavor, juiciness, and overall acceptance for Nellore bulls, but not for Brangus heifers. Pelvic suspension improves the quality of loins from *Bos indicus* bulls, which allows a reduction in the aging time from 15 to 5 days, which confirms similar results obtained in France (Legrand et al., 2017).

Thus, the MSA method can detect intramuscular variations in quality and suggest appropriate cooking methods through the use of information about the individual animals as well as post-slaughter factors. This methodology has been shown to be effective in predicting eating quality of beef not only in Australia, but also in a wide range of countries and production systems in Europe. The MSA method for predicting beef sensory quality seeks to provide for the first time in Brazil a robust carcass classification to predict beef sensory quality, as has been done in Europe (Ellies-Oury et al., 2020; Legrand et al., 2013; Liu et al., 2021, 2023b; Hocquette et al., 2020). It is also expected that the implementation of this methodology will improve sensory quality through genetic selection and will generate added value for processors and producers through increased organoleptic quality potential (MLA, 2023).

The anticipated outcomes of the implementation of the MSA method in Brazil, coupled with its growing effectiveness in forecasting the sensory attributes of beef, are expected to have favorable consequences for the economy, society, the scientific community, and technological development (Mendes, et al., 2022).

The Brazil Beef Quality (BBQ) startup has started to work in this direction for the benefits of the Brazilian beef industry by integrating quantitative and qualitative data from cattle in slaughterhouses. With support from Fapesp and EsalqTec incubator, BBQ developed a star rating system similar to MSA and 3G grading systems to classify meat quality for consumers. So far, BBQ has classified more than 100,000 carcasses, collaborating with companies like VPJ, Barretto Steak, and Beauvallet group (Brazil Beef Quality, 2024).

Data from slaughtered animals are entered into the Beef registration web platform, which is interconnected with the Beef Score software. The algorithms process the information and provide real-time carcass scores. Depending on the score obtained (on a scale of 1 to 100), carcasses are either disqualified or receive the Brazil Beef Quality seal. If they pass the assessment, they can be classified into three categories: 3 stars (40 to 60 points, suitable for daily consumption), 4 stars (61 to 80 points, indicating very good meat), and 5 stars (over 80 points, indicating an excellent or premium quality standard). The certification training is conducted by the company's team, which hires professionals to oversee data collection during slaughter (Brazil Beef Quality, 2024), including the analysis of ossification maturity following the methodology of the Australian certifying body (AUS-MEAT) as described (Baldassini et al., 2023).

5.3. Use of portable or handled devices

Conventional methods of carcass grading by operators are sometimes considered poorly repeatable or poorly reproducible. For this reason, and also to spare time, there is a need to implement non-invasive instrumental measurements on the production line instead of working with accredited graders (Coombs et al., 2021). Despite some disadvantages, non-destructive methods that rely on instrumentation have many benefits (Table 4): ease of use, reduced time, speed, cost, consistency, and the potential for increased accuracy and reliability (Hocquette et al., 2012). As computing power increases, more sophisticated statistical methods and algorithms become more easily accessible in handheld devices. This, in turn, makes previously unfeasible sensing technologies available in the form of small devices, which in turn allow their use in novel environments with sometimes unexpected applications (Sanchez et al., 2022).

Numerous scientific articles have been published exploring the use of various sensing technologies to both quantitatively and qualitatively predict both carcass composition and meat quality. Kombolo-Ngah et al. (2023) investigated the use of handheld NIRS (Visible Near-infrared Spectroscopy) spectrometers in the chiller for predicting marbling scores of intact meat muscles at slaughterhouses in France and Italy with NIR measurements taken at different points on the *Longissimus thoracis*. Marbling was assessed according to the MSA/3G protocol. These results

Table 4

Advantages and disadvantages of non-invasive techniques for predicting beef quality (based on studies by Cheng et al. (2015); Sanchez et al. (2022); Hocquette et al. (2012) and authors' expertise).

Technique	Advantages	Disadvantages
Hyperspectral Imaging (HSI)	Has potential for evaluating meat quality because it integrates both spectroscopic and imaging techniques.	Advanced algorithms for data processing need to be developed
Ultrasound Imaging	Can estimate the marbling in live animals	Low predictive accuracy compared to other techniques, and offers limited potential for evaluation of carcass marbling
Visible Near-infrared Spectroscopy (NIRS)	Is a rapid, non-invasive, cost-effective, and environmentally friendly analytical technique	Depends on reference method used for calibration; requires a large number of representative samples to develop a prediction model; has low sensitivity for the prediction of contents of minor constituents; generates complicated spectral data with limited transfer of calibration between different instruments
X-ray Computed Tomography	Is a promising technique for evaluating IMF content of both meat and live animals	Has commercial applications, but more investigation is needed to improve robustness of the system and to reduce costs of current instrumentation.
Magnetic Resonance Imaging	Is a potential technique for the evaluation of beef quality	Has high cost and the strict testing environment required makes it unsuitable for its application in the industry

provide moderately predictive accuracy of marbling scores, suggesting potential applicability in the European beef industry for predicting MSA marbling classes ($R^2 = 0.46 - 0.59$).

Conversely, Coombs et al. (2021) highlighted that their study, based on non-identical carcass sites sourced from a local supermarket, found that the smartphone NIRS sensor was comparable in accuracy and precision to benchtop NIRS for predicting IMF% ($R^2 > 0.75$). Raman spectroscopy, according to Cama-Moncunill et al. (2020) presented a promising method for rapid assessment of IMF % ($R^2 = 0.89$), while ultrasound, as suggested by Beriain et al. (2021) showed potential in predicting IMF % ($R^2 = 0.62$).

Stewart et al. (2021) demonstrated the effectiveness of a prototype automated vision system using hyperspectral imaging (HSI) in beef grading. This system accurately predicted chemical intramuscular fat percentage (IMF%) and marbling with a remarkable coefficient of determination ($R^2 = 0.76$). Stewart et al. (2024) evaluated the precision, accuracy, and repeatability of the Frontmatec Q-FOM™ Beef grading camera in Australian carcasses. The Q-FOM™ device demonstrated precise and accurate prediction of continuous traits such as eye muscle area (EMA) ($R^2 = 0.89$), MSA marbling ($R^2 = 0.95$), and chemical IMF% ($R^2 = 0.94$). The Q-FOM™ achieved predictions equivalent to expert grader assessments in 61 %, 64.3 %, and 60.8 % of cases for categorical traits including AUS-MEAT marbling, meat color, and fat color scores, respectively. In addition, 95 % of the predictions fell within ± 1 classes of expert scores. The Q-FOM™ showed high repeatability and reproducibility across all evaluated traits.

Lee et al. (2015) demonstrated that magnetic resonance imaging has exceptional potential for predicting IMF% ($R^2 = 0.98$). Additionally, Anderson et al. (2018) demonstrated the significant potential of X-ray computed tomography in predicting IMF% ($R^2 = 0.63-0.89$), while Prieto et al. (2010) showed that computed tomography could effectively

predict IMF% ($R^2 = 0.86$).

However, it must be acknowledged that some of these techniques were developed primarily for laboratory use, and their industrial feasibility has not been extensively studied. A notable drawback of all these technologies is the necessity of a large number of reference images, graded according to the grading system of the country in which the instrument(s) will be used. In addition, accurate calibration of devices requires the development of custom algorithms (Table 4; Cheng et al., 2015). None of these technologies is currently used at a large scale in commercial slaughterhouses either in France or in Brazil. However, the Danish Q-FOM™ Beef handheld camera has been recently approved in Australia for use in commercial plants to assess MSA criteria mainly marbling.

5.4. The future of MSA and automated methods

Several objective, non-destructive technologies are already on the market. Many are limited by their lack of portability or high installation costs (Scholz et al., 2015), as well as the drawbacks due to their dependence on a reference method (Table 4; Cheng et al., 2015). Therefore, it is a challenge to overcome these obstacles to their effective use through creation of a strong calibration model using data from on-line processes to more accurately reflect industrial variability. However, the recent development and proliferation of portable handheld devices has facilitated the application of techniques on a large scale, with rapid acquisition of spectra and obviating the need for complex sampling protocols and transport of samples to a laboratory (Goi et al., 2022; Kademi et al., 2019).

To meet the needs of the beef industry, in addition to calibrating these new non-destructive techniques based on reference methods, the Meat Livestock Australia has conducted research in Australia. Currently, the only device certified by MSA/AUS-MEAT for use in Australia is the Q-FOM™ Beef handheld camera manufactured by Frontmatec Smoerum A/S (Frontmatec, 2023; Stewart et al., 2024). This instrument consistently grades beef ribeye in agreement with MSA/AUS-MEAT standards and with highly trained graders. Marbling, IMF%, eye muscle area, meat color, fat color, and rib fat thickness are accurately measured in a few seconds using only a single photo of the ribeye (Stewart et al., 2024).

Ferreira et al. (2024) showed in a study carried out in Brazil that infrared thermography can be used to identify the dark, firm, and dry (DFD) in Brazilian beef and to identify ultimate pH in carcasses. When combined with blood parameters, infrared thermography may exhibit even greater efficacy in predicting ultimate pH in Nelore cattle carcasses. This highlights the potential utility of methods based on infrared thermography in the beef industry (Ferreira et al., 2024).

Private initiatives, such as BBQ and DGT Brasil, have also invested in these new non-destructive methods. BBQ is also developing new technologies to predict beef eating quality, such as Meat Image for carcass evaluation through imaging, Meat Score for determining tenderness through spectrum analysis, Yield Grade for predicting deboning yield, and Origin for traceability of cattle. These new non-destructive technologies are calibrated using a reference methodology similar to MSA, as well as using physico-chemical and rheological analyses (Brazil Beef Quality, 2024). DGT Brasil uses Bovine Image Analysis (BIA) software for unbiased interpretation of ultrasound images of cattle carcasses. This software facilitates generation of data for carcass traits, and offers a more precise and systematic approach to data collection (DGT Brasil, 2024).

6. Conclusion

As emphasized throughout this review, Brazilian and French beef production supply chains stand out internationally. This means that continuous improvement is necessary in order to maintain technical and, consequently, economic excellence throughout the production chain.

Expectations of beef quality are quite similar in France and Brazil, where consumers seek out affordable meat products with high organoleptic, health and nutritional qualities, produced according to strict ethical standards. Because of this, implementation of the MSA/3 G methodology and nondestructive techniques to evaluate the quality and safety of beef in both Brazil and France would create added value throughout the beef processing chain. This would make possible identification and selection of genetic criteria for improved sensory quality of beef meat. Accordingly, processor and producer revenue would be directly dependent on the eating quality of the beef produced, as has already been done in Australia. For these reasons, research and innovation are necessary for Brazilian and French beef cattle production to consolidate their superiority in global markets. In addition, further research is needed to explore the feasibility of adopting and adapting the MSA grading scheme with the International 3G Foundation in Brazil in order to maximize the benefits for the Brazilian beef industry, as it has already been done in France.

CRedit authorship contribution statement

Nathalia da Silva Rodrigues Mendes: Writing – review & editing, Writing – original draft. **Julio Cesar Colivet Briceno:** Writing – original draft. **Eliane Teixeira Mársico:** Writing – original draft. **Marie-Pierre Ellies-Oury:** Writing – review & editing, Validation, Supervision, Conceptualization. **Sghaier Chriki:** Writing – review & editing, Validation, Supervision. **Jean-François Hocquette:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Tatianne Ferreira de Oliveira:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 2. EFFECTS OF TRANSPORT STRESS ON CARCASS QUALITY IN BRAZIL AND FRANCE

Given the growing global demand for beef and high-quality meat, it is essential to investigate the effects of pre- and post-slaughter practices on beef carcasses, particularly in major beef-producing countries, such as Brazil and France, two major beef-producing countries in South America and France. These studies are specifically relevant due to the variety of cattle breeds and production systems employed in these regions. Therefore, there is a need for studies on the effects of pre- and post-slaughter practices on the carcass characteristics of cattle, along with predictions of sensory quality in order to evaluate the possible effects of practices on meat quality. This would allow selection of animals with high sensory quality potential, in order to better attract consumers who increasingly demand guarantees of the sensorial quality of meat. Few studies have had access to large commercial datasets to investigate the effects of transport stress, except those in my thesis [Mendes et al. (2024b) and Mendes et al. (2024c)]. The only study based on consumer sensory scores and the MSA grading scheme is that of Polkinghorne et al. (2018), who tested the effects of four extended transport treatments on sensory and objective beef quality.

This chapter presents two investigations of the potential effects of transport stress on carcass quality of cattle in Brazil and France. The first study examined the effect of transport with Nellore cattle (*Bos taurus indicus*) in Brazil, a tropical breed known for its resilience in extensive production systems. The second study explored the potential impact of transport stress on Limousin cows (*Bos taurus taurus*), a late-maturing breed well known in France.

These studies contribute to understanding how transport stress impacts beef quality in different breeds and production systems and provide valuable insights for improving animal welfare and beef eating quality standards in industrial settings in both countries.

In the first study, entitled “Does transport stress have any effect on carcass quality of Nellore cattle (*Bos taurus indicus*) in Brazil? — A case study”, the key hypothesis tested in our case study was that pre-slaughter transport of bovines over extended distances could induce stress in cattle, leading in turn to diminished carcass quality due to elevated pH levels, while controlling for factors such as hot carcass weight and maturity.

A total of 30,230 Nellore carcasses from a commercial slaughterhouse were assessed 24 hours *postmortem* to determine whether transport stress affects meat quality.

In the second study, entitled “Does transport potentially affect the eating quality of beef from

Limousin cows in France? — A case study”, we hypothesized that pre-slaughter transport of cows could cause stress to the animals, resulting in lower-quality carcasses due to a higher ultimate pH caused by the stress induced by transport. In brief, this study investigated the effects of transport stress on Limousin cows transported to slaughter from farms located in different geographical regions in France, with a specific focus on the impact on ultimate pH and marbling. For the first time in France, potential consequences of transport stress on beef eating quality were assessed using the MSA grading scheme.

2.1. Does transport stress have any effect on carcass quality of Nellore cattle (*Bos taurus indicus*) in Brazil?

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Does transport stress have any effect on carcass quality of Nellore cattle (*Bos taurus indicus*) in Brazil? – A case study

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Abstract

With the increasing concomitant demands for Brazilian beef and in particular high-quality beef, there is a need for observational studies of the effects of pre- and post-slaughter practices on beef carcass traits. We hypothesized in our case study that pre-slaughter transport of bovines over significant distances would induce stress in animals, and that this would reduce carcass quality because of higher pH resulting from long-distance transportation. To test this hypothesis, 30,230 Nellore carcasses from a private slaughterhouse were evaluated 24 h *postmortem*. Analysis showed correlations between animal maturity, ultimate pH, distance, and carcass weight. More precisely, there was a slight positive correlation between ultimate pH and weight (but not with transportation distance) and a slight positive correlation between maturity and weight. A linear regression model ($R^2 = 0.016$) failed to show distance having a significant effect on ultimate pH ($P = 0.63$), while carcass weight significantly affected ultimate pH ($P < 0.001$) with a low coefficient of 0.0003. Maturity negatively affected ultimate pH also ($P < 0.001$) but with also a small effect (-0.0008). Results (from 95% confidence intervals of variance of the random effects and of the random errors) showed that the variability within farms was higher than between farms. The linear mixed model showed that maturity had a significant effect on carcass weight value ($P < 0.001$) with a large coefficient of 2.90. The R^2 of the linear mixed model was 46.03%. In conclusion, while weight and maturity both affect ultimate pH, long distances did not significantly impact ultimate pH and therefore the beef quality from Nellore cattle. This could be because of low stress during transport, as well as the physical characteristics of the Nellore breed that favor greater resistance to tropical climatic conditions.

Lay Summary

With the increasing concomitant demands for Brazilian beef and for high-quality beef, there is a need for observational studies of the effects of pre- and post-slaughter practices on beef carcasses. In our case study, we hypothesized that pre-slaughter transport of bovines over significant distances would induce stress in animals and that this stress would reduce carcass quality because of the higher pH which would result from long-distance transportation. To test this hypothesis, 30,230 Nellore carcasses from a private slaughterhouse were evaluated 24 h *postmortem*. Analysis showed correlations between animal maturity, ultimate pH, distance, and carcass weight. More precisely, there was a slight positive correlation between ultimate pH and weight (but not with transportation distance) and a slight positive correlation between maturity and weight. Statistical analysis showed that the variability within farms was higher than between farms. In conclusion, while carcass weight and maturity both affect ultimate pH, long distances did not significantly affect ultimate pH, and therefore had no significant effect on the quality of beef from Nellore cattle. This could be because of low stress during transport, as well as the physical characteristics of the Nellore breed that favor greater resistance to tropical climatic conditions.

Key words: animal stress, beef, carcass traits, eating quality

Introduction

Beef eating quality is an intrinsic quality trait, which depends on both pre- and post-slaughter factors (Liu et al., 2022; Pogorzelski et al., 2022). The main attributes used to characterize beef eating quality are flavor, juiciness, tenderness, and overall liking. These descriptors appear to be highly variable and dependent on many interacting factors that are difficult to manage, such as the *antemortem* properties (breed, age, maturity, carcass fat level, fatty acid composition of cuts, etc.)

and the *postmortem* elements (slaughter processes, such as carcass handling, aging, and storage (Devlin et al., 2017)). Prior to slaughter, animals are exposed to situations that can trigger stress responses, which can reduce the sensory quality of the meat (Gruber et al., 2010).

An observational case study would be able to determine whether transport time might be a significant source of stress. For the purposes of this paper, transport time means the total time that an animal is confined in a vehicle without food,

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water, or rest to transport it from the farm to the slaughterhouse. This includes time spent waiting to depart after loading, time in transit, and stationary periods, as well as waiting to off-load (Schwartzkopf-Genswein et al., 2012). Transport time can be significant in large countries such as Brazil, where livestock are often transported long distances from farm to slaughterhouse, which may be located in another part of the country. Brazilian legislation, Normative Instruction 09/2021, allows a maximum of 12 h continuous transportation before requiring a rest stop for food and water (Brazil, 2021). Improper handling during transport and at the slaughterhouse can lead to muscle glycogen depletion, inadequate acidification, and high ultimate pH. This results in darker meat, with lower sensorial properties, especially tenderness (Gruber et al., 2010), juiciness, and flavor (Hemsworth et al., 2011). For example, it is well known that an ultimate pH higher than 6 between 12 and 48 h *postmortem* results in dark meat cuts (a defect known as dark, firm, and dry [DFD]) with a shorter shelf life because of increased susceptibility to microbial contamination (Pérez et al., 2013). However, most studies of the effects of transport time on beef quality have been conducted using *Bos taurus taurus* cattle reared and transported in systems different from those used in Brazil (Maria et al 2003; Gonzalez et al., 2012 a,b; Chulayo et al., 2016; Polkinghorne et al., 2018), where zebu cattle, which are characterized by a more reactive temperament, predominate (Cooke et al., 2020). Zebu beef is typically less tender with less marbling than that of taurine cattle (*Bos taurus taurus*), particularly when compared to the Angus breed (Seideman et al., 1982; De Andrade et al., 2020).

Information on the effects of transport times on the quality of meat from zebu cattle is still scarce, as there have only been a limited number of studies of these animals, and moreover, only in the northern and southern regions of Brazil (Ferreira et al., 2006; Mendonça et al., 2018; Lacerda et al., 2022). Even though the central-western region is unquestionably important for the Brazilian beef industry (ABIEC, 2022) studies of the effects of transport time in this vitally important region on beef quality are lacking.

We hypothesized that pre-slaughter transport of bovines causes stress to the animals, and results in carcasses of lower quality with a higher final pH because of that stress. Consequently, the aim of this observational case study was to investigate the effects of stress during transport between farm and slaughterhouse, specifically on ultimate pH for Nellore cattle, while controlling for hot carcass weight and maturity.

Material and Methods

Institutional Animal Care and Use Committee (IACUC)

This slaughterhouse is regulated by the Brazilian Federal Inspection Service (S.I.F 2872).

Article 110 of the Regulamento Industrial e Sanitário de Produtos de Origem Animal - RIISPOA (Brazilian Industrial and Sanitary Regulation of Animal Products), requires that cattle be given a rest period and water. Fasting in the slaughterhouse pens for 24 h prior to slaughter. Pre-harvest handling conformed to good animal welfare practices with slaughter procedures following the Sanitary and Industrial Inspection Regulation for Animal Origin Products (Brasil, 2004, 2021). These documents are the Animal Movement

Permit and the farmer's declaration of having followed the standard and expected protocols (Brasil, 2021). Slaughter conditions conformed to traditional or Halal procedures (CIBALLAHAL, 2022).

Dataset

We used a data set provided by a private company located in Inhumas (Goiás, Brazil) (49°28'14.84"W and 16°20'31.42"S). This slaughterhouse can process up to 700 cattle per day (80 to 90 animals/h) and is regulated by the Federal Inspection Service (S.I.F. 2872). The climate in this region is tropical with an average annual temperature of 23.1 °C with an average rainfall of 1,516 mm with a Heat Index in Inhumas of 22% (Brasil, 2022).

The rainy season is frequently cloudy and overcast; the dry season is almost always cloudless. Throughout the year, temperatures generally range from 16 to 32 °C and rarely fall below 13 °C or above 36 °C (Brasil, 2022).

The company purchases animals from different areas of the state of Goiás, and maintains them within a production system typical of this region, i.e., a pasture-based tropical conditions system. These animals are representative of the beef cattle reared in central-western Brazil. Pre-harvest handling conformed to good animal welfare practices and slaughter procedures and followed the Sanitary and Industrial Inspection Regulation for Animal Origin Products (Brasil, 2004) and Technical Regulations for Pre-slaughter Management and Humane Slaughter and the stun methods authorized by the Ministry of Agriculture, Livestock and Supply (BRASIL, 2021).

The data set for the period from January to August 2021 has 35,126 records of beef carcass traits such as breed (Nellore or Crossbreed), category (Bull, Cow, Dutch bull, Dutch cow, Heifer, Marruco ox, Taurus), conformity, maturity (age), carcass weight, and ultimate pH. Categories are based on age and sex and can be further classified into calves or heifers, heifers, or bullocks, which in turn may be castrated or whole, as well as cows or bulls for slaughter. Conformity refers to the standards to which this meat should be processed for the market for which it is intended. During the period in which this study was conducted, the meat followed the standards established for the following countries: Brazil, China, and Halal consumers' countries (Iran and Saudi Arabia) Central Islâmica Brasileira De Alimentos Halal (CIBALLAHAL, 2022).

Maturity (age) was determined by dentition: milk teeth (up to 20 mo), two teeth (21 to 24 mo), four teeth (25 to 30 mo), six teeth (31 to 41 mo), and eight teeth (42 mo for above). Following the post-harvest and head inspection, the number of permanent incisors was recorded for each Nellore bull. A pair of teeth was considered to be present when either tooth of a pair had penetrated the gum. Carcass weight refers to the edible portion after slaughter, which is composed of meat, fat, and bones, and is measured in kilograms (kg). The ultimate pH was measured with a pH-meter (AK103 - Akso Produtos Eletronicos Ltda) in the *Longissimus thoracis* muscle at 13th rib of the left half of the carcass at parallel points in the same section, and 24 h post-slaughter. With regard to carcass temperature and ambient temperature, the slaughterhouse maturation system varies according to market: Chile requires 2 to 4 °C for 24 h from 10 °C ambient, while Uruguay and other countries require 4 °C for 24 h from 10 °C ambient. Brazil's

standards for carcass temperature consist of a minimum of 2 °C and a maximum of 5 °C 24 h after slaughter from 10 °C ambient.

In addition, animals were evaluated according to fat finishing, which was performed visually using a 9-point scale with scores from 1 to 9 (1 - absent fat; 2,3,4 - scarce; 5,6,7 - medium; 8 - uniform, and 9 - excessive fat). The distance from farm to slaughterhouse is given in kilometers, with each 100 km corresponding to 1 h 30 min driving time.

The numbers of the different modalities of the variables are shown in Table 1. We started with 35,126 records of beef carcasses. Of these, 99.28% were Nellore breed, 97.18% bulls non-castrated, 98.99% Halal, and 89.14% fat finishing. Restricting our target population to Nellore bulls with Halal conformity and rare fat finishing, meaning 30,230 carcasses, reduced the number of potential confounding variables (Table 1). Because of the large sample size, each of the variables studied can have significant effects, but this was minimized by focusing on ultimate pH and the variables of interest, i.e., a distance between farm and slaughterhouse, carcass weight, and maturity. For this reason, our sample is limited to ultimate pH, distance from farm to slaughterhouse, carcass weight and maturity as shown in Table 2.

Table 1. Profiles of carcasses based on breed, category, fat finishing and conformity

Parameter	Value	<i>n</i> ¹	%
Breed	Crossbreed	253	0.72
	Nellore	34,873	99.28
Category	Bull	34,135	97.18
	Cow	610	1.74
	Dutch bull	79	0.23
	Dutch cow	8	0.02
	Heifer	173	0.49
	Marruco ox	48	0.14
	Taurus	73	0.21
	Fat finishing	Excessive	6
	Medium	3,748	10.67
	Rare	31,311	89.14
	Uniform	61	0.17
Conformity ²	Brazil	1	0.003
	China	350	1.00
	Halal	34,775	99

¹Number of carcasses.

²The standards according to which this meat should be processed for its intended market.

Slaughter Process and Conditions

The company follows regularly inspected procedures for slaughtering animals (Brasil, 2004). Animals are processed for slaughter only after documents accompanying the lot are inspected. These are the Animal Movement Permit and the farmer's declaration of having followed the standard and expected protocols. Both drivers and stockyard staff have been trained in animal welfare. Animal lots are separated by origin. After unloading, the livestock trucks are washed and disinfected. The animals rest and are given water for at least 6 h before slaughtering. Animals approved for slaughter pass through a spray bath of pressurized hyper-chlorinated water. Slaughter conditions are conformed to traditional or Halal procedures. After this, an assistant from the Inspection Service determines the age of the animals using dentition and then stamps the carcass with its age group. The half-carcasses are graded for fat finishing, absence or presence of bruising, sex, and weight. After the half-carcasses are stamped by the Federal Inspection Service, they are weighed and traceability labels are applied to the hindquarter, forequarter, and flank. The half-carcasses are washed with jets of pressurized water to remove bone fragments and blood clots, then, they are placed in chillers suspended by the Achilles tendon at $+4 \pm 1$ °C to undergo maturation after a pH drop. After chilling, the half-carcasses are classified by ultimate pH (see section "Institutional Animal Care and Use Committee (IACUC)").

Statistical Analysis

The data were analyzed using R software (version 4.1.2 - R Core Team, 2022). After descriptive analysis, a box plot according to DuToit et al. (2012). Median values are indicated by the line within the box plot. The box extends from the 25th to 75th percentiles and whiskers indicate the minimum and maximum values. Analysis of Variance (ANOVA) was performed using the `aov()` function to determine the significant differences between carcass characteristics.

Pearson correlation was calculated with the `ggplot2` package using the "pairs.panels" function.

Principal Component Analysis (PCA) was performed using the package "FactoMineR" to represent and model multidimensional point cloud datasets, showing whether relationships exist between the studied variables. PCA allows for the calculation of new variables, called principal components, which capture the variability in the data. This enables information to be described with fewer variables than originally present. The principal components are linear combinations of the original variables. The first principal component is the combination of variables that explains the greatest amount of variability in the data. The second and subsequent principal components describe the maximum amount of remaining variability and

Table 2. Raw values for mean, standard deviation (SD), coefficient of variation (CV), minimum, and maximum for the measured traits for our studied population of 30,230 carcasses

	Mean	SD	CV (%)	Minimum	Maximum
Ultimate pH	5.75	0.07	1.22	5.0	6.04
Distance, km	203	115.59	57.44	10	547
Time, h	3	1.73	57.44	0.15	8
Carcass weight, kg	298.9	34.14	11.41	150.5	553
Maturity, months	203	1.97	48.47	0	8

must be independent (orthogonal) between them and to the first principal component (Husson et al., 2016).

Multivariate Regression Models were developed by using the “lm” (linear model) function and “lm.beta” R Package (Behrendt, 2014). The linear regression models were carried out to study the relationship between pH and explanatory variables such as carcass weight, maturity (age), and distances as follows:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \epsilon_i,$$

where y_i represents the i th measured pH on the beef carcass, β_0 is the intercept, $\beta_1, \beta_2, \beta_3$ are the regression coefficients, x_{i1} represents the i th carcass weight, x_{i2} represents the physiology animal maturity evaluated on carcass (this parameter being highly correlated to chronological age), x_{i3} represents the i th farm and ϵ_i the random error.

We fitted a mixed model to analyze if the carcass pH variance within the farms was higher than between the farms. Mixed-effect models are used to describe relationships between a response variable and some of the covariates in data when grouped according to one or more classification factors. Examples of such grouped data include longitudinal data, repeated measures data, multilevel data, and block designs. By associating common random effects with observations sharing the same level of a classification factor, mixed effects by grouping the data by grouping the data models flexibly represent the covariance structure induced by the grouping of the data (Pinheiro and Bates, 2000).

The statistical model can be expressed as follows:

$$y_{ij} = \mu + b_i + \epsilon_{ij},$$

Where y_{ij} represents the i th pH measured on i th farm and j th carcass, μ is the intercept, b_i is the random effect for i th farm and ϵ_{ij} the random error.

Additionally, we fitted a mixed to model the carcass weight in function of maturity using the farm as a random effect. The model was the following:

$$y_{ij} = \beta_0 + \beta_1 x_i + b_i + \epsilon_{ij},$$

where y_{ij} represents the i th weight measured on i th farm and j th carcass, β_0 is the intercept, β_1 is the straight slope, x_i represents the maturity (age) evaluated on i th farm, b_i is the random effect for i th farm and ϵ_{ij} the random error. Confidence intervals for the random effect variance represent the ultimate pH variability between farms, and confidence intervals for random error represent the ultimate pH variability within farms. For this model, the likelihood ratio test was performed to assess the significance of the random effect in the model. The value of R^2 was calculated using the rsq library. All computations related to fitting mixed models were done using the nlme R package (Pinheiro and Bates, 2022).

Results and Discussion

Descriptive Analysis

The pH distribution is left-skewed and has low variability (Figure 1a), with a coefficient of variation of 1.22% (Table 2) and an interquartile range less than 0.1. It can be seen that the median value is 5.75 and therefore 50% of the samples

have pH values less than 5.75. The first quartile 25% is for has an ultimate pH value of less than 5.71, and the third quartile 75% has is for ultimate pH values higher than 5.79. The box plot shows many outliers which are easily detectable which contrasts with the low sample variability of ultimate pH (Figure 1b). This may be because of technical problems (pH-meter calibration, for instance), operator error, biological problems in specific carcasses, and so on. It is worth noting that the removal of outliers does not significantly affect these results, given the large sample size.

The ultimate pH range in this study agrees with the available literature (Pérez et al., 2013) and as required by the two markets (Iran and Saudi Arabia) to which the company exports beef with Halal conformity. Iran allows a maximum ultimate pH of 6.2 as specified by its regulatory agency, and Saudi Arabia allows a maximum ultimate pH of 6.0 as specified by its regulatory agency. The ultimate pH averaged 5.74 ± 0.07 which is consistent with the findings of Silva et al. (2019), whose values were 5.78 ± 0.01 , where these authors evaluated the effect of castration on the carcass and meat quality traits of Nellore cattle. Our results also fit with those of Lacerda et al. (2022), where the ultimate pH mean was 5.82 ± 0.11 .

In our data, 22.30% of the total number of carcasses had an ultimate pH higher than 5.8 and lower than 6.04 (the maximum pH value in this study). We also emphasize that an ultimate pH higher than 5.8 is considered DFD meat by some authors, since these changes in final pH cause considerable losses for the beef sector, as the most frequent problems caused by stress in cattle are weight loss, carcass lesions and altered meat quality, mainly due to increased pH (>5.8), affecting tenderness and meat color (dark meat) (Lomiwes et al., 2014; Hughes et al., 2017).

Pérez et al. (2013) consider meat to be DFD with an ultimate pH higher than 6 between 12 and 48 h *postmortem* to result in dark meat cuts with a shorter shelf life because of increased susceptibility to microbial contamination. In our data, only 0.023% of the total number of carcasses had an ultimate pH higher than 6.0.

We chose to compare our pH results with the literature, considering we did not analyze meat color, shear force, etc. The ultimate pH range in this study was acceptable to the two markets (Iran and Saudi Arabia) to which the company exports beef with Halal conformity. Iran allows a maximum ultimate pH of 6.2 as specified by its regulatory agency; and Saudi Arabia allows a maximum ultimate pH of 6.0 as specified by its regulatory agency, while Brazil allows a maximum ultimate pH of 6.0 as specified by its regulatory agency.

These ultimate pH values can be explained by 1) the fact that animals were raised using a pasture system, which leads to higher ultimate pH values than grain-fed cattle (Apaoblaza et al., 2020) and 2) the use of non-castrated males, which can lead to increased stress, because castrated animals are easier to handle than non-castrated animals, since castration results in changes in behavior, namely in becoming calmer, gentler, more obedient, and more amenable to management (Duarte et al., 2011). These two reasons would justify the abnormal ultimate pH in some evaluated carcasses but are insignificant when compared to the effects of road transport time on ultimate pH as considered in this study (Figure 1a and b).

The distribution of distances between farm and slaughterhouse is left-skewed with a high variability (Figures 2a and b), with a coefficient of variation of 57.44% (Table 2). The

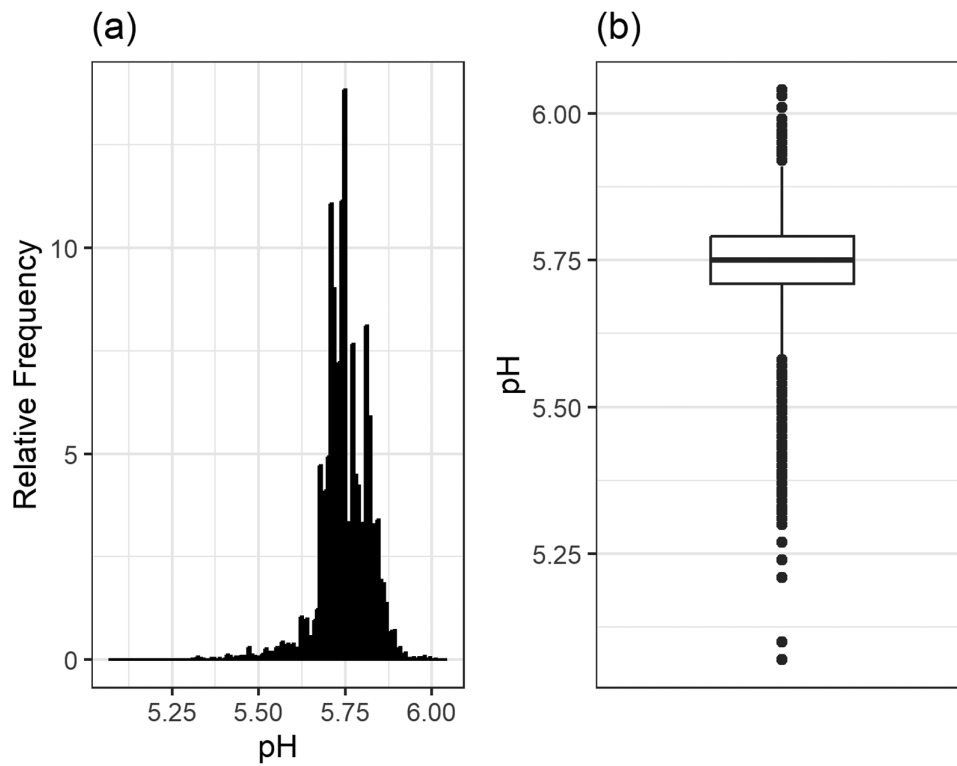


Figure 1. Frequency distribution of ultimate pH values in beef carcasses, represented as a histogram (a) and box plot (b).

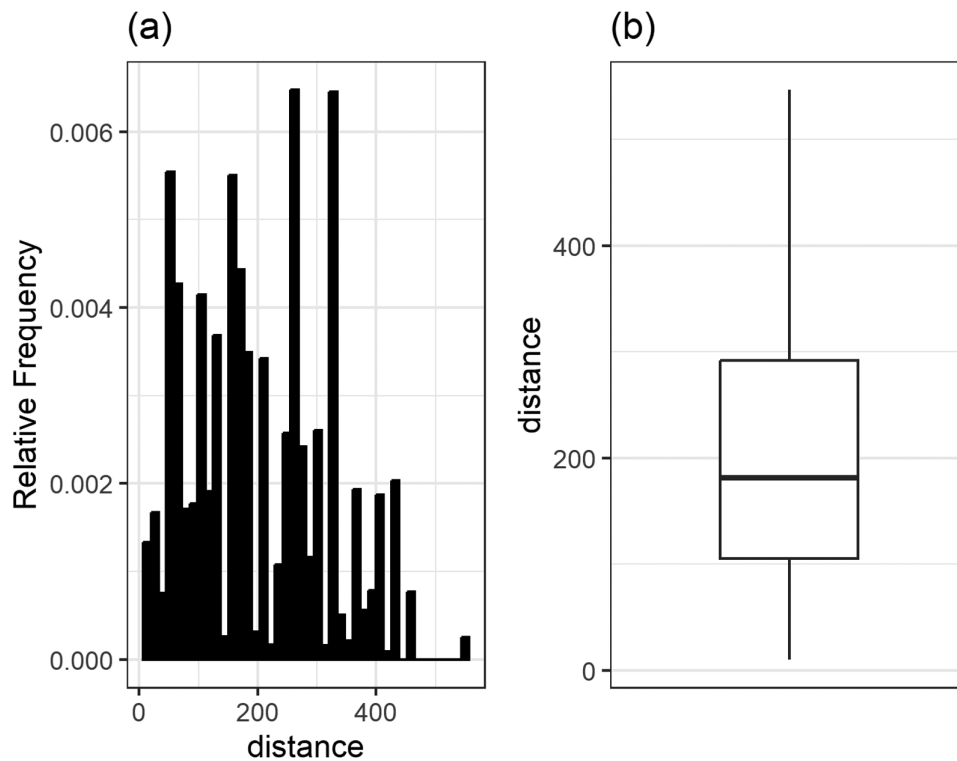


Figure 2. Frequency distribution of distance between farm and slaughterhouse (km) in beef carcasses, represented as a histogram (a) and box plot (b).

median value is 181 km and the first quartile 25% with a distance value of less than 105 km and the third quartile 75% has a distance value of more than 292 km. It should be noted that the slaughterhouse in this study was located near the geographic center of the Goiás state, and that the average

distance was not as great as those reported in Chile (Werner et al., 2013) or Canada (Gonzalez et al., 2012 a,b; Warren et al., 2010), which had an average distance greater than 400 km. However, the distances reported for the present study are similar to those in studies conducted in the northern and

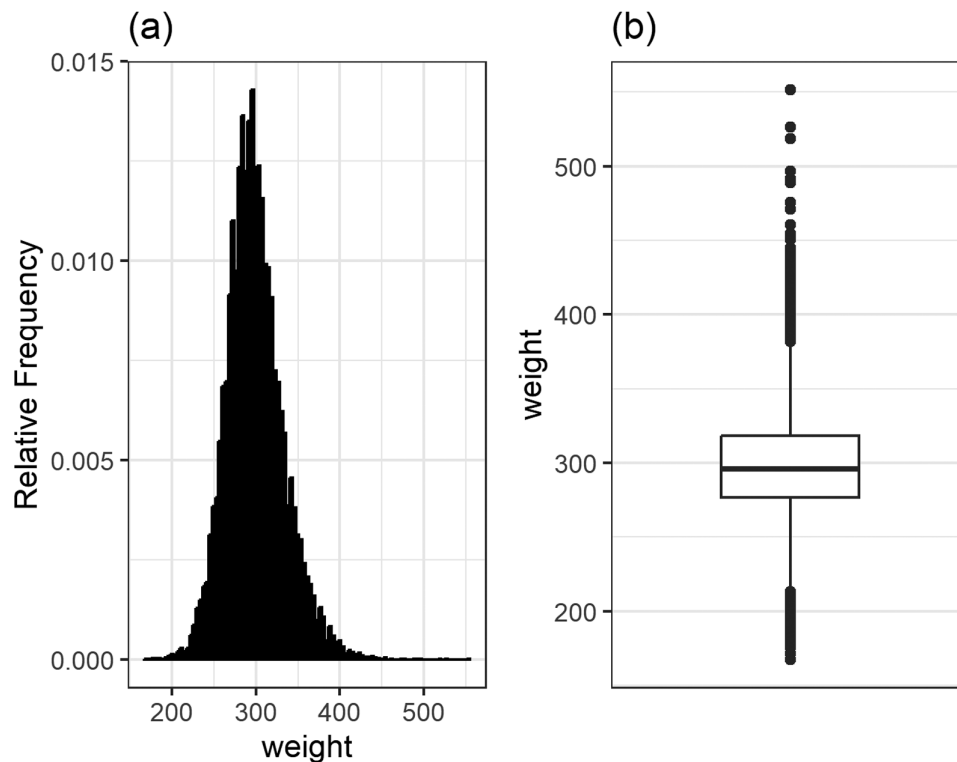


Figure 3. Frequency distribution of hot carcass weight (kg) in beef carcasses, represented as a histogram (a) and box plot (b).

southern regions of Brazil (Mendonça et al., 2018; Lacerda et al., 2022), and are in accordance with Brazilian legislation, Normative Instruction 09/2021, which allows a maximum of 12 h of continuous transport before requiring a rest stop for food and water (Brasil, 2021).

Although animal transport of long duration is more likely to compromise animal welfare than that of shorter duration, it is important to recognize that it is not the duration of the journey per se, but the associated negative aspects, i.e., lack of food, lack of water and high temperature, which are the source of any detrimental effects. Stress from extreme temperatures and lack of food, water, and rest, for example, are all exacerbated by length of exposure, i.e., journey duration (Nielsen et al., 2011). Furthermore, once animals have adapted to their new situation, distance is a relatively minor problem when compared to loading densities, vehicle design, road conditions, or driver skill (Strappini et al., 2009). In this study, these factors were controlled for, and the distance had no significant influence on beef quality, as shown by the ultimate pH values.

The weight distribution is left-skewed and has high variability (Figure 3a), with a coefficient of variation of 11.41%. The median value is 296.50 kg with the first quartile 25% having a weight value of less than 275.50 kg and the third quartile 75% with a weight value of more than 319.50 kg. The many outliers shown in the box plot (Figure 3b) can be explained by different ages. This agrees with the results of Bureš and Bartoň (2012) who evaluated the effects of gender and age at slaughter on growth, feed intake, carcass composition, and meat quality of *musculus longissimus lumborum* attributes in Charolais × Simmental. They found that bulls slaughtered at 14 mo of age were lighter than those slaughtered at 18 mo of age at the end of the fattening period. This same result in Nellore bulls was also observed by Silva

et al. (2019). The average hot carcass weight in the present study was 298.90 ± 34.14 kg and which agrees with the value of 248 ± 34.20 kg observed for Nellore bulls by Mello et al. (2018) and with 236.60 kg found by Silva et al. (2019).

The maturity distribution is left-skewed and has high variability (Figure 4a), with a coefficient of variation of 48.47%. The median is 4 teeth and the first quartile 25% with a maturity value of less than 2 teeth and the third quartile 75% has a value of more than 4 teeth. The box plot indicates many outliers (Figure 4b). This is due to the sample size and in the present study, the experimental design did not stipulate the age range of the animals studied since the objective was to make an exploratory analysis of the company's data. This agrees with results from Duarte et al. (2011) with most of the animals with 4 permanent incisors teeth and when evaluating the physical and chemical characteristics of meat from Nellore bulls with 4 permanent incisors teeth he found acceptable results for tenderness.

Correlations Between Beef Carcass Traits

The matrix correlation between beef carcasses shows weak correlations between traits and no relationship between the two variables of interest namely ultimate pH and distance (Table 3).

There was no significant correlation between ultimate pH and distance ($r = 0.01$) on the one hand and between ultimate pH and maturity ($r = 0.01$) on the other hand. In the conditions studied, the hypothesis that long distances would significantly interfere with beef quality was not confirmed for the Nellore breed. In this study, the transportation distance and time may have been insufficient to cause enough stress to the animals to deplete glycogen stores. A longer transport time (14 h) may result in changes to the rumen environment, leading to an increased acetate/ propionate ratio. This would

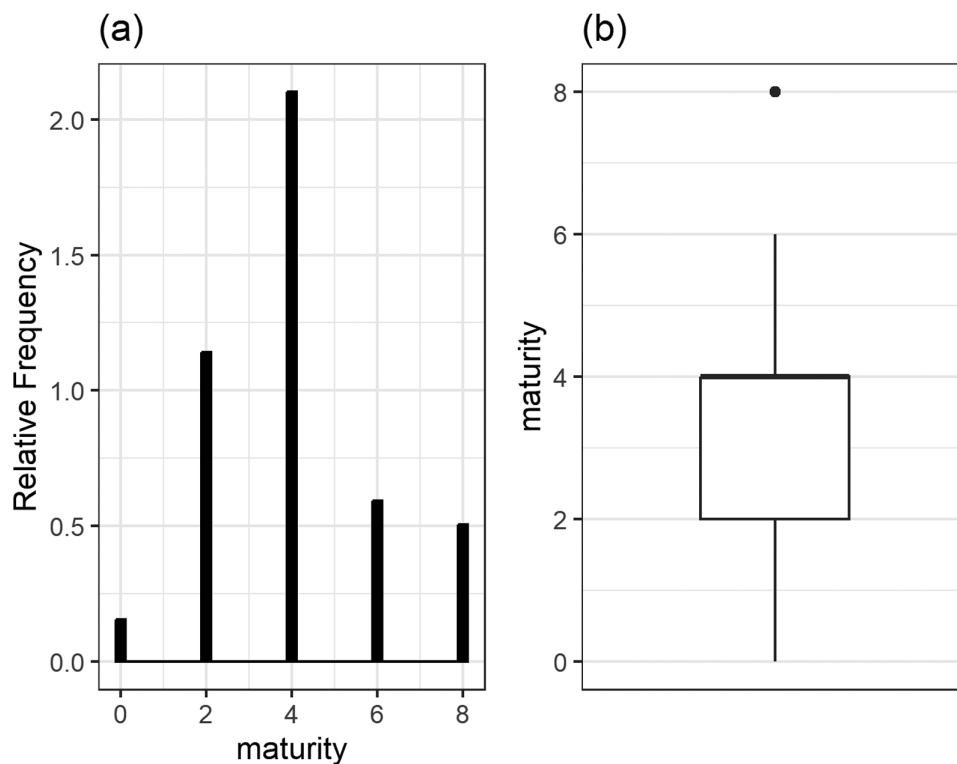


Figure 4. Frequency distribution of maturity (age) in beef carcasses, represented as a histogram (a) and box plot (b).

Table 3. Correlation coefficients between beef carcass traits

	pH	Distance	Weight	Maturity
Ultimate pH	1	0.01 ¹	0.12 ²	0.007 ¹
Distance, km	—	1	0.05 ²	-0.03 ²
Carcass Weight, kg	—	—	1	0.23 ²
Maturity, months	—	—	—	1

¹Correlation is not significantly different ($P > 0.05$)

²Correlation is significantly different at 0.01 ($P < 0.01$).

reduce the quantity of circulating glucose and affect ultimate pH (Deng et al., 2017). This probably did not occur in the animals studied because even the longest time (8 h) did not impede the decline in ultimate pH.

Another factor may be due to the physical characteristics of the Nellore breed, which is very resistant to heat due to its larger body surface area and greater number of sweat glands. The characteristics of its hair also facilitate heat exchange with the environment. In addition, the digestive tract is 10% smaller than that of European cattle breeds (ACNB, 2022). Therefore, their metabolism is lower and generates less heat. According to Dewell (2010), larger cattle cannot handle heat stress as well as smaller cattle because increased fat deposition prevents cattle from regulating their heat effectively. Solar radiation is a critical component that can lead to losses from heat stress. In our study, the average weight was 300 kg which contributed to these animals being able to handle the heat. This result agrees with values for ultimate pH obtained by Lacerda et al. (2022) who investigated the effects of different pre-slaughter road transport times on sensory evaluation and instrumental measurements of meat quality of Nellore cattle. They observed that, with the longest

transport being 6 h, no noticeable effect on ultimate pH or meat quality.

Weak but significant correlations were obtained between ultimate pH and carcass weight ($r = 0.12$, $P < 0.01$) on the one hand and, between distance and carcass weight on the other ($r = 0.05$, $P < 0.01$). This is in agreement with González et al. (2012a), which aimed to identify and quantify several factors affecting shrinkage in cattle during long-haul commercial transport (≥ 400 km; $n = 6,152$ trips). They concluded that transport duration was the variable with the most influence on shrinkage, especially at high ambient temperatures because both factors have a multiplicative effect on each other. Thus, every attempt should be made to reduce transport duration and shrinkage, such as by avoiding unnecessary delays through careful trip planning and efficient border crossing inspection protocols for feeder cattle. Transport should be more carefully managed during hot weather to minimize avoidable shrinkage. Again, hot carcass weight was found not to be affected by pre-slaughter road transport distance. This may be because even the longest transport time added to the waiting time in the holding pen was insufficient to reduce carcass weight. In addition, other factors related to transportation

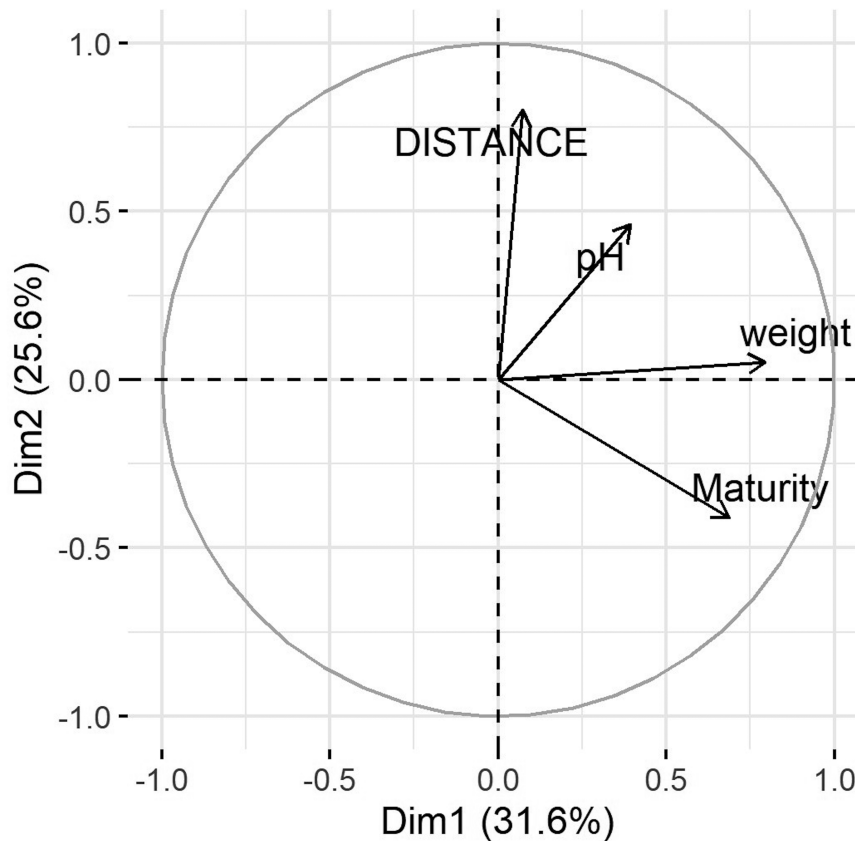


Figure 5. Principal component analysis. This analysis was performed using the following variables: distance, ultimate pH, weight, maturity. Projection of variables in a “XY” plane defined by the axes for the first two principal components (PC1 and PC2), showing the percentage of explained variability in the two PCs of the plot.

can contribute to changes in carcass weight, such as animal density, and lot mixing in truck compartments (Mendonça et al., 2019). However, in the current study, these factors were controlled for, so that the effects of transport distance could be isolated and reliably determined (Table 3).

Transportation distance and maturity had a negative weak relationship ($r = -0.03$, $P < 0.01$), with a low correlation between carcass weight and maturity ($r = 0.23$, $P < 0.01$). This significant correlation is due to the fact that the age at which an animal is slaughtered determines its weight and composition of the carcass because of its stage of maturity (Pethick et al., 2007).

In the PCA, the distance between farm and slaughterhouse, carcass weight, maturity, and ultimate pH were considered simultaneously in the right upper third of the plot. This shows why the first two PCAs explain only 57.2% of the total variability of the dataset, with 31.6% corresponding to the first principal component and 25.6% to the second principal component. Results from Principal Component Analysis (PCA) confirmed a low correlation between ultimate pH and distance and a significant correlation between maturity and carcass weight (Figure 5). The contribution of the ultimate pH in the first dimension is 16.82% and in the second dimension is 11.91%; distance from farm to slaughterhouse contributes 2.16% and 63.25%, in the first and second dimensions, respectively; carcass weight contributes 49.47% in the first dimension and 0.09% in the second dimension; and animal maturity contributes 31.55% and 24.76% in the first and second dimensions, respectively.

However, these results should be interpreted with caution due to the large amount of noise in the data. Because of this, it is important to emphasize that in the current study, our protocol was insufficient to adequately test our hypothesis, because the primary objective of the present case study was to make an exploratory analysis of the company’s data, taking into consideration all the data obtained during the 6-mo period evaluated, to have a robust dataset with pre- and post-slaughter data.

pH as a Function of Carcass Weight, Maturity, Distance

Results from the regression analysis showed that distance does not have a significant effect on pH ($P = 0.634$). Carcass weight significantly affects pH ($P < 0.001$) with a low coefficient of 0.000266, and, as such, has a very small effect.

Animal maturity (age) negatively affects pH as well ($P < 0.001$) but also with a very small effect (the coefficient being -0.000806).

$$y_i = 5.67 + 0.000266x_{i1} - 0.000806x_{i2} + 0.00000165x_{i3}$$

Where y_i represents the measured ultimate pH, x_{i1} represents the carcass weight, x_{i2} represents the animal maturity evaluated for the carcass, x_{i3} represents the distance between the farm and the slaughterhouse.

The value of R^2 was 0.016, which indicates that only 1.6% of total variability can be explained by this regression model. Therefore, 98.4% of the variability is attributable to other

Table 4. Point estimate of variance components of random effects and model error respectively, using the restricted maximum likelihood method. Lower and upper bounds of 95% confidence intervals of the variance components of random effects and model error

Variation	Point estimate	Lower limit	Upper limit
Random effects	0.02979055	0.02698031	0.0328935
Random error	0.06518885	0.06466902	0.06571286

factors not considered here. Thus, results from the multiple regressions model confirm the previous results from the PCA. However, the effects even though small were detectable due to the large sample size.

pH Variability Between and Within Farms

Results from 95% confidence intervals of variance of the random effects and of the random error showed that the variability within farms is higher than between farms (Table 4).

These results may be explained by the fact each farm is at a different distance from the slaughterhouse, and by each farm having provided several carcasses with different characteristics. Because of this, the variability of the pH of the carcasses provided by each farm is greater than the variability of carcass pH between farms. The estimate of the random effect variance is smaller than the estimate of the random error variance of the model. This may be due to the high variability in the characteristics of carcasses and in meat quality of cattle is multifactorial. Indeed, the high variability as reported by Clinquart et al. (2022) is often linked to the priorities of the farming system. The conclusion reached was that the diversity of farming systems is a consequence of the diversity in several factors: breed (dairy or beef), age, and sex (bulls, steers, heifers, cull cows) used to produce beef. Further, there are other factors linked to farming practices (e.g., diet, especially grazing) that have a strong influence on the sensory, nutritional, technological, and extrinsic attributes of meat quality (Clinquart et al., 2022).

Liu et al. (2022) also reported the synergies and antagonisms between beef quality dimensions. To give two examples: the effect of genetics alone (highly muscled breeds, local breeds, etc.), and different diets (pasture vs inland, organic vs conventional on grass) have different effects on the attributes of meat quality. These two factors vary to a greater or lesser degree within a given farm's herd as well as between the herds of different farms. Although the study of genetic improvement of the Nellore breed is widespread in Brazil, the animals used in the present study were not genetically identified as Nellore either individually or in aggregate but were classified as Nellore by the farms. This results in variability of carcass characteristics, even when they come from the same farm as reported in the literature, even when the animals are of the same gender. This justifies the result obtained through the mixed model (Table 4).

It is worth noting that improvements at the farm level can be impeded or even eliminated by poor transport, substandard slaughter and processing practices. All these considerations explain why inter-animal variability in quality can be high, even when a population of animals are products of the same farming system (Duarte et al., 2011). In the present study, pre- and post-slaughter protocols were those recommended by Brazilian legislation.

Modeling the Relationship Between Carcass Weight and Maturity and Farms

Results from a linear mixed model show that maturity has a significant effect on the carcass weight ($P < 0.001$) with a large coefficient of 2.90. A ratio likelihood test outperformed the mixed model multiple regression. The value of R^2 in the linear mixed model is 46.03%, which indicates that this total variability can be explained by the mixed regression model. Therefore, 53.97% of the variability is attributable to other factors not considered here. The Linear Mixed Model of the relationship between carcass weight and maturity and the farms confirms the results for Pearson's correlation between carcass weight and maturity (Table 3), as well as by PCA (Figure 5). As previously noted, these results were also found by other researchers (Bureš and Bartoň, 2012; Silva et al., 2019). Consistent with Pethick et al. (2007), Silva et al. (2019), and Bureš and Bartoň (2012), we conclude that the age at which an animal is slaughtered determines the weight and composition of the carcass based on the stage of maturity reached.

Several factors should be considered when developing guidelines to reduce cattle transport stress and shrinkage: the type of cattle, ambient temperature, transport duration, driving quality, and time and origin of loading (González et al., 2012a).

Conclusion

Beef carcass traits can be affected by carcass weight and maturity, but only to a limited extent. The hypothesis that long distances would significantly affect beef quality was not confirmed for the Nellore breed in the conditions studied. This could be because of low stress during transport, as well as the physical characteristics of the Nellore breed that favor greater resistance to tropical climatic conditions.

In addition, the strategy of purchasing animals within a radius of 300 km, equivalent to a maximum of 8 h of transport time, is consistent with the literature on changes in the quality of bovine carcasses due to transport time. This is an observation beneficial to the company and conforms to the standards required by the Brazilian market and to those markets, to which Brazil exports.

An experimental study on a much smaller scale, with an assessment of stress indicators, such as lactate, glucose concentrations, cortisol concentration and creatine kinase, norepinephrine and epinephrine, or bruise score sheet to evaluate the consequences on beef eating quality, is necessary to understand any interaction between these parameters and the benefits for the supply chain so that the meat industry can further improve animal welfare and meat quality during pre-slaughter commercial operations. This study which used a dataset provided by a slaughterhouse can serve as a source of useful indicators on a large scale. Although meat production has become more efficient and line speed has increased, there

is still room for improvement throughout the pre-slaughter logistics chain.

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2.2. Does transport affect the eating quality potential of beef from Limousin cows in France? - A case study

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Does transport affect the eating quality potential of beef from Limousin cows in France? - A case study

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ABSTRACT

We hypothesized that transportation might impact beef sensory quality, particularly as the distance between farms and the slaughterhouse increases. Specifically, we expected that pre-slaughter transport over longer distances would induce stress in the cattle, resulting in elevated ultimate pH and, consequently, reduced beef quality. Thus, this study aimed to specifically study the effects of transport in commercial conditions of Limousin cows from farms located in different areas of France to slaughter on ultimate pH (pHu) measured in the *Longissimus thoracis* muscle (LT), marbling (two major factors affecting eating quality) and the MSA Index (a global indicator of potential eating quality at the carcass level). Cattle were studied according to distance (<50 km; between 50 and 150 km; and between 150 and 250 km from the slaughterhouse) and according to transport time from the farm to the slaughterhouse (divided into short, moderate, and extended). We found that neither distance nor transport time significantly affected pHu of beef and the other studied parameters (cold carcass weight, meat color, MSA Marbling and MSA Index). Consequently, in our commercial conditions, we concluded that the effects of transport on beef carcasses and beef eating quality of Limousin cows are negligible.

1. Introduction

The effect of road transport on beef quality is a multifaceted issue encompassing various stressors such as load density, microclimates, handling procedures, conditions and duration of transport (González, Schwartzkopf-Genswein, Bryan, Silasi & Brown, 2012; Mendes et al., 2024b; Schwartzkopf-Genswein, Ahola, Edwards-Callaway, Hale & Paterson, 2012, 2016). These have been shown to have a negative effect on beef eating quality in addition to raising animal welfare concerns (Astruc & Terlouw, 2023; Gruber et al., 2010; Padalino, Menchetti, Mininni, Tullio & Nanni Costa, 2021; Prache et al., 2022; Wigham, Butterworth & Wotton, 2018). Transport time appears to have the most pronounced consequences on beef quality with significant economic impacts because of its effects on carcass weight, sensory qualities, and mortality rates during transport (González et al., 2012).

In order to reduce these stress factors associated with animal transport, European Commission (EC) (2005) was promulgated. This regulation imposes specific requirements depending on transport duration (whether less than or greater than 8 h) and the species transported (specifying minimum load density and maximum duration of the journey). The European Food Safety Authority (EFSA) (2022) recently stipulated that adult cattle should not be transported for longer than 29 h, after which they must have access to food and water for 24 h.

Ultimate pH (pHu) is a relevant indicator of beef quality, significantly influencing its shelf life, processability, and water retention, and can be used to infer the effects of transport from farm to slaughterhouse on the final quality of beef. Of particular importance are the effects of suboptimal handling during transportation (Ponnampalam et al., 2017), which can result in muscle glycogen depletion, inadequate acidification, and less than optimal ultimate pH after slaughter (Gagaoua et al., 2021).

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This can lead to darker beef with less desirable sensory properties, especially reduced tenderness, juiciness, and flavor (Gruber et al., 2010), resulting in a higher incidence of DFD (Dark, Firm and Dry) beef (Gruber et al., 2010; Hemsworth et al., 2011). Insufficient glycogen stores result in beef exhibiting characteristics associated with DFD (Ponnampalam et al., 2017; Wicks et al., 2019). Since each animal reacts to stress differently, stress levels prior to slaughter need either to be directly measured or to be kept at a very low level. Due to this variability of stress reactions to environmental stimuli, statistical models used to predict beef eating quality need to take this variability into account (Terlouw et al., 2021). In practice, dark-cut carcasses are discounted during beef carcass grading and devalued, which causes economic losses for the beef sector. This is the case, for example, when using grading schemes such as Meat Standards Australia (MSA) where carcasses with pH_u > 5.7 and meat color scores >3 are excluded.

A challenge in this context is to correctly assess the sensory quality of beef. So far, the best approach to do so is the MSA grading scheme (Bonny et al., 2018b; Mendes et al., 2024a). It is based on precise protocols to collect data gathered both before and at the slaughterhouse to predict beef eating quality (Bonny et al., 2018b). MSA is regarded as one of the most sophisticated beef grading systems, because it not only evaluates the potential eating quality of various cuts according to different cooking methods (Bonny et al., 2018b), but also estimates the potential eating quality of the whole carcass (McGilchrist, Polkinghorne, Ball & Thompson, 2019). A European adaptation of the MSA protocol which is the 3G (Guaranteed Global Grading), (Global Guaranteed Grading 2023) protocol is being studied in different European countries (Hocquette et al., 2020).

Information on the effect of transport time on beef eating quality in practical and commercial conditions is still limited, especially in France, the leading beef producer in the European Union (EUROSTAT, 2022; reviewed by Mendes et al., 2024a). Indeed, only a few studies have had access to large commercial datasets to investigate the effects of stress during transport, with the notable exceptions of Levakhin et al. (2017) with calves from the Russian federation, Polkinghorne, Philpott and Thompson (2018) with Australian steers and Mendes et al. (2024b) with mainly entire males from Brazil. Mendes et al. (2024b) concluded that long distances did not have a significant impact on ultimate pH and therefore on quality potential of beef from Nellore males in Brazil. Similarly, Polkinghorne et al. (2018) showed that transportation had no significant effect on characteristics of live steers and carcasses, consumer sensory scores and objective beef quality of the *Longissimus lumborum*, also known as striploin. Levakhin et al. (2017) indicated a higher sensitivity to transport of Limousin calves compared to other cattle types.

In addition, predicting beef eating quality using commercial data is a challenge except when using the MSA model when carcasses are graded according to the MSA protocols. The only study on transport effect on consumer sensory scores using the MSA grading scheme is that of Polkinghorne et al. (2018) with Australian steers, but this work was limited to effects on eating quality potential of the striploin.

The MSA grading scheme is based on different predictors of eating quality including marbling, known to be positively correlated with beef sensory traits such as juiciness, color, tenderness, and taste (Stewart et al., 2021). The French National Food Conference recently recommended that the meat sector, represented by INTERBEV, should introduce marbling into the French beef classification system (EtatsGénéraux de l'Alimentation EGA, 2018). The inclusion of marbling in the French or even European classification scheme could improve the quality and economic value of beef products as there is no significant relationship between the EUROP carcass classification and the eating quality of beef (Bonny et al., 2016, 2017; Liu et al., 2020). Moreover, the MSA index is another crucial parameter of interest recently suggested to assess the potential eating quality of the whole carcass (McGilchrist et al., 2019). This index describes the average consumer eating experience for the entire carcass by combining all the eating quality scores (MQ4), by

weighting tenderness, juiciness, flavor liking and overall acceptability scores of each muscle based on its most common cooking method, MQ4 scores being weighted proportionally to the weight of each individual cut in relation to the total weight of all cuts (Bonny et al., 2018a).

Based on this updated tools and knowledge, for the first time in France, potential consequences of transport stress on beef eating quality were assessed in commercial conditions using the MSA index at the carcass level. Indeed, we hypothesized that transportation might impact beef sensory quality, particularly as the distance between farms and the slaughterhouse increases. Additionally, this study investigated for the first time the effects of stress of cows (which produce the major part of beef in France) from a late-maturing breed (Limousin) during transport to slaughter from farms located in different geographical areas, considering that the Limousin breed may be more sensitive to transport stress (Levakhin et al., 2017).

2. Material and methods

2.1. Data set

The dataset used in this study, provided by CV Plainemaison-Beauvallet, a commercial slaughterhouse in Limoges, consists of records from 4407 beef carcasses from Limousin cows, with each carcass having its own record. Quality checks were applied to validate this dataset, including verification of completeness (ensuring all records contained necessary information), consistency checks across different variables, and exclusion of records with missing or implausible values. These procedures were implemented to ensure the reliability and integrity of the data used in the analysis. This slaughterhouse is the major one involved in beef production from the Limousin breed. It was also selected to ensure that all animals were processed under consistent and standardized conditions, minimizing variability in carcass treatment and, thus, ensuring the reliability of the results. This choice was crucial for maintaining the integrity of the study's focus on the effects of transport, as it avoided potential confounding factors associated with differing slaughter practices. These cattle were slaughtered between January 2020 and October 2022. Entries contain among others beef carcass traits, such as age in months (itself related to animal maturity) and cold carcass weight (CCW). Carcass weight is typically measured within 2 h of slaughter after removal of head, hide, feet/legs, thoracic organs, internal fats, and internal organs and is expressed as cold carcass weight, which is 0.98 times the hot carcass weight according to the EUROP guidelines (Commission of the European Communities, 2008).

The company purchased these animals from different geographical areas in France, but mainly from the central-western region (Zones 1 and 2) because of their proximity to the slaughterhouse. These animals are representative of beef cattle raised in the Limousin region of France and all animals were transported by very experienced drivers. The drivers and stockyard staff had previously received training in animal welfare practices. The geographical zones were defined as follows: zone 1 (less than 50 km from the slaughterhouse), zone 2 (between 50 and 150 km), zone 3 (between 150 and 250 km) and zone 4 (>250 km), as shown in Fig. 1. Transport time from the farm was an average of 1.3 h (see Table 1). The transport time from farms to the slaughterhouse was divided into the following categories for pH_u and CCW: short (less than or equal to 47 min), moderate (between 47 and 71 min) and extended (> 71 min). For MSA data, Marbling and MSA Index, these categories were short (less than or equal to 22 min), moderate (between 22 and 42 min) and extended (> 42 min). These divisions are derived from the box plots in Figs. 2 and 3 (the box extends from the 25th to the 75th percentile, with whiskers indicating minimum and maximum values).

Animals were handled in accordance with the French animal protection regulations defined by the French legislation (Code Rural, articles R214-64 to R214-71; Legifrance, 2016). Animals from zones 3 and 4 were transported to the slaughterhouse the day before slaughter. In all cases and for all zones, all animals were in good conditions on arrival.

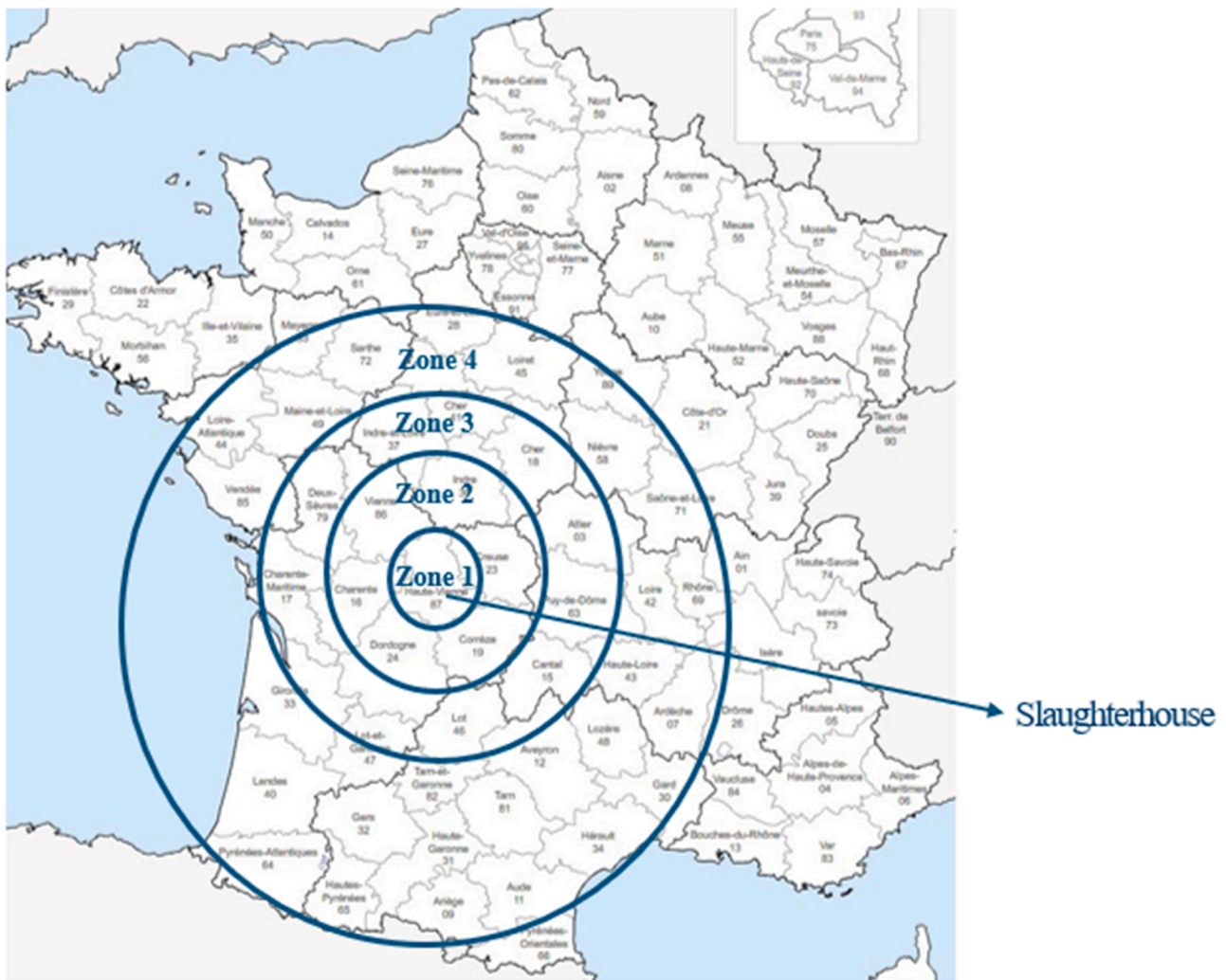


Fig. 1. Geographical distribution of farms by distances from farms to the slaughterhouse.

Table 1

Descriptive statistics (mean, standard deviation (SD), coefficient of variation (CV), minimum, and maximum) for the measured traits for the studied cattle population.

	n	Mean	SD	CV (%)	Minimum	Maximum
ultimate pH	4407	5.76	0.13	2.22	5.05	6.30
Distance (km)	4407	98.96	71.03	71.77	5.5	596
Time (min)	4407	78.87	46.39	58.82	12	364
Animal age (months)	4407	110.49	46.39	45.03	5	256
Cold Carcass Weight (kg)	4407	407.88	70.96	17.77	140.9	701.2
EU Conformation score ¹	4407	8.93 (R+)	1.96	21.99	1	14
EU Fat score ²	4407	7.49 (3-)	2.83	37.77	1	9
Marbling	524	310.8	100.34	32.29	100	740
Meat Color	524	2,31	0.75	32.51	1 (1A)	6
MSA Index ³	524	50.46	4.03	7.99	37.82	62.49

¹ European conformation score were converted from P (- / = / +), O (- / = / +), R (- / = / +), U (- / = / +), and E (- / = / +) to classes from 1 (P-) to 15 (E+) according to Hickey et al. (2007).

² European fat scores were converted from 1 (- / = / +), 2 (- / = / +), 3 (- / = / +), 4 (- / = / +), and 5 (- / = / +) to classes from 1 (1-) to 15 (5+) according to Hickey et al. (2007).

³ 5-day MSA Index = carcass predicted MSA score calculated as the weighted sum of the predicted MQ4 (meat quality score) scores of all MSA cuts. The model assumes that all the animals were Achilles hung, and that all cuts were aged for 5 days and cooked according to the most common cooking method for each cut (McGilchrist et al., 2019).

Before slaughter, all animals were not given food for 24 h but had unrestricted access to water. Exsanguination from the jugular vein was performed after use of an electrical captive-bolt pistol. Slaughter was performed in accordance with EU regulations (European Commission (EC), 2009). Carcasses were dressed according to standard commercial

practices and were split between 30 and 50 min post exsanguination then chilled for 24 h at 2 – 4°C.

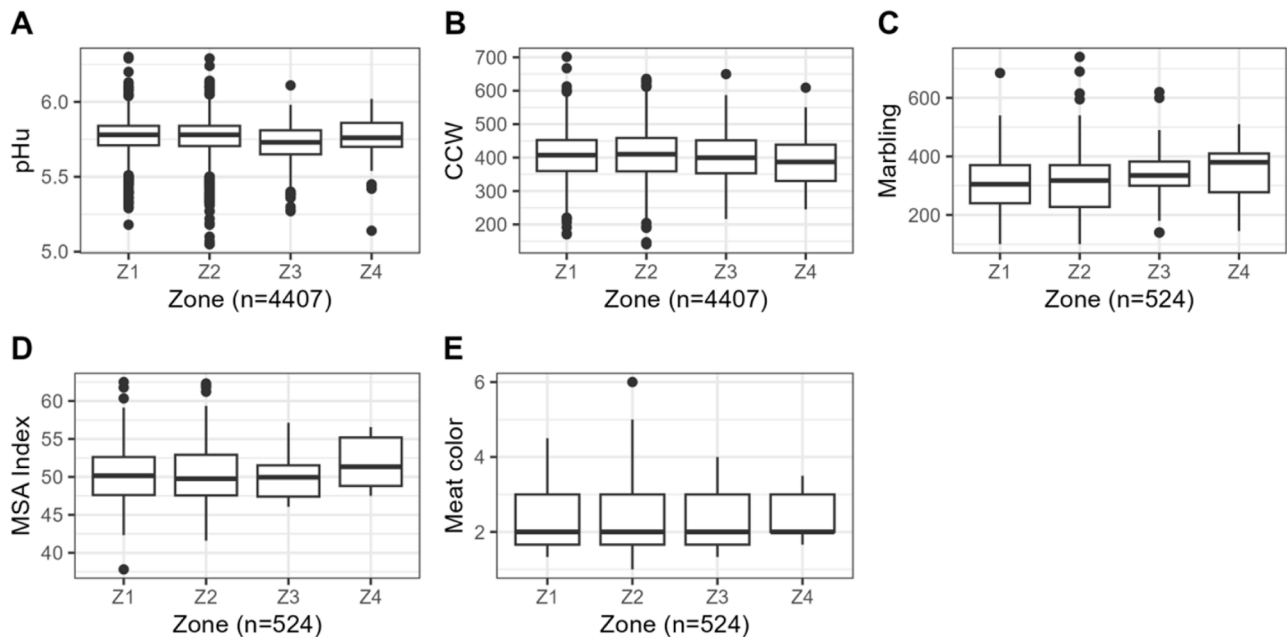


Fig. 2. Box plots of the distribution of pHu ($n = 4407$ carcasses) (A), Cold Carcass Weight (CCW, $n = 4407$ carcasses) (B), Marbling ($n = 524$ carcasses) (C), MSA index ($n = 524$ carcasses) (D) and Meat color (E) ($n = 524$ carcasses) in the different geographical zones studied in France.

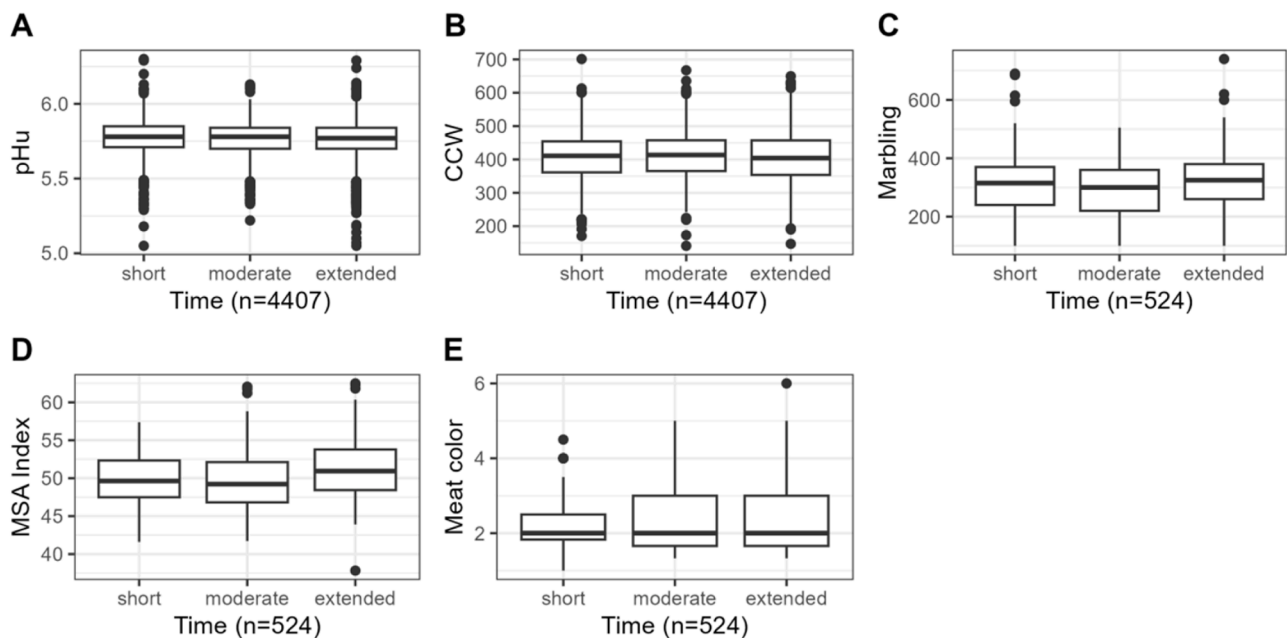


Fig. 3. Box plots of the distribution of pHu ($n = 4407$ carcasses) (A), Cold Carcass Weight (CCW, $n = 4407$ carcasses) (B), Marbling ($n = 524$ carcasses) (C), and MSA index ($n = 524$ carcasses) (D) and Meat Color (E) according to transport time class (short, moderate and extended).

2.2. Measurements

The carcasses were assessed according to EUROP criteria. This was done at the slaughterhouse by experts of the EUROP grid (Commission Regulation (EC) 1249/2008). According to the EUROP grid, five conformation classes were used (E, U, R, O, and P) as well as five fatness classes (from 1 to 5). Assessments of carcass conformation and fatness were based on visual inspection of carcasses. Depending on the degree of muscularity, carcasses received a score of 'E' for the most muscularity through to 'P' for carcasses with the least muscularity. European Union regulations have 3 subdivisions for each conformation: high "+", medium "=" and low "-". For this reason, an incremental scale ranging

from 1 to 15 was used, with 1 corresponding to P- (very low muscularity) and 15 to E+ (very high muscularity). In addition, the degree of fat cover of the carcasses (hereafter fatness score), which corresponds to the amount of fat on the outside of the carcass, was numerically scored from 1 (the leanest) to 5 (the fattest), with 3 subdivisions for each fatness score (-, = and +) as for conformation. This conversion of European conformation and fat scores into a continuous 15-point scale has been described by Hickey et al. (2007).

Ultimate pH (pHu) was assessed after 24 h of *postmortem* chilling at an average temperature between 0 and 4°C. Before measurement, the pHu meter was first calibrated at chilling temperature using pH 4 and pH 7 buffers. The pHu was measured in the *Longissimus thoracis* muscle (LT)

between the 6th and 7th ribs, anterior striploin piece.

2.3. MSA grading of carcasses and calculation of the MSA index

In addition, 524 carcasses were graded for MSA traits: ossification and marbling scores, rib fat thickness at the 10th rib and hump height using MSA chiller assessment standards by an MSA-certified grader under the auspices of AUS-MEAT and the International Meat Research 3G Foundation (AUS-MEAT, 2018).

After 24 h of *postmortem* chilling at an average temperature between 0 and 4°C, carcasses were graded. Marbling assessments were performed in accordance with the ABCAS reference standards (Meat, Livestock, Australia & Meat Standards, Australia, 2001,2018) as recently described (Kombolo-Ngah et al., 2024), following the UNECE Bovine Language Standards. The marbling standards have been tailored to European cattle and consumers through extensive collaborative research in Europe, with data storage facilitated by the IMR3GF (International Meat Research 3G Foundation).

The MSA marbling score, which provides a more detailed scale (ranging from 100 to 1190 in increments of 10), was used to indicate the amount, size, fineness and distribution of fat inclusions. Evaluation of MSA marbling scores and Meat color were performed at the 5th rib of the carcass according to the methodology described by Liu et al. (2021). A grader certified by the AUS-MEAT and International Research Meat 3G Foundation performed the assessments. The grader underwent uniform training and maintained certification in accordance with the Australian Beef Chiller Assessment System (ABCAS) standards in order to minimize variability in assessments. After cutting, the ribeye was exposed to air for a minimum of 20 min and up to 3 h to allow the meat to bloom prior to assessment according to MSA procedures. Grading was performed using standard visual cards provided by ABCAS to assess MSA scores.

The MSA index was developed to provide feedback to the producer about the potential eating quality of his beef carcasses, with the opportunity of ranking animals and monitoring the impact of management and genetic changes on eating quality (McGilchrist et al., 2019). The MSA index was calculated with assumption of the standard aging time of 5 days. More detailed information about the MSA grading can be found in McGilchrist et al. (2019).

2.4. Statistical analysis

The data were analyzed using R software (version 4.3.0 - R Core Team, 2023). Descriptive analysis was done using a box plot according to DuToit, Steyn and Stumpf (2012). Median values are indicated by the line within the box plot.

One way classification analysis of variance model (ANOVA) was performed on the data set using the `avov()` function to determine significant differences between treatments:

$$y_{ij} = \mu + \tau_i + \epsilon_{ij} ; i = 1, \dots, a, j = 1, \dots, n.$$

where y_{ij} represents the ij -th measured values for the respective response variable of j th observation in the i th treatment, μ is the intercept, τ_i is the treatment effect, and $\epsilon_{ij}N(0, \sigma^2)$ is the random error. In this model, the treatment represents either the geographic zone or the class of transport time, and the response variable represents the ultimate pH, Cold Carcass Weight (CCW), the Marbling score, Meat color or the MSA index. Tukey tests were performed to determine which means differ in a set of contrasts (Behrendt, 2014).

We also fitted a mixed model to determine the relationship between each response variable related to meat eating quality (ultimate pH (pHu), Cold Carcass Weight (CCW), MSA Marbling, and MSA index) and geographic zones in France or class of transport time, while accounting for the random effects of producers within each zone or class of transport time. Meat color is not a predictor of quality in the MSA Index and was therefore not included in the linear mixed model analysis. This approach

was to confirm the previous ANOVA analysis especially when data were not normally distributed (i.e. with a significant Bartlett test for the variables ultimate pH and cold carcass weight in different times divided into short, moderate and extended). The statistical model can be expressed as follows:

$$y_{ij} = \mu + \tau_i + b_{ij} + \epsilon_{ij}$$

where y_{ij} represents the i th measured values for the respective response variable for observation j in zone or class of transport time, μ is the intercept, τ_i is the fixed effect of geographic zone or class of transport time, $b_{ij}N(0, \sigma_b^2)$ is the random effect of the producer within the zone or class of transport time and $\epsilon_{ij}N(0, \sigma^2)$ is the random error. This model allowed us to assess the impact of class of transport time on pH while considering the variability introduced by individual producers within each zone or class of transport time (Pinheiro, Bates & Core Team, 2023).

3. Results and discussion

3.1. Variability in carcass data between and within geographical zones

Descriptive statistics of animal and carcass traits of Limousin cows are reported in Table 1.

The ultimate pH mean value for the current study was 5.76 ± 0.13 , with a coefficient of variation of 2.22% (Table 1), which is consistent with findings from Liu et al. (2021), who reported mean values of 5.7 ± 0.16 . Additionally, the mean pHu values reported in other studies are within the normal range for cattle, with values of 5.59 ± 0.14 and 5.57 ± 0.11 with or without extreme values, respectively (Gagaoua, Picard & Monteils, 2017, 2018a, 2018b). This indicates that most of the animals were not likely to have experienced significant pre-slaughter stress, since 3.43% of the cows had an ultimate pH higher than 6.0, which is a threshold associated with glycogen loss related to stress (Gagaoua, Picard, Soulat & Monteils, 2018c).

It should be noted that there is no technical or regulatory limit in France for meat with a high ultimate pH. Whereas the Afnor V46 001 standard (December 1996) refers to a value of 6.0, the generally accepted limit is between 5.8 and 6.0. This limit varies according to market requirements (INTERBEV, 2023). These results are generally consistent with MSA standards, reflecting acceptable levels of pHu for commercial grading. Additionally, strict adherence to MSA requirements is not necessary for research purposes, allowing for some flexibility in exploring different aspects of meat quality under varied conditions (MLA, personal communication).

It should be noted that a pH value exceeding 5.8 is frequently designated as DFD (Dark, Firm and Dry) by some researchers (Hughes, Clarke, Purslow & Warner, 2017; Lomiwes, Farouk, Wu & Young, 2014; Ponnampalam et al., 2017). Such variations in ultimate pH can lead to significant losses in the beef industry. It is worth noting that stress in cattle can result in weight loss, carcass lesions, and reduced meat quality. These are primarily due to elevated ultimate pH levels (>5.8), which can impact tenderness and meat color (resulting in darker meat) (Hughes et al., 2017; Lomiwes et al., 2014).

Only the pHu showed any significant zone-dependent variation (Table 2). These findings suggest that monitoring ultimate pH levels in carcasses post-slaughter and implementing strategies to minimize stress in cattle would ensure higher meat quality and reduce economic losses in the beef industry (Hughes et al., 2017; Ponnampalam et al., 2017).

The mean carcass weight was 407.88 ± 70.96 kg with a coefficient of variation of 17.77% (Table 1). This is consistent with findings by Liu et al. (2021), who reported a mean carcass weight of 356.5 ± 95.8 kg for predominantly Limousine cows. As shown in Table 2, no significant difference in cold carcass weight was observed across different zones.

The mean MSA marbling score obtained in our study (310.8) was slightly higher than that of 288 at the 5th rib reported by Liu et al.

Table 2

Carcass traits in different geographic zones in France of the following traits pHu ($n = 4407$ carcasses), Cold Carcass Weight (CCW, $n = 4407$ carcasses), Meat color and Marbling ($n = 524$ carcasses) and MSA Index ($n = 524$ carcasses).

	Geographic zone according to the distance between the farm and the slaughterhouse				SEM ¹	P value
	Zone 1	Zone 2	Zone 3	Zone 4		
pHu	5.77 ^a	5.76 ^a	5.72 ^b	5.75 ^{a,b}	0.002	<0.05
CCW (kg)	405.84	409.70	403.64	392.81	1.069	NS
Marbling	308.46	306.20	333.55	354.21	4.374	NS
Meat Color	2.30	2.31	2.43	2.31	0.030	NS
MSA Index	50.36	50.50	50.13	51.91	0.227	NS

^{a,b} Means with different letters within a row are significantly different (p value <0.05).

¹ SEM - Standard error of the mean.

(2021). This result was derived from 208 mainly French Limousine cows, which were graded according to the Australian Beef Carcass Chiller Assessment System (ABCAS) used in the MSA/3G grading scheme. Carcasses analyzed in the current study were slightly heavier than those of Liu et al. (2021), which is consistent with more expressed marbling. Consistent with Liu et al. (2021) and this study, Polkinghorne et al. (2018) found an MSA Marbling score of 291. Santinello et al. (2024) evaluated a dataset comprising 55 young bulls and heifers from late-maturing breeds at an Italian abattoir. This assessment was performed in accordance with MSA guidelines, considering both the locations and sides of carcass grading. It reported a mean MSA marbling score of 458, which is notably higher than the marbling values obtained in our study and by Liu et al. (2021). This can be partly explained by the intensive rearing conditions in specialized Italian fattening farms, where young bulls are fed a diet rich in concentrates for six months before slaughter (Santinello et al., 2024).

The mean meat color score observed in our study (2.30) was slightly lower than those reported by Liu et al. (2021) at the 5th rib (2.5) in a study conducted in France, which used 208 mainly French Limousin cows, and significantly lower than the results found by Polkinghorne et al. (2018) at the 10th rib in a study conducted in Australia, which involved a total of 343 steers (3.2). Factors such as diet, ultimate pH, and muscle type can influence the characteristics of meat color (Mancini, Hunt, 2005), which explains the differences observed between the studies. Notably, there was no significant difference in meat color across different geographical regions within. The mean meat color in our study is considered acceptable according to the MSA grading scheme (<3), although meat color is not a parameter used in the prediction model of the MSA Index, as outlined by the MSA grading system (AUS-MEAT, 2018).

The mean MSA Index found in the current study (Table 1) was similar (50.46) to the values reported by Liu et al. (2021). However, it should be noted that the MSA marbling score plays a key role in determining the MSA Index, especially when other predictive factors are held constant (same hanging method, no *Bos indicus* content, no hormone growth promotion status, etc.) (Pethick, Hocquette, Scollan & Dunshea, 2021). Furthermore, Limousine cull cows are generally slaughtered once they have completed their growth phase, and therefore exhibit homogeneous marbling deposition along grading sites. This is likely related to their greater age (Liu et al., 2021). Santinello et al. (2024) observed a higher MSA index (61) for young bulls. This may be explained by the fact that the cull cows are likely producing less muscle rich in connective tissue than younger animals, which may decrease tenderness. In addition, young animals in the Italian finishing system are fed a diet rich in concentrates, which favors marbling deposition (Santinello et al., 2024) and therefore eating quality.

Mixed linear models were fitted to data, and confidence intervals for variance components and contrast of least square means were estimated. Results from the 95% confidence interval for the variance of components of the producer effect within zones the carcass traits within geographic

zones showed that there is significant variability between producers in Cold Carcass Weight, Marbling and MSA Index, but pHu showed no significant variability between producers (Table 3).

Furthermore, when accounting for variability between producers, the contrasts of least square means revealed statistical significance only between zone 1 and 3, and between zone 2 and 3, regarding ultimate pH (pHu), as well as between zone 1 and 4 for marbling. Values of pHu were found to be lower in the geographic zone 3, far from the slaughterhouse (5.72 versus 5.77, $P < 0.05$, Fig. 2). Importantly, the rest periods for cattle in zones 1 and 2, as well as in zones 3 and 4, were similar, with animals from zones 3 and 4 having been transported the day before slaughter. However, the only significant difference was observed in zone 3, suggesting that the rest period did not influence any parameter including the pHu value. Although no confounding effect related to the rest period was observed, the lower pHu observed in zone 3 is likely attributable to factors specific to that geographic zone, potentially including regional production systems or environmental conditions. These potential confounding effects and other limitations of the dataset are acknowledged in the conclusion.

3.2. Variability in carcass data as function of transport time

The effects of class of transport time (short, moderate and extended) on beef carcass traits are reported in Table 4 and Figs. 3 and 4.

Mendes et al. (2024b) investigated the effects of stress during transport using a large data set (30,230 Nellore carcasses) and concluded that long distance did not have a significant impact on pHu, and, consequently, on the quality of Nellore beef in Brazil. In their study, animals were sourced within a 300 km radius of the slaughterhouse, corresponding to a maximum transport time of 8 h. In contrast, the present study with Limousin cows in France observed minimal or even negligible effects of distance and transport time on pHu. This is likely due to the low stress levels experienced during transport, supported by the strategy of sourcing animals within a 99 km radius (equivalent to a maximum transport time of 6 h). These findings are consistent with existing literature, which suggests that shorter transport distances and well-managed pre-slaughter conditions can minimize the impact of transport on meat quality (Lacerda et al., 2022; Polkinghorne et al., 2018).

In this study with Limousine cows, transport time—whether short, moderate, or extended—had a significant effect on pHu, CCW, as shown in Table 4, and MSA Index (Fig. 4). However, the effects observed in our study were small. The differences in findings between Mendes et al. (2024b) and our study may be attributed to the distinct physical characteristics of the Nellore breed, as highlighted by Mendes et al. (2024b).

Although we did not directly measure stress indicators (e.g., lactate, glucose, cortisol, creatine kinase, norepinephrine, epinephrine, or bruising scores), our results are consistent with other studies (Gruber et al., 2010; Hultgren, Schiffer, Babol & Berg, 2022; Polkinghorne et al., 2018) that used these indicators to assess the effects of transport on beef quality. These studies, conducted with smaller sample sizes, similarly reported no significant impact of transport time on ultimate pH.

Polkinghorne et al. (2018) found that extending the transport time from 12 to 36 h did not negatively impact beef eating quality according

Table 3

Lower and upper limits of the 95% confidence interval for the variance components of the producer effect within zones of the following traits pHu ($n = 4407$ carcasses), Cold Carcass Weight (CCW, $n = 4407$ carcasses), Marbling ($n = 524$ carcasses) and MSA Index ($n = 524$ carcasses).

Trait	σ^2	
pHu	2.5%	97.5%
Cold Carcass Weight (kg)	0.00	0.05
Marbling	68.09	71.19
MSA Index	31.92	59.47
	1.65	3.03

Table 4

Carcass traits in different times divided into short, moderate and extended of the following traits pHu ($n = 4407$ carcasses), Cold Carcass Weight (CCW, $n = 4407$ carcasses), Marbling ($n = 524$ carcasses) and MSA Index ($n = 524$ carcasses).

	Pre-slaughter transport time (h)*			SEM ¹	P value
	short	moderate	extended		
pHu	5.77 ^a	5.76 ^{a,b}	5.75 ^b	0.002	<0.05
CCW (kg)	408.20 ^{ab}	412.21 ^a	405.60 ^b	1.069	<0.05
Marbling	309.70	296.02	319.33	4.384	NS
Meat Color	2.27	2.36	2.30	0.030	NS

^{a,b} Means with different letters within a row are significantly different ($P < 0.05$).

¹ SEM - Standard error of the mean.

* The transport time from farms to the slaughterhouse was divided into the following categories for pHu and CCW: short (less than or equal to 47 min), moderate (between 47 and 71 min) and extended (more than 71 min). For MSA data (marbling and color), these categories were short (less than or equal to 22 min), moderate (between 22 and 42 min) and extended (> 42 min).

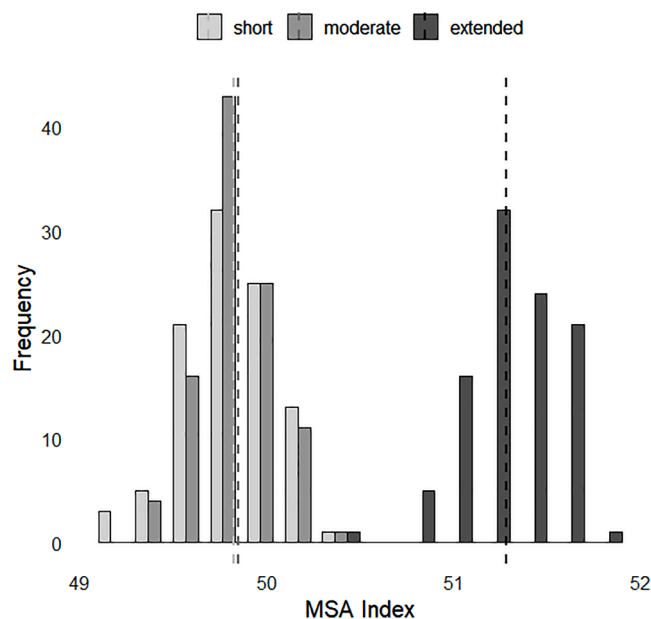


Fig. 4. Distribution of MSA Index ($n = 524$ carcasses) across different transport times [short (less than or equal to 22 min), moderate (between 22 and 42 min) and extended (> 42 min)]. The dotted lines represent the average MSA Index for each transport time group. Shades of gray indicate transport duration: light gray for short, medium gray for moderate, and black for extended transport times.

to the MSA grading scheme and physico-chemical analyses. From this, it can be inferred that the present study provided similar results regarding beef eating quality, because transport time was unlikely to be sufficient to cause any significant stress and depletion of glycogen stores in our animals. Longer transport duration may alter the rumen environment, thereby increasing the acetate/propionate ratio, which, in turn, would reduce blood glucose levels and contribute to affect ultimate pH (Deng, He, Zhou, Xu & Xiong, 2017) in addition to glycogen depletion in muscles. However, this is unlikely to have occurred in the animals studied, because even the longest transport time (6 h) did not hinder decline in pHu.

In addition, pHu values were lower for the extended times, which were farther away from the slaughterhouse (5.75 versus 5.77, $P < 0.05$, Table 4, Fig. 3), which is possibly due to transport conditions, with driver experience being an important factor. In the development of comprehensive guidelines for reducing cattle transport stress, it is essential to consider multiple factors, including the type or breed of

cattle, ambient temperature, transport duration, driver experience, and road conditions (González et al., 2012). In this study, we specifically focused on the impact of transport duration on pHu and meat quality in controlled commercial conditions.

A practical approach to measure stress levels in individual animals at the time of slaughter could involve using threshold values for various indicators, including ultimate pH, within the MSA grading scheme. Such methods for assessing stress would enable more precise evaluations of pre-slaughter practices, such as transport duration and conditions (Polkinghorne et al., 2018).

Transport time, whether short, moderate, or extended, had a significant effect on the MSA Index (Table 4). This effect may be due to the interaction of transport-induced stress with a range of factors contributing to meat quality, such as marbling, hanging method, and ultimate pH (Pethick et al., 2021). In this commercial-scale study, meat color was evaluated as a proxy for ultimate pH, as these measures are generally correlated (Polkinghorne et al., 2018). The absence of any transport effect on color suggests a minimal practical impact of transport time on pHu, reinforcing the finding that transport has a negligible effect on beef quality.

Pre-slaughter transport distance was found to have a slight, but significant effect (Table 4), possibly because other factors, such as animal density, and lot mixing in truck compartments, related to transportation affect carcass weight (Mendonça et al., 2019). Variability in carcass characteristics has multiple sources, and is often related to the priorities of the farming system used (Clinquart et al., 2022). Even when carcasses originate from the same farm with animals of the same gender, there is noticeable variation in carcass characteristics (Chriki et al., 2013; Liu, Ellies-Oury, Stoyanchev & Hocquette, 2022). Along with Bureš and Bartoň (2012) and Silva et al. (2019), we conclude that the age at which an animal is slaughtered determines the weight and composition of the carcass due to the stage of physiological maturity at that time. This supports the result obtained from the variance analysis model.

It is worth noting that improvements in rearing practices at the farm level can be impeded or even completely negated by poor transport, substandard slaughter and processing conditions (Duarte et al., 2011; Mendes et al., 2024b). In the present study, the pre- and post-slaughter protocols used were those recommended by EU legislation and guidelines on Animal Welfare.

Mixed linear models were fitted to data, and confidence intervals for variance components and contrast of least square means were estimated. Results from the 95% confidence interval for the variance of components of the producer effect within different classes of transport time (short, moderate and extended) showed that there is significant variability between producers in Cold Carcass Weight and Marbling, but pHu and MSA Index showed no significant variability between producers (Table 5).

Furthermore, the contrasts of least square means revealed statistical significance only between short and extended transport times; regarding ultimate pH (pHu), as well as between moderate and extended transport times for marbling, CCW and MSA Index. The results from the linear mixed model were similar to those from the ANOVA for all carcass traits

Table 5

Lower and upper limits of the 95% confidence interval for the variance components of the producer effect within different times (short, moderate and extended) of the following traits pHu ($n = 4407$ carcasses), Cold Carcass Weight (CCW, $n = 4407$ carcasses), Marbling ($n = 524$ carcasses) and MSA Index ($n = 524$ carcasses).

Trait	σ^2	
pHu	2.5%	97.5%
Cold Carcass weight	0.00	0.07
Marbling	68.09	71.19
MSA Index	30.93	60.65
	0.00	2.41

except for MSA marbling.

4. Conclusion

We concluded that neither the distance from the farm to the slaughterhouse nor the transport time to slaughter had little effect on the ultimate pH of beef from Limousin cull cows. Using the MSA Index, potential effects on the eating quality of beef are small, even negligible. However, we observed significant variability in the variables studied, including potential eating quality, both between beef producers within a single zone and between producers in different geographic zones.

Weak effects, or even the absence of effects, of distance and transport time between farm and slaughterhouse prior to slaughter may be explained by low levels of stress experienced by animals during transport, associated with the strategy of only purchasing animals within a radius of 99 km, which is equivalent to a maximum transport time of 6 h.

Although the findings suggest that transport has minimal impact under these conditions, the study did not include physiological stress measurements, such as cortisol, lactate, glucose, or creatine kinase, which could provide deeper insights into the stress levels experienced by animals. Future research could benefit from smaller-scale, controlled studies that incorporate these stress markers to evaluate their effects on beef quality. Such studies would enhance our understanding of how these physiological factors interact with quality monitoring systems along the value chain, ultimately supporting the meat industry's efforts to advance animal welfare and optimize meat quality in commercial pre-slaughter operations.

Ethics statement

This work did not need any ethical approval since it is based on commercial data already collected by one private company.

CRedit authorship contribution statement

Nathalia da Silva Rodrigues Mendes: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Renato Rodrigues Silva:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Moïse Kombolo-Ngah:** Formal analysis, Data curation. **Pierre-Philippe Rivet:** Formal analysis, Data curation. **Jérôme Tondusson:** Validation, Funding acquisition. **Tatianne Ferreira de Oliveira:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Sghaier Chriki:** Writing – review & editing, Validation, Supervision. **Marie-Pierre Ellies-Oury:** Writing – review & editing, Validation, Supervision. **Jean-François Hocquette:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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2.3. Discussion

Contrary to our initial hypothesis, we found that in both studies, the transport time associated with the distance between the farm and the slaughterhouse did not significantly affect the ultimate pH (pHu) of the studied carcasses from two different bovine genotypes in Brazil and France. While the potential consequences of transport stress on beef eating quality have not been studied in Brazil, the French study suggests that these effects are likely to be minimal.

These results can be explained by the low stress levels experienced by the animals during transport. This supports the strategy of the private company to purchase cattle within a 300 km radius in Brazil (equivalent to a maximum of 8 hours of transport) and 99 km in France (equivalent to a maximum of 6 hours of transport). These findings reflect compliance with Brazilian and European Union legislation on animal welfare. Additionally, this might be explained also at least in part by the physical characteristics of the Nelore breed, which is more resistant to tropical climatic conditions. Similarly, transport stress was not found to affect carcass traits of Limousin cows in our French study, despite previous findings by Levakhin et al. (2017), which reported significant effects in Limousin calves. The differences between these studies may be attributed to the use of calves in their research, compared to the more stress-resistant cows in our study, as well as the longer transport time in their study (5 hours versus an average of 80 minutes in ours).

The French study provided valuable large-scale data, especially when combined with indicators of eating quality, such as MSA marbling scores and the MSA index. The use of the MSA index indicated that the potential effects on beef eating quality were at most minor. However, we observed significant variability in the studied variables, including potential eating quality, both among beef producers within a single zone and between different geographic zones.

Our findings in Brazil and France are consistent with other studies (Gruber et al., 2010; Mendonça et al., 2019; Hultgren et al., 2022; Polkinghorne et al., 2018), which evaluated stress indicators such as lactate, glucose, cortisol, creatine kinase, norepinephrine, and epinephrine concentrations, or used bruising score sheets to assess beef quality. Prolonged transport times may alter the rumen environment, increasing the acetate/propionate ratio and reducing blood glucose levels, which in turn affects ultimate pH (Deng et al., 2017) through glycogen depletion in muscles. However, this seems unlikely to have occurred in our study, because even the

longest transport times (8 hours in Brazil and 6 hours in France) did not prevent normal decline in pHu.

When developing guidelines to mitigate cattle transport stress, several factors need to be considered, including breed, ambient temperature, transport duration, driver experience, and road conditions (González et al., 2012). A practical method for assessing stress at the time of slaughter would require establishing threshold values for different metrics, including ultimate pH within the MSA grading scheme. This would enable a more precise understanding of how pre- slaughter practices, such as transport time and conditions, affect meat quality (Polkinghorne et al., 2018).

Ferreira et al. (2024) demonstrated that Brazilian consumers did not show a clear preference for beef with different pH values at 48 hours post-mortem, although steaks with higher pHu were preferred for tenderness and fresh appearance. The sensory analysis methodology involved evaluating both raw and grilled steaks by a panel of 138 pre-screened consumers. Marbling evaluation was performed using the USDA photographic standard for grading, with no significant differences observed in marbling scores across groups with varying pHu values ($\text{pH} < 5.8$, $5.8 \leq \text{pH} < 6.0$, and $\text{pH} \geq 6.0$).

The variability of carcass traits observed between producers in our studies is often linked to the characteristics of the farming system, which refers to priorities of the farmers reflected by their decisions regarding their production methods, such as whether to focus on grazing or grain- finishing, the choice of breed (dairy or beef), and the use of different animal categories (bulls, steers, heifers, cull cows), all of which can lead to significant variation in carcass traits (Clinquart et al., 2022). Even when animals originate from the same farm, are of the same gender, follow the same feeding regime, carcass traits can vary significantly (Albechaalany et al., 2024; Chriki et al., 2013b; Liu et al., 2022). Furthermore, factors such as the type of diet, particularly the use of grazing versus concentrated feeds, strongly influence the sensory, nutritional, technological, and extrinsic attributes of meat quality (Clinquart et al., 2022).

CHAPTER 3. NON-DESTRUCTIVE METHODS FOR MEASURING AND PREDICTING MARBLING

Innovative and non-destructive methods have been developed to meet consumer demands for high-quality beef and to improve the evaluation of sensory parameters such as marbling, without the need for sample collection and further analysis in a lab. These emerging technologies are promising because they are not only non-invasive but also fast, accurate, and cost-effective, allowing for the direct assessment of meat quality, especially carcass traits such as marbling (Mendes et al., 2024a).

Given the importance of marbling for meat quality, this chapter discusses studies that investigate the development of more consistent and accessible methods for its evaluation, replacing the reliance on MSA-accredited graders with objective measurement technologies.

In the first study, titled **Prediction of marbling in ribeye quartered at 5th- 6th rib of French beef using the Q-FOMTM Beef grading camera**, aimed to assess the potential of the Q-FOMTM Beef camera in predicting marbling scores in cattle slaughtered, taking into account the specificities of slaughtering in that country.

In the second study, we aimed to assess the feasibility of NIRS-based solutions in Brazil by comparing evaluations from MSA-certified graders with those from NIRS devices.

Our hypothesis is that the use of the Q-FOMTM Beef camera and near-infrared spectroscopy (NIRS) as among the best analytical techniques will allow marbling prediction, reducing costs and reliance on trained graders, while maintaining the high levels of accuracy and reliability required by the MSA grading scheme.

3.1 Prediction of marbling in ribeye quartered at 5th- 6th rib of French beef using the Q-FOMTM Beef grading camera

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Prediction of marbling score in ribeye quartered at the 5th- 6th rib of French beef using the Q-FOM™ beef assessment camera

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ABSTRACT

In the Meat Standards Australia (MSA) and Guaranteed Global Grading (3G) grading schemes, beef marbling is scored visually in the chiller by accredited graders from 100 to 1190 marble score points in increments of 10. This study aimed to evaluate a hand-held camera (Q-FOM™ Beef) for determining MSA marbling scores of carcasses quartered between the 5th and 6th rib. The carcasses were scored by two accredited graders, including an expert grader (i.e. a more experienced grader). The R^2 of correlation between scores of the two graders for 377 carcasses was 0.78 with a RMSE of 47.9. The R^2 of correlation between the scores of the expert grader and the Q-FOM™ for 285 carcasses was 0.75 with a RMSE of 44.9. For the grader-to-grader comparison, 75.9 %, 97.1 % and 100 % of the values were within 50, 100 and 200 marbling points, respectively. For the comparison between Q-FOM™ predictions and the expert grader, 78.6 %, 96.8 % and 99.7 % of the values were within 50, 100 and 200 marbling points, respectively. Both between visual graders and the Q-FOM™ against expert grader showed acceptable accuracy performance and fulfilled the accreditation criteria defined by AUS-MEAT in Australia. Additionally, 124 Q-FOM™ images were assessed on-screen by the expert grader. The R^2 of correlation between the in-chiller and on-screen MSA marbling scores was 0.78 with a RMSEP of 48.7. Thus, on-screen assessing met requirements for accreditation, and both in-chiller and on-screen visual assessments of MSA marbling score are acceptable inputs for developing a Q-FOM™ Beef marbling model.

1. Introduction

Intramuscular fat (IMF%) is found in muscle tissue between skeletal muscle fibers. Marbling is the visible white flecks and streaks of IMF (Hocquette et al., 2010; Lee & Choi, 2019; Lee, Yoon, & Choi, 2019). Both IMF% and marbling score have a significant effect on a number of beef quality traits such as juiciness, color, tenderness, and taste (Chen, Li, Du, & Cao, 2019; Hocquette et al., 2010; Stewart, Gardner, et al., 2021). Both Dikeman (1996) and Hocquette et al. (2011) found that

variation of 10 to 15 % of tenderness evaluation, and 2 to 56 % of variation in flavor, can be accounted for by IMF%, respectively. IMF% and marbling score varies between species, between breeds, and even more between muscle types in the same animal (Chriki et al., 2013). Other factors affecting IMF% and marbling score include gender, age, and feeding regimen (Chambaz, Scheeder, Kreuzer, & Dufey, 2003; Chriki et al., 2013; Hocquette et al., 2011; Thompson, 2004).

Approximately 75 % of the variation in IMF% can be explained by variation in visual scores by skilled assessors (reviewed by Ferguson,

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2004). In addition, Stewart, Gardner, et al. (2021), showed that visual marbling scores and data from chemical IMF% analyses give similar results ($R^2 = 0.32$ and $R^2 = 0.28$ respectively) in predicting beef eating quality. According to Stewart, Toft, et al. (2024) whether direct MSA marbling assessment or IMF% derived models for MSA marbling are used, the results are largely the same. The shortcomings of chemical methods for determining intramuscular fat percentage (IMF%) include that they are time-consuming, labor-intensive, and destructive to samples. These limitations hinder their practical application in an industrial environment. To address these issues and to reliably predict beef eating quality in an industrial setting, grading systems relying upon carefully trained and accredited graders were developed internationally and especially in Europe (reviewed by Hocquette et al., 2020).

However, in the EU, beef carcasses are evaluated using the EUROP grid, which describes the carcass conformation and fatness scores, but this grid does not include marbling indicators despite previous recommendations (Monteils et al., 2017). Studies in France (Bonny et al., 2018; Legrand, Hocquette, Polkinghorne, & Pethick, 2013; Liu et al., 2021) and in other European countries (Farmer & Farrell, 2018; Pogorzelski, Woźniak, Polkinghorne, Poitorak, & Wierzbička, 2020) have shown the importance of marbling for beef eating quality. Thus, the French National Food Conference recently recommended that the meat sector, represented by INTERBEV, introduce marbling into the French beef grading system (Etats Generaux de l'Alimentation EGA, 2018).

The MSA was developed in the 1990s to assess beef palatability under commercial conditions (Watson, Polkinghorne, & Thompson, 2008). Since then, it has come to be widely recognized as an innovative method for predicting beef eating quality (review by Bonny et al., 2018; Mendes, Briceno et al., 2024). The United Nations Economic Commission for Europe has recommended following the guidelines of the Guaranteed Global Grading (3G) protocols (Guaranteed Global Grading, 2023) which are similar to the MSA ones, since both grading systems (MSA and 3G) are based on the same control points and protocols, of which one of the most important is marbling (Hocquette et al., 2020).

In both the MSA and 3G protocols, marbling is evaluated in the chiller by accredited graders, who make their assessment at one quartering site between the 5th to 13th rib depending on the country (Meat, Livestock Australia, Meat Standards Australia, 2024). Historically, two marbling scores were designed: 1) the AUS-MEAT marbling score on a scale of 0 (no visual marbling) to 9 (extensive visual marbling) which provides an indication of the amount of marbling in beef and 2) the MSA marbling score on a scale from 100 to 1190 in increments of 10, which provides indications of amount and distribution of marbling. MSA accreditation is expensive due to the initial training, and the additional requirement of regularly renewing certification every six months adds to this expense. In addition, the visual assessment of the ribeye in this way varies from grader to grader, and even assessments by the same grader can vary over the course of a workday (Stewart, Toft, et al., 2024). For these reasons, there is a need for more consistent, reliable, and cost-effective methods for assessing carcasses for marbling instead of MSA-accredited graders.

Implementations of several technologies have been studied to address this problem of quantitatively and qualitatively predicting carcass composition and meat quality (Mendes, Briceno et al., 2024; Sanchez, Arogancia, Boyles, Pontillo, & Ali, 2022). These include Hyperspectral Imaging (HSI) (Stewart, Lauridsen, et al., 2021) which serves as the foundational technology for the Q-FOM™ camera (Drachmann et al., 2024; Stewart, Lauridsen, et al., 2021). Unlike traditional HSI systems, the Q-FOM™ integrates specific algorithms for beef quality assessment, setting it apart as a unique tool among current sensing and imaging methods (Drachmann et al., 2024). Additional methods include Magnetic Resonance Imaging (Lee et al., 2015), X-ray Computed Tomography (Anderson, Cook, Williams, & Gardner, 2018), Computerized Tomography Imaging (Prieto et al., 2010), Near-infrared Spectroscopy (Kombolo-Ngah et al., 2023) including smartphone NIRS sensor (Coombs, Fajardo, & González, 2021), Raman spectroscopy

(Cama-Moncunill et al., 2020) and ultrasound (Berain et al., 2021). However, these techniques were mostly developed for laboratory use, with only a few studies evaluating their industrial implementation. An additional disadvantage of all these technologies is the need for a large number of reference carcasses that have been evaluated according to the grading system of the country in which the device(s) is to be used. Algorithms must be developed for each implementation, as well, in order to be accurately calibrated (Cheng, Cheng, Sun, & Pu, 2015).

The most promising avenue of research is the development of a portable handheld device for use in slaughterhouses as a replacement for certified graders or as a toolkit to assist certified graders. The Q-FOM™ Beef handheld camera developed by Frontmatec Smoerum A/S is certified by MSA/AUS-MEAT for use in Australia in carcasses quartered caudal to the 10th to 13th rib (AUS-MEAT, 2023). In addition, the Q-FOM™ camera stands out for its incorporation of three-dimensional sensors and advanced image segmentation algorithms that enhance its precision and repeatability across diverse carcass phenotypes. Unlike conventional HSI systems, which often face challenges related to carcass presentation and operator bias, the Q-FOM™ utilizes a real-time guidance system to standardize image acquisition, thereby minimizing the impact of environmental and operational variability (Stewart, Toft, et al., 2024). This advancement makes the Q-FOM™ not merely an HSI-based device, but an integrated tool tailored for robust and objective beef quality assessment in commercial settings. Marbling, IMF%, Eye Muscle Area, Meat Color, Fat Color, and Rib Fat Thickness are all measured within a few seconds after capturing an image of the ribeye cut surface in the chiller, allowing for adequate blooming. The Q-FOM™ system is characterized by high precision and accuracy in predicting continuous traits such as marbling score and/or chemical IMF% (Drachmann et al., 2024; Stewart, Toft, et al., 2024).

Consequently, this study evaluated the potential of the Q-FOM™ Beef camera to predict MSA marbling scores of French beef cattle in one slaughterhouse in France, especially the practice of quartering at the 5th–6th rib. Additionally, the feasibility of using on-screen images to perform MSA marbling measurements was also examined. The study further compared the MSA marbling and AUS-MEAT marbling scores provided by 3G-accredited graders.

2. Materials and methods

2.1. Experimental design

All the beef carcasses for this study were provided by a commercial slaughterhouse located in Limoges, France (Plainemaison Aquitaine-Beauvallet, Limoges), and were obtained from animals reared and slaughtered in France. A total of 420 carcasses were randomly selected for variability in terms of breed (54.5 % Limousin, 2.9 % Charolais, 11.9 % Aubrac, 19.3 % Primholstein, 4.3 % Montbéliarde, 0.2 % Salers, etc), category (4.3 % Bull, 77.9 % Cow, 11.4 % Heifer, 1.9 % Ox, 4.5 % Steers), age (from 10 to 220 months) and weight (from 101.6 to 730.6 kg). This ensured that the studied animals were representative of the commercial variability of the company's beef carcasses.

Animals were transported the day before slaughter and slaughtered early in the morning at the slaughterhouse in compliance with ethical guidelines for animal care. Transport time from the farm was about 1 h to 1.4 h and animals had free access to water until slaughter. The exsanguination from the jugular vein was performed after penetrating stunning using a captive-bolt pistol. Slaughtering was performed in compliance with French welfare and EU regulations (Council Regulation (EC) No. 1099/2009). The carcasses were dressed according to standard commercial practices and between 30 and 50 min post exsanguination the carcasses were split in half then chilled for 24 h at 2–4 °C.

These beef carcasses were hung by the *Archilles tendon* and were quartered between the 5th and 6th rib. Carcasses with cut surface damage and presence of residues (blood, fat, bone or meat) on the ribeye were discarded prior to evaluation of the marbling score either by the

graders and by the Q-FOM™ camera for comparison of both measurements.

2.2. MSA marbling assessment

After 24 h of *post-mortem* chilling in a cold room maintained at an average temperature between 0 and 4 °C, the processed carcasses were assessed. Marbling assessments were performed in accordance with the ABCAS reference standards (Meat, Livestock Australia, Meat Standards Australia, 2024), following a benchmark established by the UNECE Bovine Language Standards, using MSA marbling scores. The marbling standards have been tailored to European cattle and consumers through extensive collaborative research in Europe, with data storage and use facilitated by the IMR3GF (International Meat Research 3G Foundation).

The MSA marbling score, which provides a detailed scale (ranging from 100 to 1190 in increments of 10), was used to indicate the amount, size, fineness and distribution of fat inclusions in beef carcasses. Evaluation of MSA marbling scores was performed according to the MSA methodology (AUS-MEAT, 2022a) described by many authors, for example, Liu et al. (2021) and Stewart, Toft, et al. (2024). However, in this specific study, evaluation of MSA marbling scores was performed on the 5th rib of the carcass (Liu et al., 2021).

Two 3G accredited graders, including one expert grader, performed the evaluations. Both graders have undergone uniform training and received consistent updates in accordance with the Australian Beef Chiller Assessment System (ABCAS) standards to minimize technical variability in their assessments. An expert grader, while also accredited, possesses extensive experience and is recognized for superior expertise and accuracy in marbling assessments. They are often used as benchmarks for comparisons and are recognized as experts for research projects. Thus, the expert grader is considered to provide the best reference data. The expert grader independently assessed all 420 carcasses in the experiment. Of these, 377 carcasses were also evaluated by both 3G graders, including the expert grader, providing a set of common evaluations for comparative analysis. For model calibration, 285 carcasses were selected based on the best segmentation quality of the ribeye area, ensuring the reliability of the data used for accurate model training. After cutting, the ribeye was exposed to air for a minimum of 20 min and up to 3 h to allow the meat to bloom prior to the MSA marbling assessment. Blooming refers to the color change resulting from oxygenation of myoglobin when the meat surface is exposed to oxygen (Jacob, 2020). Assessing was performed using standard visual cards provided by ABCAS to assess AUS-MEAT and MSA scores (AUS-MEAT, 2022a).

2.3. Image analysis for MSA marbling

Among the 420 carcasses included in the trial, a subsample consisting of 285 carcasses was visually assessed by the expert grader in the chiller. A total of 779 images (i.e. between 2 and 3 images per carcass) were acquired using the hand-held Q-FOM™ Beef camera. Prior to image acquisition, excessive bone dust and fat smears present on the cut surface were removed using either the blade of a knife, a traditional fabric commonly used in French abattoirs to cover carcasses or simply paper. These cleaning methods were selected for their effectiveness in removing surface contaminants while maintaining the presentation and quality of the ribeye area for imaging. The camera was positioned over the assessing surface using a real-time built-in camera operator guiding tool appearing on the screen during image capture.

Each morning, a self-test was performed by placing the camera in a self-test stand with a NIST traceable chessboard and triggering image capture. The self-test verifies that color and geometry measures established during calibration are within acceptable limits. In a first analysis with the 285 carcasses, a Q-FOM™ Beef calibration model using the expert grader MSA Marbling score as reference was developed. The construction of the Q-FOM™ Beef calibration model was a multi-step

process involving specific hardware configurations, experimental design, and advanced image processing techniques, as outlined in Stewart, Toft, et al. (2024).

Two months later, a PDF file containing the Q-FOM™ images from 100 of those carcasses was presented to the expert grader. The carcasses were assessed again by evaluating the marbling score of the captured images. Triplicate images of 12 different carcasses were included in the PDF file to determine the expert grader's repeatability via a blind test. The expert grader was not informed that triplicate images were included, and all images (a total of 124 pages) were presented in a randomized way using a consecutive ID number.

2.4. Statistical analysis

The datasets utilized in this study were sourced from three distinct origins: (a) a dataset from 377 carcasses with marbling scores provided by the expert grader and a 3G accredited grader. This dataset was used to compare the consistency of marbling scores between the two graders; (b) a subset consisting of 285 carcasses with marbling scores provided by the expert grader and images captured by the Q-FOM™ beef camera. This dataset was used to develop a MSA marbling score prediction model for the Q-FOM™ beef camera and (c) additionally 124 images were assessed for marbling score by the expert grader on-screen. This dataset was used to compare the consistency of marbling scores between on-site in-chiller and on-screen assessing by the expert grader only.

2.4.1. Model assessment

The dataset was analyzed using R software (version 4.3.0 - R Core Team, 2023). The assessment of model precision and goodness of fit on test datasets between the Q-FOM™ Beef camera predicted data and the expert grader MSA Marbling scores was conducted using coefficients of determination (R^2), root mean squared error (RMSE), and bias, as described by Tedeschi (2006).

For the relationships between actual MSA marbling score of the independent validation, the R^2 and root mean squared error of the prediction (RMSEP) were used to report the precision, whereas the slope of the relationship between actual and predicted values and bias were used to report accuracy. Bias is defined as the difference between the actual and the predicted value at the mean of the predicted trait, as described by Stewart, Toft, et al. (2024).

In this study, we employed confusion matrices to assess agreement between evaluations performed by the expert grader and the secondary grader for AUS-MEAT marbling scores. Precision was calculated as the average proportion of scores assigned by the secondary grader that fell within a ± 1 class range of those assigned by the expert grader. Accuracy was measured as the proportion of carcasses for which the secondary grader's scores matched exactly with the median scores assigned by the expert grader. Furthermore, bias was analyzed by comparing the differences between the expert grader's scores and those predicted by the secondary grader across all class levels (James, Witten, Hastie, & Tibshirani, 2013; Kuhn & Johnson, 2013).

2.4.2. Discriminant analysis

The marbling scores in the different datasets were classified into three homogeneous MSA marbling classes: Low, Medium, and High. The thresholds for these classes were: Low (≤ 290), Medium ($290 < \text{scores} \leq 360$), and High (> 360). These classes are derived from the 25th to the 75th percentile, with whiskers indicating minimum and maximum values. The use of these divisions is justified by the need to more accurately reflect the intrinsic variability within the dataset, ensuring that subsequent analyses are based on a stratification that is representative of the observed data. This approach allows for a categorization that is more aligned with the actual distribution of MSA Marbling scores in the present study, thereby ensuring that the statistical analyses capture the differences in sensitivity within each identified class with greater precision.

The confusion matrix, which describes the classification performance of the discrimination model, was evaluated based on three metrics: sensitivity, specificity, and overall accuracy for each class.

$$\text{Sensitivity (\%)} = \frac{TP}{TP + FN} \times 100$$

$$\text{Specificity (\%)} = \frac{TN}{FP + TN} \times 100$$

$$\text{Accuracy (\%)} = \frac{TP + TN}{TP + TN + FP + FN} \times 100$$

where FP, FN, TP, and TN represent the number of false positives, false negatives, true positives, and true negatives predicted during external validation, respectively. Sensitivity and specificity are used to calculate the true rates: sensitivity represents the model's ability to correctly assign the sample to the actual class it belongs to, whereas specificity indicates the model's ability to correctly identify the class to which the sample does not belong (Almeida, Fidelis, Barata, & Poppi, 2013). Accuracy is the overall proportion of correctly classified samples.

The overall accuracy of the confusion matrix was also evaluated using receiver operating characteristic (ROC) curves, where AUC-ROC (Area Under the ROC Curve) corresponds to the area under a ROC curve and provides a single value that measures the overall performance of a binary classifier (Hanley & McNeil, 1982). The AUC ranges from 0.5 to 1, where the lowest value represents a random classifier, and the highest value represents a perfect classifier (Hanley & McNeil, 1982). Three AUC-ROC curves were measured to evaluate the model's ability to discriminate between the different classes, and this was performed for both models.

3. Results

3.1. Variability in carcass data

The descriptive statistics (mean, standard deviation (SD), coefficient of variation (CV), minimum, and maximum) of animal and carcass traits along with MSA traits measured by certified graders and predicted by the Q-FOM™ beef camera between the 5th and 6th rib are shown in Table 1.

Table 1
Descriptive statistics for the cattle population.

	Mean	SD	CV (%)	Minimum	Maximum
Animal maturity (months)	74	52.93	71.76	10	220
Cold Carcass Weight (kg)	372.0	95.30	25.62	101.6	730.6
EU Conformation score ¹	6.84	3.58	52.3	1	14
EU Fat score ²	3.87	3.30	85.60	1	9
MSA Marbling score (Visual)	313.08	91.29	29.16	100	650
MSA Marbling score (Q-FOM™) ³	313.78	77.92	24.83	111	486.3
AUS-MEAT Marbling score (Visual)	0.95	0.83	87.71	0	4

¹ Following Hickey et al. (2007), European conformation scores were converted from P (-/=/+), O (-/=/+), R (-/=/+), U (-/=/+), and E (-/=/+)

to classes from 1 (P-) to 15 (E+).

² Following Hickey et al. (2007), European fat scores were converted from 1 (-/=/+), 2 (-/=/+), 3 (-/=/+), 4 (-/=/+), and 5 (-/=/+)

to classes from 1 (1-) to 15 (5+).

³ Predictions of MSA marbling scores for 285 carcasses by Q-FOM™ Beef's current algorithms.

3.2. Comparison of MSA marbling scores between visual assessments performed by an expert grader and the 3G accredited grader

Using 377 carcasses, the R² of prediction between scores from the expert grader and the 3G accredited grader was 0.78 with a RMSE of 47.9 MSA marbling points (Fig. 1).

To be accredited for MSA marbling visual assessing in Australia, ≥49 % of the samples must be within 50 MSA-MS marbling points from the score assigned by an expert grader, ≥79 % of the samples must be within 100 MSA marbling points and ≥ 97 % must be within 200 MSA Marbling points. Comparing the 3G accredited grader's assessment of MSA marbling scores to the expert grader scores revealed that the accreditation requirements were met, since 75.9, 97.1 and 100.0, respectively, were within the requirements shown above (Fig. 2).

When carcasses are grouped in three classes based on MSA marbling score, the highest sensitivity was achieved for samples correctly predicted to have low MSA scores (≤ 290), with a sensitivity of 83.3 % in the analyzed dataset. Lower sensitivities were observed for samples in the medium (290 < scores ≤ 360) and high (> 360) MSA classes, with sensitivities of 53.3 % and 79.6 %, respectively. On the other hand, specificity ranged from 82.2 % to 93.3 % for all the classes. The confusion matrix for the dataset had an overall accuracy of 73.7 % (Table 2).

In Fig. 3, the ROC curves demonstrate an AUC of 0.840 for MSA marbling scores provided by the expert grader compared to the other 3G accredited grader. The ROC curves for the different classes show high sensitivity at almost all points, suggesting that the 3G accredited grader has a high probability of correctly classifying marbling scores when compared to the expert grader. More generally, we observed a good discriminatory ability of the graders in distinguishing between different marbling classes.

The interpretation of the AUC-ROC curves was guided by the criteria outlined by Yang and Berdine (2017). According to their study, an AUC value of 0.5 indicates no discriminatory power, values between 0.5 and 0.6 indicate poor discrimination, values between 0.6 and 0.7 represent acceptable discrimination, values between 0.7 and 0.8 indicate excellent

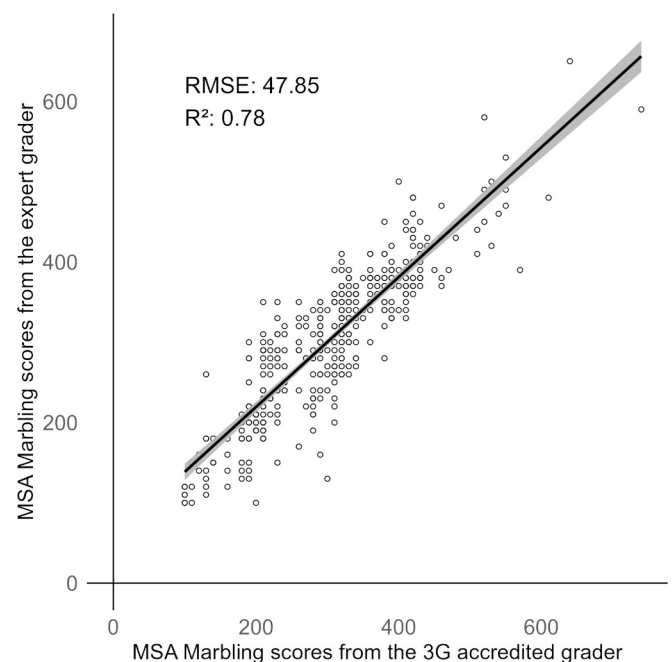


Fig. 1. Relationship between marbling scores measured by the expert grader (Y axis) and the 3G accredited grader (X axis) for 377 carcasses. The regression line is shown with a shaded 95 % confidence interval, showing the precision of the relationship between the two graders.

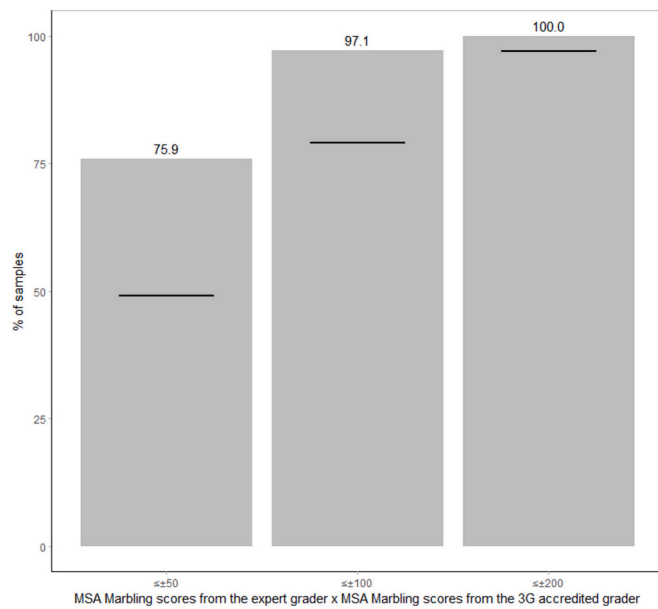


Fig. 2. Histograms showing the percentage of samples (grey bars) assigned a specific MSA marbling score by the expert grader and the 3G accredited grader, within the acceptance thresholds indicated on the x-axes. The black lines represent the AMILSC approved minimum requirements of accuracy standards for MSA marbling assessment ($N = 377$ carcasses) (AUS-MEAT, 2022b).

Table 2

Confusion matrix for MSA marbling classes using a dataset containing MSA marbling scores provided by the expert grader and a 3G accredited grader, comprising 377 carcasses.

MSA class	Low marbling score (MSA ≤ 290)	Medium marbling score ($290 < \text{MSA} \leq 360$)	High marbling score (MSA > 360)	Total
Low predicted	135	33	0	168
Medium predicted	26	57	22	105
High predicted	1	17	86	104
Model performance, %				
Sensitivity	83.3	53.3	79.6	
Specificity	84.7	82.2	93.3	
Overall Accuracy				73.7

discrimination, and values above 0.9 signify outstanding discrimination. Based on these thresholds, our model demonstrated the ability to predict both the low and high classes effectively, as the AUC values exceeded 0.8 for our models.

The Low MSA Marbling Class (≤ 290) achieved an AUC of 0.840, indicating a high degree of consistency between the evaluations of the expert grader and the 3G accredited grader for carcasses with lower marbling. The Medium MSA Marbling Class ($290 < \text{scores} \leq 360$) recorded an AUC of 0.677, suggesting greater variability in the consistency of evaluations for carcasses with medium marbling between the two graders. The High MSA Marbling Class (> 360) attained the highest AUC of 0.865, reflecting strong concordance between the expert grader and the 3G accredited grader for carcasses with MSA Marbling scores exceeding 360. This highlights the second grader's ability to closely correspond their assessments with those of the expert grader for high-quality carcasses.

Fig. 4 displays a confusion matrix heatmap of AUS-MEAT marbling

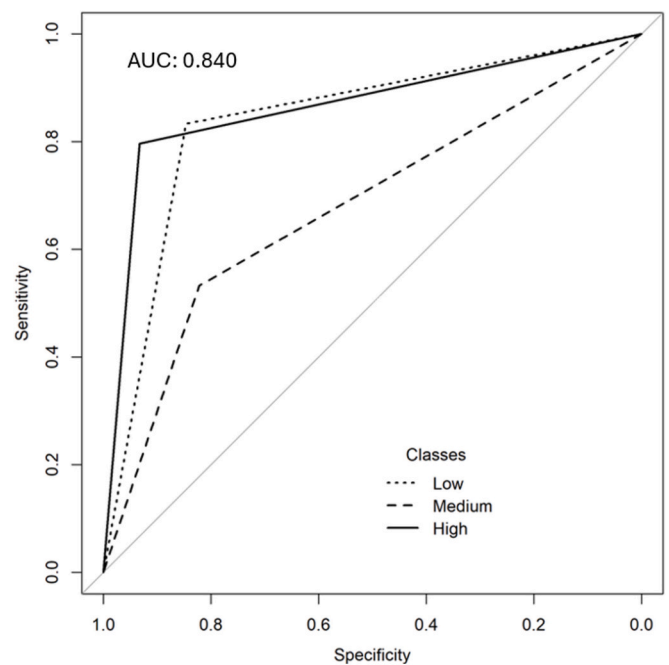


Fig. 3. ROC Curves for MSA marbling scores provided by the expert grader compared to the 3G accredited grader for 377 carcasses. The dotted, dashed, and solid lines represent the ROC curves for the Low (≤ 290), Medium ($290 < \text{scores} \leq 360$), and High (scores > 360) marbling classes, respectively. The diagonal line represents predictions no better than random guessing, and the closer a curve is to the upper-left corner, the better the model's predictive ability. The AUC value of 0.840 indicates excellent discrimination for the model.

Expert grader AUS-MEAT marbling score	5	4	3	2	1	0
5						
4				2		2
3			3	3	1	
2	1	25	37	7		
1	53	95	16			
0	112	20				
3G accredited grader AUS-MEAT marbling score	0	1	2	3	4	5

Fig. 4. Confusion matrix heatmap for AUS-MEAT marbling scores measured by the expert grader and the 3G accredited grader for 377 carcasses. 65.5% of the carcasses (diagonal) were classified similarly by the expert grader and the 3G accredited grader. Allowing ± 1 class deviation between the expert grader and the 3G accredited grader resulted in 99.7% agreement.

scores. Most carcasses were correctly classified or fell within ± 1 of the score assigned by the 3G accredited grader. This validates the reliability of the AUS-MEAT marbling assessments conducted by the 3G accredited graders.

3.3. Q-FOM™ beef MSA marbling score performance

A Q-FOM™ Beef calibration model using the expert grader MSA marbling scores (MSA-MB) as reference was developed on a dataset including 285 carcasses (Fig. 5).

For the comparison between predictions from the Q-FOM™ Beef camera and data from the expert grader, 78.6%, 96.8%, and 99.6% of the values were within 50, 100, and 200 marbling points, respectively (Fig. 6). This shows that the Q-FOM™ Beef camera can predict MSA marbling scores with good accuracy and precision in carcasses quartered

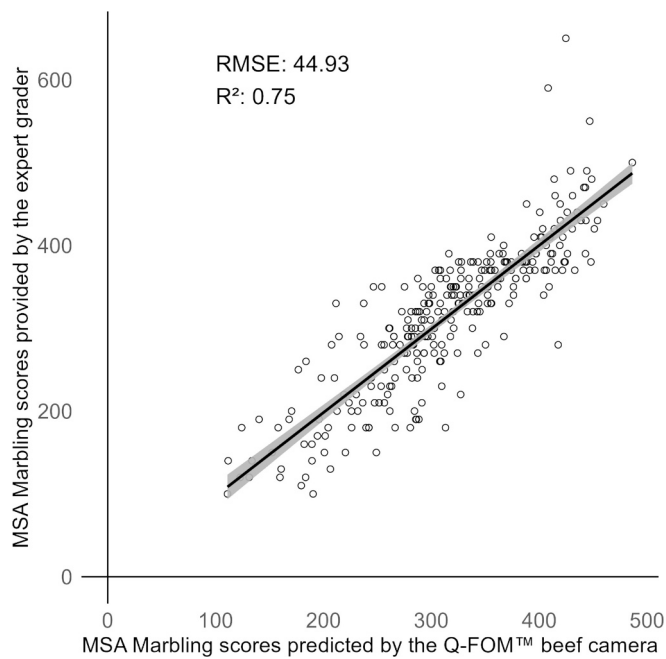


Fig. 5. Relationship between MSA marbling scores predicted by the Q-FOM™ beef camera and the expert grader ($N = 285$ carcasses). The regression line includes a shaded 95 % confidence interval, showing the variability and precision of the predictions relative to the expert assessments.

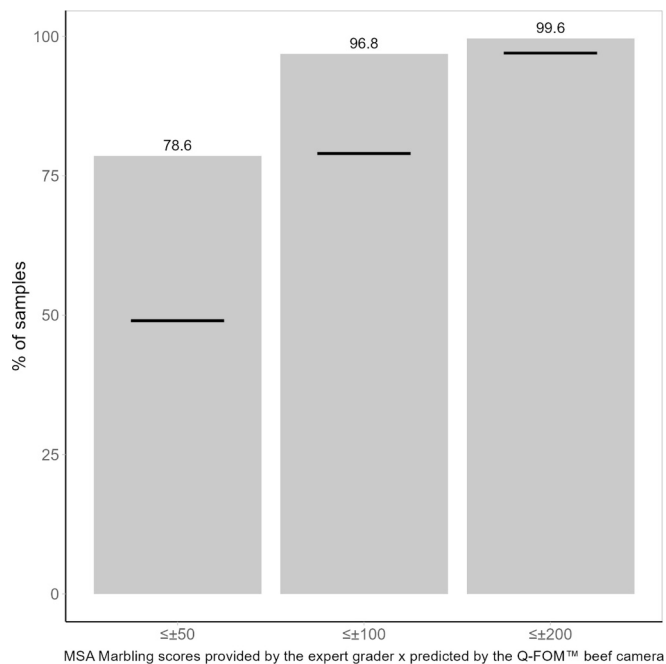


Fig. 6. Histograms showing the percentage of samples (grey bars) assigned a specific MSA marbling score by the expert grader and the Q-FOM™ Beef camera, within the acceptance thresholds indicated on the x-axes. The black lines represent the AMILSC approved minimum requirements of accuracy standards for MSA marbling assessment ($N = 285$ carcasses) (AUS-MEAT, 2022b).

at the 5th to 6th rib. These results are consistent with previous studies, who demonstrated the accuracy of the Q-FOM™ Beef camera in assessing ribeye traits (including marbling) in beef carcasses quartered at the 10th to 13th (Stewart, Toft, et al., 2024).

The Q-FOM™ MSA Marbling calibration model maintained a high

level of precision and accuracy (Figs. 5 and 6). The Q-FOM™ calibration and validation models for MSA marbling also demonstrated high precision and accuracy, as reported by Stewart, Toft, et al. (2024). The Q-FOM™ calibration model tended to score marbling lower than the expert MSA grader when MSA marbling scores were high (+500). This may result from biases in the data used for calibration, or it may be from limitations in algorithms for image analysis. Further analysis and studies are needed to determine the importance of this phenomenon for high marbled carcasses. Contrary to our findings, Stewart, Toft, et al. (2024) reported an increase in bias with higher marbling scores, where the Q-FOM™ camera tended to assign higher marbling scores than the mean scores provided by MSA graders. However, it is important to note that the range of marbling scores differed significantly between the studies, with a broader range observed in the study by Stewart, Toft, et al. (2024), which reported scores ranging from 120 to 1160 compared to our study’s range from 100 to 650 reflecting the phenotypic characteristics of European breeds. Despite these differences in range, the consistent upward bias with higher marbling scores underscores the need for further optimization ensuring that the Q-FOM™ system accurately predicts carcasses with extreme marbling levels.

When the carcasses were divided into three groups using MSA marbling scores, our analysis showed that the highest sensitivity was achieved for samples predicted to have low MSA scores, reaching 78.7 % in the dataset. Conversely, sensitivity was lower for samples in the medium (65.1 %) and high (78.0 %) MSA classes. Specificity, however, ranged from 79.4 % to 92.3 % across all classes. The confusion matrix for the dataset demonstrated an overall accuracy of 74.4 % (Table 3).

The ROC curves show an AUC of 0.845. This value is slightly higher than that obtained in the comparison with the second grader, indicating that the Q-FOM™ beef camera has a slightly better or comparable discrimination capability compared to the human second grader. Additionally, the ROC curves suggest that the Q-FOM™ beef camera is able to classify the different marbling classes with a high level of accuracy (Fig. 7).

The Low MSA Marbling Class (≤ 290) with an AUC of 0.845 demonstrates the Q-FOM™ beef MSA marbling score model’s power to accurately identify samples with low MSA Marbling scores with minimal false positives. The Medium MSA Marbling Class ($290 < \text{scores} \leq 360$) recorded an AUC of 0.723, suggesting adequate discrimination but with a higher likelihood of classification errors, especially within the transition zone between the Low and High classes. The High MSA Marbling Class (> 360) achieved the highest AUC, with a value of 0.851 (Fig. 7). This outcome highlights the model’s robustness in accurately classifying carcasses with MSA marbling scores exceeding 360, demonstrating excellent precision and a low rate of false negatives.

Table 3

Confusion matrix for MSA marbling classes with model performance using a dataset containing MSA marbling scores provided by the expert grader and scores predicted by the Q-FOM™ beef camera, comprising 285 carcasses.

MSA class	Low marbling score (MSA ≤ 290)	Medium marbling score ($290 < \text{MSA} \leq 360$)	High marbling score (MSA > 360)	Total
Low predicted	85	17	0	102
Medium predicted	21	56	20	97
High predicted	2	13	71	86
Model performance, %				
Sensitivity	78.7	65.1	78.0	
Specificity	90.4	79.4	92.3	
Overall Accuracy				74.4

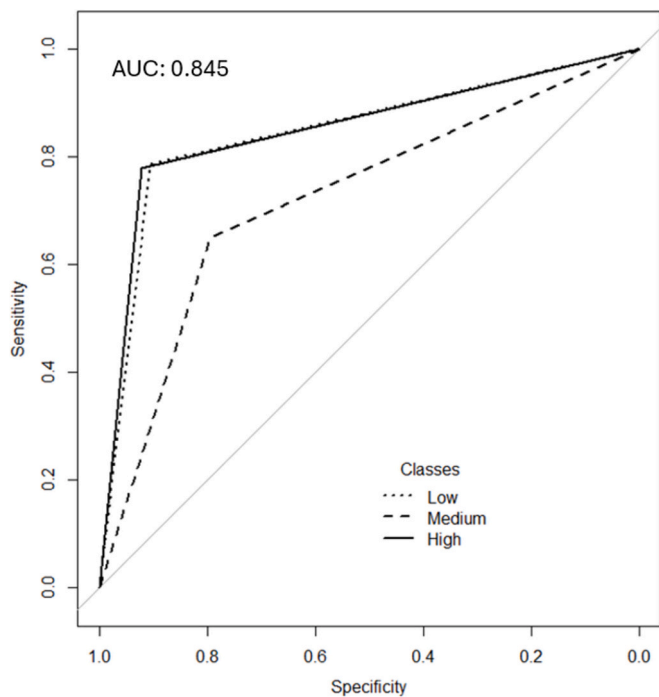


Fig. 7. ROC Curves for MSA Marbling Classes provided by the expert grader compared to those predicted by the Q-FOM™ beef camera for 285 carcasses. The dotted, dashed, and solid lines represent the ROC curves for the Low (≤ 290), Medium ($290 < \text{scores} \leq 360$), and High ($\text{scores} > 360$) marbling classes, respectively. The diagonal line represents predictions no better than random guessing, and the closer a curve is to the upper-left corner, the better the model's predictive ability. The AUC value of 0.845 indicates excellent discrimination for the model.

3.4. Comparison of in-chiller assessment to on-screen image assessing by the same expert grader

In another analysis, images of a subset ($N = 100$ carcasses, 124 images) of the 285 carcasses were assessed on-screen by the expert grader. The R^2 of prediction between the in-chiller and on-screen images was 0.78 with a RMSE of 48.7 (Fig. 8). The scatter plot in Fig. 8 highlights two notable outliers, which correspond to the carcasses shown in Fig. 9. The difference in scores between in-chiller assessment and on-screen image assessment was within 50 MSA-MS for 79.8 %, within 100 MSA-MS for 96.8 %, and within 200 MSA-MS for 100 % of the carcasses analyzed. This suggests that on-screen assessment of MSA marbling scores would be an acceptable method to develop a marbling calibration model, although we acknowledge that the dataset could be expanded to include more carcasses. (See Fig. 10.)

Our research, which utilized 100 unique carcasses and 12 of these carcasses with triplicate images, is one of the first to explore this approach with a specific focus on the variability of MSA Marbling score (100 to 650) at the 5th–6th ribbing site. While these findings are promising and provide a solid foundation, further investigation is required to confirm these results across a broader range of marbling scores and carcass types. Expanding the dataset to include a wider range of images and phenotypes would enhance the robustness of the calibration model, ensuring its applicability across different conditions.

The outliers shown in Fig. 9 revealed significant differences between the MSA marbling scores obtained from on-screen assessments and traditional in-chiller assessments. In Fig. 9a, the MSA marbling score was 480 in-chiller, but 610 when assessed on-screen. This discrepancy can be attributed to several factors, including errors during in-chiller evaluations due to time constraints, as well as typographical mistakes that can occur during assessment. Similarly, in Fig. 9b, the other sample

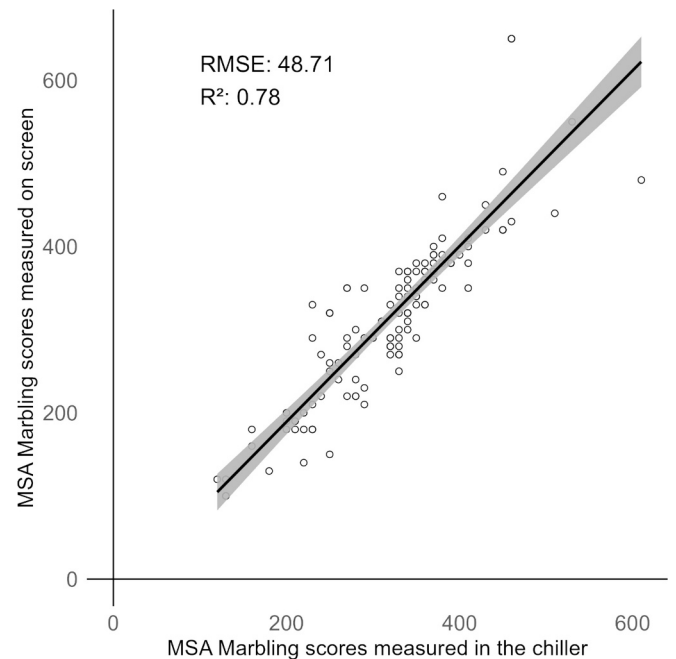


Fig. 8. Relationship between MSA Marbling scores measured in the chiller to on-screen image assessing by the same accredited expert grader ($N = 100$ carcasses, 124 images). The regression line with a shaded 95 % confidence interval shows the precision of the on-screen assessments compared to the chiller measurements.

displayed a marbling score of 650 with traditional assessment and 460 on screen.

When carcasses are divided into three classes by their MSA marbling score, the greatest sensitivity was achieved for samples correctly predicted to have high MSA scores, with 75.5 % in the analyzed dataset. Lower sensitivity was obtained for samples belonging to medium (68.6 %) and low MSA classes (77.5 %). On the other hand, specificity ranged from 76.4 % to 96.4 % for all classes. The confusion matrix for the dataset had an overall accuracy of 74.2 % (Table 4).

The ROC curves show an AUC of 0.824. This value is slightly lower than that obtained from the comparison of the traditional assessments by the expert grader with assessments using the Q-FOM™ beef camera. The ROC curves also suggest that on-screen assessments using images provided by the Q-FOM™ beef camera can be used to classify different marbling classes with a high degree of accuracy (Fig. 11).

The Low MSA Marbling Class (≤ 290) has an AUC of 0.82, indicating that the expert grader's on-screen assessment of Q-FOM™ acquired images can accurately identify samples with in-chiller low MSA Marbling scores. This suggests that the on-screen assessment is effective in correctly identifying carcasses with lower marbling scores, giving a low number of false positives. The Medium MSA Marbling Class ($290 < \text{Scores} \leq 360$) showed an AUC of 0.72, implying good discrimination but with a higher tendency for classification errors. The High MSA Marbling Class (> 360) exhibited the highest AUC, with a value of 0.87 (Fig. 11). This shows the robustness of the model for correctly identifying carcasses with MSA marbling scores greater than 360, and consequently a low number of false negatives.

4. Discussion

4.1. Range and variability of marbling scores

The European conformation and fat scores in our study are consistent with Liu et al. (2021) and Drachmann et al. (2024). In addition, the average MSA marbling score obtained in our study was 313, which is consistent with the values of 293 to 329 reported by Liu et al. (2020) for

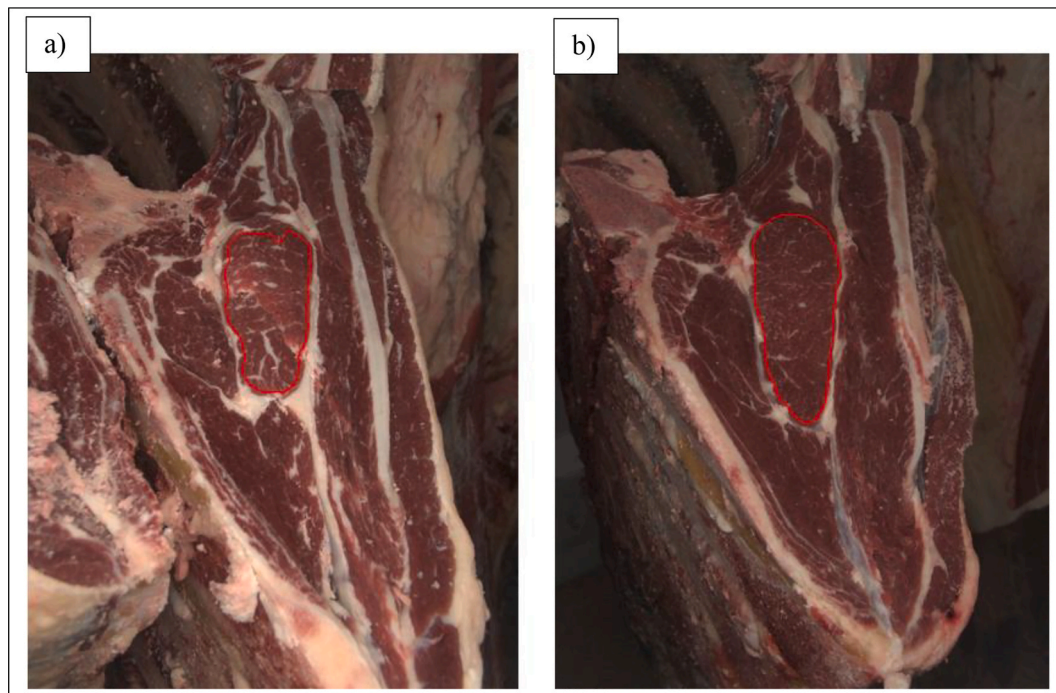


Fig. 9. Images captured using the Q-FOM™ camera of the *Longissimus thoracis* muscle surfaces from bovine carcasses identified as outliers in Fig. 8, representing cases with significant discrepancies between the marbling scores assigned by the expert grader in the chiller and those from on-screen assessments: (a) 480 MSA points (chiller) and 610 MSA points (on-screen image); (b) 650 MSA points (chiller) and 460 MSA points (on-screen image).

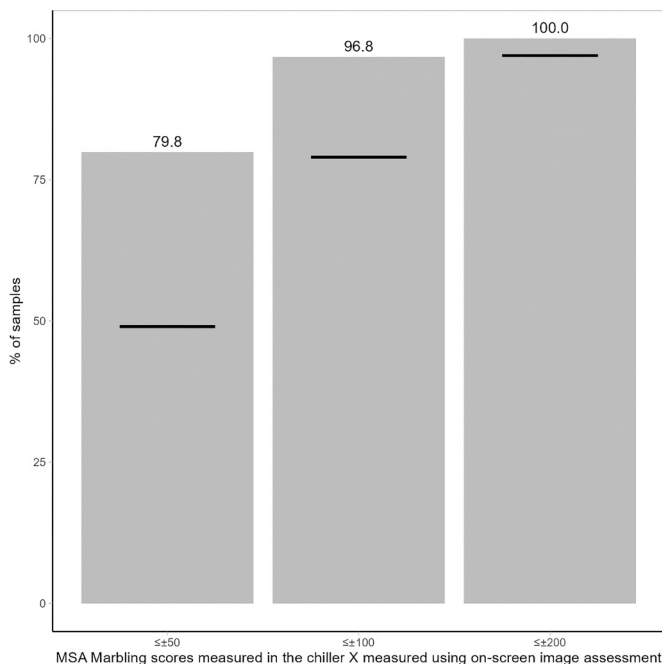


Fig. 10. Histograms showing the percentage of Q-FOM™ acquired images (grey bars) assigned a specific MSA marbling score by the expert grader in-chiller and on-screen, within the acceptance thresholds indicated on the x-axes. The black lines represent the AMILSC approved minimum requirements of accuracy standards for MSA marbling assessment ($N = 124$ images) (AUS-MEAT, 2022b).

a variety of European cattle and with the value of 310.8 reported by Mendes, Silva, et al. (2024) for Limousin cows, but it is slightly higher than that of 288 obtained by Liu et al. (2021) on the 5th rib from 208 bovines mainly French Limousine cows.

Table 4

Confusion matrix for MSA marbling classes with model performance using a dataset containing MSA marbling scores provided by the expert grader in the chiller and scores provided by the same grader using on-screen images ($N = 100$ carcasses, 124 images).

MSA class	Low marbling score (MSA ≤ 290)	Medium marbling score (290 < MSA ≤ 360)	High marbling score (MSA > 360)	Total
Low predicted	37	8	0	45
Medium predicted	12	24	9	45
High predicted	0	3	31	34
Model performance %				
Sensitivity	75.5	68.6	77.5	
Specificity	89.3	76.4	96.4	
Overall Accuracy				74.2

Our average MSA Marbling scores were also lower than those reported in Australian studies by Stewart, Toft, et al. (2024), who examined a diverse range of carcass phenotypes, and Stewart, Gardner, and Tarr (2024), who focused on Angus, Hereford, and *Bos indicus* cattle breeds, with scores of 495 and 445, respectively.

Additionally, the mean AUS-MEAT Marbling score in our study was 0.95, which is slightly higher than the score reported by Liu et al. (2021), but lower than the mean values observed by Santinello et al. (2024), and both Stewart, Toft, et al. (2024) and Stewart, Gardner, and Tarr (2024), who reported scores of 2.11 and 2.0, respectively.

The differences observed in our study compared to the Australian results are likely to be explained by differences in cattle breeds (Stewart, Gardner, and Tarr, 2024; Stewart, Toft, et al., 2024). Indeed, higher MSA Marbling scores are typically observed in early maturity breeds such as Angus and Hereford. By contrast, late-maturity European breeds, such as Limousin, Charolais, and Blonde d'Aquitaine, typically exhibit lower

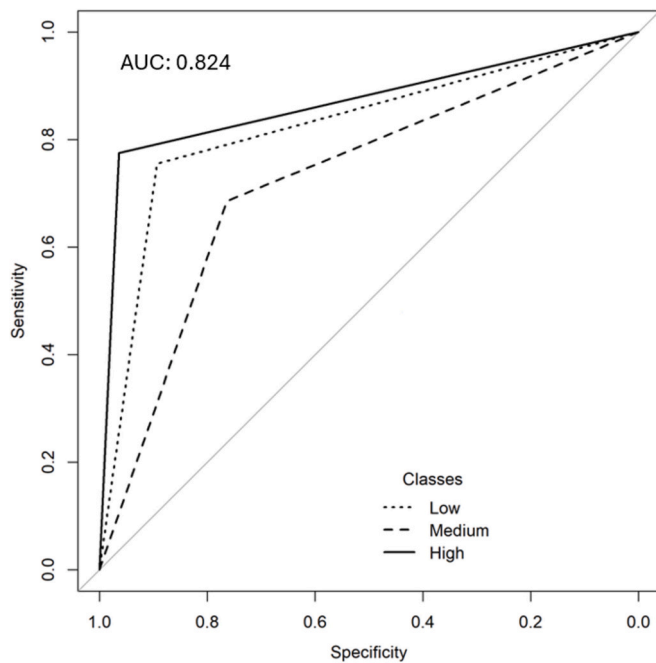


Fig. 11. ROC Curves for MSA Marbling measured on-screen image assessing by the expert grader ($N = 124$ images). The dotted, dashed, and solid lines represent the ROC curves for the Low (≤ 290), Medium ($290 < \text{scores} \leq 360$), and High ($\text{scores} > 360$) marbling classes, respectively. The diagonal line represents predictions no better than random guessing, and the closer a curve is to the upper-left corner, the better the model's predictive ability. The AUC value of 0.824 indicates excellent discrimination for the model.

IMF content, even at similar maturity levels. These breeds face lower ability in depositing IMF% before intermuscular and subcutaneous fat, resulting in reduced marbling and, consequently, lower meat quality compared to early maturity breeds (Pethick, Harper, & Oddy, 2004). The characteristics of the production systems also play a critical role. European systems tend to focus on producing heavier carcasses from late-maturing beef breeds with less marbling despite using diets rich in maize or forages, which contrasts with the Australian systems where cattle from more early-maturing breeds are reared in feedlots using cereals in the finishing diet (Hocquette et al., 2018).

The differences observed in our study compared to those reported in Italian research can be partially attributed to the intensive rearing conditions on Italian feedlots, where young bulls are fed a diet supplemented with concentrates for six months prior to slaughter (Santinello et al., 2022; Santinello et al., 2024). In contrast, our rearing conditions are more extensive than the Italian ones.

The average marbling score and also its range of the studied carcass population are important for developing prediction models of marbling score. Consequently, there was a possibility that the calibration models of the Q-FOM™ camera initially designed for more marbled beef were not adapted to the European cattle due to lower and less variable marbling levels. Our results showed it is not the case since human graders can provide reliable data for marbling assessment. Indeed, despite that the MSA Marbling scores in our study ranged from 100 to 650, compared to the broader ranges (120 to 1160 and 160 to 1190 respectively) observed in the studies by Stewart, Gardner, and Tarr (2024) and Stewart, Toft, et al. (2024), our results demonstrated the capability to develop a robust model to predict marbling score with high accuracy. The broader range of MSA Marbling scores in these Australian studies may have contributed to their ability to create models using devices with enhanced predictive accuracy due to the greater variability in the data. However, our study also achieved strong predictive performance, suggesting that even with a more constrained range of

marbling scores, the model can effectively capture the relevant factors influencing marbling and produce reliable predictions.

While the variability for MSA marbling between scores from accredited human graders is low enough, the presence of bias between the Q-FOM™ Beef camera calibration model and the expert grader underscores a critical issue associated with using human-derived scores for calibrating and validating measurement technologies (Jang, Ishdorj, Anderson, Purevjav, & Dahlke, 2017; Stewart, Toft, et al., 2024). As new technologies develop, there is a risk that new devices might not be calibrated and/or accredited using compatible reference data. This issue is particularly significant because it hampers the comparison of the performance of technologies which were calibrated with data from different graders (Stewart, Toft, et al., 2024). In our study, to minimize this problem, we have developed a calibration model based on the expert grader reference data. More generally, to mitigate this problem, the Australian Meat Industry Language and Standards Committee has recently endorsed chemical IMF% as an industry trait, highlighting the necessity of objective gold standard traits for validating technologies (AUS-MEAT, 2022c).

4.2. Prediction of marbling score and IMF%

Previous studies by Stewart, Toft, et al. (2024) and Drachmann et al. (2024) established the efficacy of the Q-FOM™ system in predicting IMF %. Further, Stewart, Gardner, and Tarr (2024) developed and validated models to use chemical IMF% to find equivalent MSA marbling scores and AUS-MEAT marbling score. Consequently, IMF% can be used as a proxy for MSA marbling score in comparison of our results with those of other studies. Additionally, our research focuses on the feasibility of the Q-FOM™ beef camera to predict MSA marbling score in French cattle breeds, which exhibit a limited marbling range when compared to the cattle breeds found in Australia.

The sensitivity, specificity, and overall accuracy results indicate that the models are particularly effective in identifying samples with low MSA scores, while their performance in predicting medium and high MSA classes is slightly lower. The high specificity values indicate that the models are reliable in correctly identifying samples that do not belong to each class, reducing the rate of false positives. These findings suggest that the models used in this study demonstrate a higher effectiveness compared to the results reported by Kombolo-Ngah et al. (2023), who also evaluated the implementation of handheld near-infrared spectrometers for the on-line prediction of beef marbling score. This superior performance underlines the quality of the device, and the robustness of the models used in this study in distinguishing between different marbling classes, demonstrating the potential usefulness of the Q-FOM™ beef camera in practical applications.

The analysis of the ROC curves and AUC values suggests that both models (expert grader vs. second grader and expert grader vs. Q-FOM™ beef camera) have a good discriminatory ability between different MSA marbling classes. The AUC close to 0.85 for both models indicates robust performance in correctly classifying the marbling classes.

Comparing the two models, the Q-FOM™ beef camera showed a slightly higher AUC, suggesting that it may be a viable alternative to the 3G accredited grader for evaluating marbling scores. However, the difference is not substantial, and both methods are effective for classifying MSA marbling.

4.3. Prediction of the marbling scores using the camera on-site and from images

The prediction accuracy and precision of in-chiller and on-screen evaluations are nearly equivalent to those of expert and 3G graders. This suggests that when in-chiller trials are not feasible, on-screen assessing by an expert grader could serve as a viable alternative. It remains to be elucidated if on-screen assessment by accredited graders would also be a viable alternative in the future. Moreover, this approach

would allow for the inclusion of a diverse range of cattle, sexes, and feeding, thereby enhancing the robustness of predictive models for MSA marbling score. While on-screen assessing may not be applicable to all quality traits (e.g., tenderness, color), it appears to perform well for MSA marbling, demonstrating comparable accuracy and precision to visually performed in-chiller assessments.

Discrepancies were observed in only two carcasses (Fig. 9a and b), suggesting a possible need to calibrate and standardize monitor settings to account for variations in luminosity, contrast, and color, but it is likely to result from simple errors. Additionally, it is possible that these discrepancies stem from errors made by the expert grader in predicting the marbling scores for these two samples. In the chiller, assessments are conducted under controlled conditions, with specific lighting and angles as prescribed by the MSA methodology. These conditions are carefully chosen to enhance the accuracy of visual assessments by minimizing glare and shadows. In contrast, on-screen evaluation lacks such controlled lighting, relying instead on monitor settings and on the picture taken by the Q-FOM™ camera, which can introduce variability in the perception of marbling and potentially lead to overestimation of marbling scores.

The rapid assessment conducted in the chiller, which is required to minimize production interruptions, may contribute some variability. However, in this study, an expert grader performed the assessments, accustomed to the fast-paced and challenging conditions of industrial environments, thereby reducing the likelihood of error. Consequently, the controlled environment and lighting in the chiller offer a consistent and potentially reliable assessment as on-screen evaluations.

These findings emphasize the critical importance of maintaining consistent assessment conditions across different evaluation methods. The discrepancies noted in outlier cases suggest that even minor variations in environmental factors, such as lighting and observation angle, can significantly impact marbling assessments. Further research is required to explore the significance of these factors and to develop screen calibration techniques that can harmonize results across various platforms used for marbling assessment.

5. Conclusion

This study demonstrated for the first time that the Q-FOM™ Beef assessing camera can accurately predict MSA marbling scores using the MSA grading scheme for carcasses of breeds typical for European cattle quartered between the 5th and 6th rib, which is common practice in Europe. The Q-FOM™ Beef camera proved to be effective in predicting marbling score in the context of French beef production, where marbling scores are generally lower than beef produced in other parts of the world, particularly in Australia where the MSA grading scheme originated. Both in-chiller and on-screen visual assessments done by an expert grader were found to be reliable methods for developing a Q-FOM™ Beef marbling calibration model, making it a valuable tool for enhancing the consistency and accuracy of marbling evaluations within the French livestock industry.

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Nathalia da Silva Rodrigues Mendes: Writing – review & editing,

Writing – original draft, Formal analysis, Data curation. **Mette Christensen:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Moïse Kombolo-Ngah:** Formal analysis, Data curation. **Pascal Faure:** Formal analysis, Data curation. **Laure Thoumy:** Formal analysis, Data curation. **Alix Neveu:** Writing – review & editing, Formal analysis, Data curation. **Amanda Gobeti Barro:** Formal analysis, Data curation. **Jingjing Liu:** Formal analysis, Data curation. **Tatianne Ferreira de Oliveira:** Validation, Supervision, Funding acquisition. **Marie-Pierre Ellies-Oury:** Writing – review & editing, Validation, Supervision. **Sghaier Chriki:** Writing – review & editing, Validation, Supervision. **Jean-François Hocquette:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare to have no conflicts of interest.

Data availability

Data will be made available on request.

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3.2. Discussion

3.2.1. Performance of the Q-FOM™ Beef grading camera

Our research findings on MSA marbling assessment from the study conducted in France using the Q-FOM™ Beef grading camera demonstrated high repeatability and reproducibility of the measurement, showing consistency with similar studies. Indeed, Stewart et al. (2021b) showed the efficacy of with a camera similar to the Q-FOM one for beef grading with Australian carcasses, achieving an R^2 of 0.76 for predicting IMF% and marbling. Our results in chiller ($R^2 = 0.75$, RMSE = 44.9) and on-screen ($R^2 = 0.78$, RMSEP = 48.7) are comparable with these previous published data. Furthermore, Stewart et al. (2024b) further validated the Q-FOM™ camera with Australian beef, reporting high predictive accuracy for MSA marbling ($R^2 = 0.95$) and IMF% ($R^2 = 0.94$). Additionally, Stewart et al. (2024a) developed and validated models that utilize chemical IMF% to determine equivalent MSA marbling scores and AUS-MEAT marbling. Their results demonstrated that an IMF%-based model explained 91% of the variation in MSA marbling (Residual Standard Error = 57.9), further supporting the reliability of our findings.

With European carcasses, Drachmann et al. (2024) showed that the accuracy and precision of the Q-FOM™ calibration and cross-validated model for predicting chemical IMF% in the *longissimus thoracis* (LT) at 5th-6th thoracic vertebra. These authors showed a high level of accuracy ($R^2 = 0.91$) and a good precision (RMSECV = 1.33%), with 62.6% of the carcasses accurately predicted. Furthermore, the predictions of IMF% from Q-FOM™ and chemically determined IMF% were found to be similar for each combination of sex and crossbreeding. This suggests that Q-FOM™ IMF% predictions may be useful in breeding programs for improving meat quality. Our results confirmed the ability of the Q-FOM™ to predict the marbling score of cull cows from a late-maturing European breed, namely Limousin.

Other studies have shown accurate predictions of chemical IMF% from camera-based technologies in the LT muscle from carcasses quartered at the 12th-13th rib (Pannier et al., 2023b; Stewart et al., 2021b). Comparing model performance between studies can be challenging due to differences in datasets, particularly since R^2 varies with the IMF% or marbling range, R^2 being lower with decreasing IMF% or marbling range. Pannier et al. (2023b) reported precise IMF% predictions made by the Marel conveyor vision scanner, with an estimate of 1.16% and an R^2 of 0.87, within a model IMF% range of 3.0 – 15.1%. The variation in performance among different models may

result from segmentation accuracy, since bone dust, fat particles, connective tissue, light reflectance from surface moisture, iridescence, and variations in camera positioning can result in misleading white pixels (Stewart et al., 2021a).

Moreover, it is important to emphasize that IMF% and marbling are both three-dimensional traits that vary throughout the LT muscle, which further complicates the prediction of IMF% from surface area (Pannier et al., 2023a; Stewart et al., 2021a). The ability of Q-FOM™ to assess marbling score in muscle is constrained by its use of a two-dimensional methodology to predict three-dimensional traits, such as marbling and IMF% (Stewart et al., 2021b). The three-dimensional nature of marbling (which varies slightly within the muscle in all directions) can be biased when predicted when accessing only one surface. This is evidenced by studies conducted by Drachmann et al. (2024), Stewart et al. (2024b) and Santinello et al. (2024). Consequently, the data obtained by Q-FOM™ on the cutting surface may be subject to sampling error associated with the distribution of fat within the sample (Stewart et al. 2024b). However, this is likely to be minimal because samples for IMF% analysis are homogenized, freeze-dried and ground to maximize homogeneity (Tøgersen, Arnesen, Nilsen, Hildrum, 2003).

A study similar to that of Kombolo-Ngah et al. (2023) is being conducted in Brazil at Beauvallet Brazil, exploring the use of handheld NIRS spectrometer to predict marbling scores along the LT, with marbling assessed using the MSA/3G protocol. Kombolo-Ngah et al. (2023) showed moderate predictive accuracy, supporting the potential application of NIRS in predicting MSA marbling classes ($R^2 = 0.46 - 0.59$) in the beef industry. In contrast, Coombs et al. (2021) reported that their study, which utilized non-identical carcass sites obtained from a local supermarket, found that a smartphone NIRS sensor was as accurate and precise as benchtop NIRS in predicting intramuscular fat (IMF) ($R^2 > 0.75$).

These findings support the hypothesis that using portable tools as an analytical technique to predict the MSA marbling score in beef would reduce costs and minimize dependence on human graders, whose assessments tend to be less objective. This approach also enhances the repeatability of data compared to the existing MSA grading scheme.

Both measurement tools studied represent a promising approach to enhancing the efficiency and accuracy of marbling evaluation, reducing the subjectivity and variability inherent in manual assessments. However, further advancements are needed to achieve high repeatability and

reliability of results to fully meet the needs of the beef industry. Ongoing research in this field will be critical to further strengthen the validity and applicability of these measurement tools across the beef production chain. In this regard, both the Q-FOM™ Beef grading camera and the SCiO have the potential to meet industry demands, as demonstrated in this thesis for a wide variety of breeds and production systems.

3.2.2. Discussion and Comparison between Q-FOM™ Camera and SCiO for marbling assessment

Table 1 shows a detailed comparison of two tools used for marbling assessment in beef: the Q-FOM™ Camera and the SCiO Near-Infrared Spectrometer. The evaluation is based on feedback from three assessors in our research group, who reviewed the strengths and limitations of each device in predicting marbling under real-world conditions. This comparison provides valuable insights into the practical applications of these non-destructive tools for beef quality assessment.

The SCiO portable spectrometer and the Q-FOM™ camera both have the potential to predict marbling scores based on the MSA method on the ribeye of the animal. Each instrument uses different technologies for measurement image analysis for the Q-FOM™ camera and near-infrared (NIR) spectrometry for the SCiO. Each of these technologies has its own strengths and weaknesses (Table 1).

Table 1. Benefits and weaknesses (based on evaluations from 3 users) of two tools for measuring marbling and model performance associated. Adapted from Kombolo-Ngah et al. (2024).

Criteria / Device	Q-FOM™	SCiO	Explanatory Notes
Autonomy	++	+	The Q-FOM™ has greater autonomy due to its internal and external batteries. The SCiO requires a charging accumulator with lower autonomy.
Ease of Use	+	+++	The SCiO is more intuitive and easier to use, allowing direct animal identification via the app, while the Q-FOM™ requires more time for calibration and setup.
Direct Use in Production Line	+	+++	The SCiO is more practical on the production line due to its portability and speed, while the Q-FOM™ requires more steps for data

			collection, including calibration and manual adjustments.
Animal Identification	+++	++	The Q-FOM™ uses QR code reading, while the SCiO directly links to the app, facilitating data collection in large volumes.
Repeatability of Results	+++	+	The Q-FOM™ has higher repeatability and consistency in marbling measurements, with greater precision in continuous readings.
Interference Control	+++	+	The Q-FOM™ has superior control over environmental interferences such as light and temperature, while the SCiO may be affected by light scattering due to the heterogeneous nature of meat.
Measurement Speed	++	+++	The SCiO is much faster, with measurements taken in milliseconds after calibration, while the Q-FOM™ requires more time due to image acquisition and validation.
Ease of Maintenance	+	++	The SCiO requires less technical maintenance, while the Q-FOM™ may need specialized assistance, especially for complex calibrations.
Durability Over Time	+++	++	The Q-FOM™ is more durable and designed for long-term operations, while the SCiO may experience degradation in the light source over time.
Integration with Other Equipment	+++	+	The Q-FOM™ can be connected to other devices like pH meters and thermometers, while the SCiO lacks this functionality.
Price Accessibility	+	+++	The SCiO is significantly more affordable, costing a few hundred euros, while the Q-FOM™ costs tens of thousands of euros.
Model Performance (Validation R ²)	0.75*	0.46-0.59*	The Q-FOM™ showed higher accuracy in marbling measurements, while the SCiO, due to the nature of the spectrometer, presents more variability in results.

Notes:

+++ : Highly advantageous

++ : Advantageous

+ : Slightly advantageous

*Experimental conditions vary between studies and may influence the validation R² values.

The Q-FOM™ camera has a significant advantage in terms of battery life, whereas the SCiO's battery life is much shorter and requires frequent recharging. However, the Q-FOM™ includes an external battery, which is considerably bulkier compared to a standard battery.

In terms of user-friendliness, the SCiO is more intuitive and easier to handle compared to the Q-FOM™ camera. The SCiO allows direct animal identification via the app, while the Q-FOM™ requires a QR code to be read for each reading. The Q-FOM™ is more complex with more steps to take a reading, to calibrate, to scan a QR code, to input user information, and to validate an image, each of which takes more time but is essential for accuracy. As a result, the SCiO is easier to operate, while the Q-FOM™ demands more from the user during setup and operation.

The compact size of the SCiO also makes it easier to use on production lines compared to the larger Q-FOM™ camera. When the surface of the ribeye is scanned, the Q-FOM™ captures the entire surface, while the SCiO takes readings from several points on the ribeye, which are then averaged. This can in some cases lead to some loss of information with the SCiO and result in less representative predictions. For this reason, the repeatability and representativeness of the Q-FOM™ is higher.

The nature of NIR spectrometry used in the SCiO can introduce interference due to the heterogeneous nature of meat samples, leading to light scattering. However, this characteristic also gives the SCiO the potential to provide additional information on protein, pigment, and mineral content. On the other hand, the Q-FOM™ camera is less affected by environmental conditions such as temperature and humidity. In low-light conditions, the Q-FOM™ is equipped with LED lights and an integrated polarizing filter to ensure accurate image acquisition.

One drawback of the Q-FOM™ camera is the longer image acquisition time, as it requires multiple steps: tool calibration, operator selection, image acquisition, and validation. Image acquisition also requires specific angles to capture accurate data. In contrast, the SCiO operates faster after the initial calibration, it requires only animal identification and spectrum acquisition, which occurs within milliseconds.

The Q-FOM™ uses more advanced technology and may require expert maintenance, whereas the SCiO, although simpler, may experience a reduction in light source performance over time, affecting its durability. While we have not tested this feature, the Q-FOM™ can also connect

with other tools such as pH meters or thermometers, making it more versatile. In contrast, the SCiO is designed solely for single measurements.

There is a notable price difference between the two devices. The Q-FOM™ is significantly more expensive, costing several tens of thousands of euros, whereas the SCiO is available for a few hundred euros.

In conclusion, both tools have specific advantages and disadvantages depending on the application. The Q-FOM™ offers greater repeatability and advanced features suited for comprehensive analysis, but at a higher cost and operational complexity. The SCiO is easier to handle and more affordable, but sacrifices some precision and versatility in exchange for simplicity and speed. The choice between the two tools should be based on the specific needs of the production environment, budget constraints, and the level of precision required for marbling assessment.

CHAPTER 4. GENERAL DISCUSSION

In this research, I had the unique opportunity to access extensive commercial databases of the Beauvallet company in both Brazil and France, enabling a comparative analysis of cattle breeds, feeding systems, and the influence of pre-slaughter factors, such as transport and handling, on carcass quality and beef sensory traits. The study focuses on the predominance of bulls (*Bos indicus*) in Brazil and cows (*Bos taurus*) in France, and how these variables, along with production systems, impact beef quality. Additionally, throughout my research, I had the opportunity to work with several cutting-edge, non-destructive devices for predicting beef quality, such as the Q-FOM™, Meat@ppli, SCiO Near-Infrared (NIR) spectroscopy, and IndiGo NIR Spectrometer. The Q-FOM™ and Meat@ppli use image-based analysis to assess carcass traits, particularly marbling, while the SCiO and IndiGo operate on NIR spectroscopy principles. All devices, except IndiGo, were designed to predict marbling. The IndiGo NIR Spectrometer, on the other hand, was used to predict the fatty acid composition of beef. While this thesis will specifically present the data obtained from the Q-FOM™ and SCiO devices, the experience with these other technologies provided valuable insights into the application of such advanced tools in the industry, especially in improving predictive accuracy and enhancing beef quality assessments through non-invasive methods.

4.1. Factors affecting beef eating quality

The complexity of guaranteeing beef eating quality coupled with the difficulty of reliably grading beef according to palatability largely contribute to explain the decline in beef consumption (Hocquette et al., 2011; Pethick et al., 2021) in addition to other factors. Beef, especially its palatability, is characterized by inherent variability and dependence on many interrelated factors that are difficult to manage. Both antemortem factors (e.g., gender, age, maturity, and breed of animals, carcass fat level, FA composition of cuts) and *post-mortem* factors (slaughter, carcass handling, aging, and storage after cooking) interact in myriad ways with unpredictable effects on eating quality (Devlin et al., 2017; Liu et al., 2022).

Meat from *Bos indicus* cattle (more common in Brazil than in Europe) tends to have lower eating quality compared to *Bos Taurus* (with famous breeds in Europe), primarily due to reduced tenderness and marbling (Andrade et al., 2020; Seideman et al., 1982; EBLEX, 2012).

This is partly due to differences in the calpain-calpastatin system, muscle fiber size, and metabolic properties, which contribute to lower protein degradation and, therefore, decreased tenderness (Wright et al., 2018). As a result, some certification systems exclude *Bos indicus* meat from premium labels, limiting its market presence (Bressan et al., 2020). Furthermore, the IMF% deposition and fatty acid profile of meat from both breeds differ based on feeding systems, highlighting the importance of nutrition (Bressan et al., 2011). In Brazil, genetics-based breeding programs have been launched to address these quality gaps, particularly for *Bos indicus* breeds like Nelore, enabling them to access markets traditionally favoring *Bos taurus* (Barro et al., 2023; Bonin et al., 2021; Fonseca et al., 2020; Malheiros et al., 2020; Marestone et al., 2022; Santiago et al., 2023).

Gender also plays a crucial role in beef quality, as hormone levels and muscle composition differ between sexes (Bonfatti et al., 2013). Heifers tend to produce more tender meat compared to steers and especially compared to young bulls, which is attributed to their lower intramuscular connective tissue content, higher intramuscular fat content and smaller muscle fibers (Venkata Reddy et al., 2015). Bulls, although maturing faster and with leaner carcasses, produce tougher meat, whereas steers are rated as quite palatable with higher IMF% compared to young bulls (Nogalski et al., 2018). In addition, meat from young bulls typically scores lower on sensory evaluations compared to females and steers (Bonny et al., 2016), while intact males tend to have darker meat due to higher myoglobin levels (Neethling et al., 2017). This distinction can also be observed in the data from Beauvallet that we analyzed for Brazil and France. According to ABIEC (2023), in Brazil, the predominant breed is Nelore, and young bulls make up the majority of the cattle population. Our Brazilian study confirmed this, with 97.9% of the animals being bulls and 99.3% belonging to the Nelore breed. In contrast, France exclusively raises taurine breeds, with Charolais, Limousin, and other breeds prevalent. In the region where the Beauvallet slaughterhouse is located, the Limousin breed predominates, and the animal population consists mainly of cows, as supported by data from Idele (2023) and our own research conducted in France.

Age is another important factor influencing beef quality, as older animals tend to produce tougher meat due to increased collagen content and reduced heat stability (Hopkins et al., 2007). As animals age, the percentage of IMF and monounsaturated fatty acids (MUFAs) increases, contributing to more intense flavor but also higher levels of unhealthy saturated fats (Watkins et al., 2013). Tenderness and flavor intensity typically peak at around 18 months, although this varies between animals and muscle types (Flores, 2017; Hopkins, 2017; Kopuzlu et al., 2018). In terms of age, *Bos indicus* cattle in Brazil are generally slaughtered younger than in France

to ensure tenderness. Interestingly, in our study, the opposite was observed: the average age at slaughter in Brazil was 203 months, compared to 110.49 months in France. This discrepancy can be attributed to the extensive Beauvallet Brazil dataset, which includes records dating back to the company's early operations.

Feeding systems also play a critical role in shaping beef quality. Extensive systems that rely on pasture-based feeding are often seen as healthier and more sustainable by consumers, while grain-finishing tends to result in beef with more desirable flavor characteristics (O'Quinn et al., 2016; Pogorzelski et al., 2022). Fatty acid profile, IMF content, and overall carcass composition are significantly influenced by the type of feed, with high-quality forage often resulting in marbling similar to that of grain-finished beef (Bonny et al., 2017). Variations in breed, age, and sex further complicate the impact of feeding systems on beef quality, but these effects can be managed through standardized breeding and processing practices (Thompson, 2004; Hocquette et al., 2011). In Brazil, cattle production predominantly relies on extensive grazing systems (95%) (Embrapa, 2024), whereas in Europe, diverse systems are used, for instance including extensive grazing in France, which is associated with a higher proportion of cows (Interbev and Idele, 2023) and intensive fattening systems in Italy, where young bulls are more prevalent.

Pre-slaughter management is critical in maintaining animal welfare, meat quality, and profitability. Stress as potentially induced by transportation and handling can deplete muscle glycogen, resulting in higher pH and defects like dark, firm, and dry (DFD) meat, which negatively affects tenderness, juiciness, and flavor (Sullivan et al., 2022; Gruber et al., 2010; Hemsworth et al., 2011). Long transport times, particularly in countries like Brazil, were hypothesized to exacerbate stress, which impacts the sensory properties of beef (Schwartzkopf-Genswein et al., 2012; Cooke et al., 2020), but our results have demonstrated the opposite. Systems like MSA recommend lairage periods to allow animals to rest and restore glycogen levels, thereby improving final meat quality (Del Campo et al., 2010; Watson et al., 2008).

Interestingly, despite the potential negative impacts of long-distance transport, our results showed that proper pre-slaughter handling and transport conditions effectively mitigated these effects, as evidenced by the fact that transport distance did not significantly ($P > 0.05$) affect the ultimate pH of the carcasses for both Nellore in Brazil and Limousin in France. These findings highlight how infrastructure and management best practices can minimize stress and maintain high beef quality (González et al., 2012).

Post-harvest practices such as aging, whether wet or dry, also contribute significantly to beef quality, with dry aging producing distinct, desirable flavors (Gagaoua et al., 2022). For instance,

the specifications of Label Rouge require a minimum of 10 days of aging for grilling and roasting cuts stored on the bone, except for cuts such as skirt steak, tenderloin, and hanger steak, as described in Cahier des charges du label rouge n° LA 03/89 (2020). In contrast, for non-labeled meat, the average is about 7 days in France. In Brazil, the aging time for the OR Rouge brand is 5 days.

Alvarenga et al. (2024) evaluated the effects of medium voltage electrical stimulation (ES) at different intensities (200 V, 300 V, and 400 V) on the *post-mortem* pH decline and quality parameters of *M. longissimus thoracis* in Nellore beef. The study found that electrical stimulation, particularly at 200 V, significantly improved tenderness by reducing shear force and cooking loss during aging and frozen storage, without negatively affecting lipid oxidation. Additionally, methods such as ES enhance tenderness by accelerating glycolysis and proteolysis, especially when combined with optimal pH and temperature controls (Arroyo et al., 2014; Dikeman & Devine, 2014). These findings suggest that ES can enhance the quality and tenderness of Nellore beef, both in aging and frozen conditions.

In terms of carcass suspension, studies have shown that pelvic suspension methods can improve tenderness, juiciness, and overall sensory quality, particularly in *Bos indicus* breeds. This technique shortens aging time while enhancing meat quality (Baldassini et al., 2023; Hopkins, 2014; Moran et al., 2021). Tenderstretch has been developed by Beauvallet in Limoges (France) and in Inhumas (Brazil) and was included in the specifications of the OR ROUGE brand launched by the company.

4.2. Importance of marbling on the sensory quality of beef

Intramuscular fat (IMF%), which is the fat within the muscle tissue between skeletal muscle fibers, plays a key role in different quality traits of beef (Hocquette et al., 2010; Chen et al., 2019). IMF% varies between species, between breeds, and even more between muscle types in the same animal. Other factors affecting IMF% in animals include gender, age, and feeding especially during the finishing period (Chriki et al., 2013a; Hocquette et al., 2011; Thompson 2004; Chambaz et al., 2003). The white flecks and streaks of IMF that are visible are called marbling (Hocquette et al., 2010; Lee et al., 2018). Marbling, as IMF%, has a positive correlation with meat sensory traits such as juiciness, color, tenderness, and taste (Stewart et

al., 2021a). It has been reported that 10 to 15% of the variance in tenderness evaluation can be explained by marbling (Dikeman, 1996), and that 2 to 56% of the variation in flavor can be explained by IMF% (Hocquette et al., 2011).

The current gold standard for measuring IMF% is chemical analysis using a fat extraction method. However, chemical methods are too costly and time-consuming for routine use in the beef industry, in addition to the cost of test samples destroyed in order to carry out the necessary procedures (Ferguson, 2004; Cheng et al., 2015). Recent studies, such as Stewart et al. (2024a), have developed models that convert IMF% into visual marbling scores, which offer a viable alternative to traditional methods while maintaining precision with minimal disruption.

This approach could transition the industry towards using IMF% as an objective trait, reducing the need for destructive sampling and potentially replacing visual assessments in grading systems. Even though marbling scores are commonly used as a proxy for IMF%, correlations between IMF% and marbling scores have been found to be as low as 0.32 and as high as 0.89 depending on the study (Savell et al., 1986; Cameron et al., 1994; Taylor, Johnson, 1992). On average, ~75% of the variation in IMF% can be explained by variation in visual scores by skilled assessors (reviewed by Ferguson, 2004). In addition, Stewart et al., 2021a, showed that visual marbling scores and data from chemical IMF% analyses have similar contributions ($R^2 = 0.32$ and $R^2 = 0.28$ respectively) for the prediction of beef eating quality. Consequently, predicted MSA eating quality (MQ4) scores are almost equivalent irrespective of which marbling input value was used (direct MSA marbling assessment or IMF% derived models for MSA marbling) according to Stewart et al. (2024b). To address the shortcomings of chemical methods to reliably predict beef eating quality in an industrial setting, grading systems relying upon carefully trained and accredited graders were developed internationally and especially in Europe (reviewed by Hocquette et al., 2020). While visual assessments have been the standard for a long time, Stewart et al. (2024a) argue that IMF% is a more objective and reliable reference. Both studies by Stewart et al. (2024a, 2024b) demonstrate that IMF% can be effectively converted into visual marbling scores, ensuring that this objective measure can be integrated into existing grading systems without disrupting current practices.

In the European Union, beef carcasses are typically evaluated using the EUROP grid, which describes conformation and fatness scores but does not include marbling as an indicator, despite previous recommendations (Monteils et al., 2017). Given the importance of marbling for beef

eating quality, demonstrated by studies conducted in France (Legrand et al., 2013; Bonny et al., 2018; Liu et al., 2021) and other European countries (Farmer and Farrell, 2018; Pogorzelski et al., 2020), the French National Food Conference (États Généraux de l'Alimentation) has recently recommended that the meat sector, represented by INTERBEV, incorporate marbling into the French beef grading system (EGA, 2018). Following these recommendations, a marbling measurement grid with six classes (rated from 1 to 6) was validated (Barmon et al., 2024). Meanwhile, in Brazil, efforts are underway to establish a comprehensive classification and grading system for beef carcasses that includes marbling scores alongside other quality parameters (Nunes et al., 2024).

Thus, there is increasing effort toward integrating marbling as a sensory quality attribute, reflecting a similar trend observed in Europe.

4.3. The importance of developing a beef classification system based on consumer quality in Brazil and France

Consumer awareness of food production, including the added value of meat quality in terms of health and safety, along with a growing interest in the sustainability of animal production, has been steadily increasing. These concerns are becoming integral to consumers' expectations of beef quality (Clinquart et al., 2022). When purchasing beef, consumers typically assess its quality based on factors such as price, origin, appearance, and visible fat (Santos et al., 2021). However, when sensory attributes such as taste, tenderness, or juiciness fall short of expectations, dissatisfaction arises, reducing the likelihood of future purchases. Consistency in sensory qualities plays a crucial role in shaping consumer decisions (McCarthy et al., 2017). Moreover, consumers are willing to pay a premium for beef of superior quality (Polkinghorne & Thompson, 2010), making it essential for the industry to accurately predict and consistently deliver high eating quality in order to remain competitive (Pogorzelski et al., 2022).

Although the Brazilian and European classification systems reflect the distinct priorities and practices of their respective regions, both serving the needs of domestic and export markets, they each reveal shortcomings in effectively assessing beef eating quality (Mendes et al., 2024a). In Brazil, for example, there is no national carcass grading system based on eating quality. Instead, classification is primarily determined by factors such as age, gender, weight, and fat coverage (Nunes et al., 2024). In Europe, the EUROP system—focused largely on

production yield factors like carcass weight, muscle shape, and fat coverage—faces similar limitations, particularly its inability to accurately predict beef eating quality. This shortcoming impairs its ability to meet consumer expectations, especially as the European beef sector faces growing competition from imported meats and alternative protein sources. As a result, improving beef eating quality has become critical for maintaining global competitiveness (Bonny et al., 2016; Liu et al., 2020; Liu et al., 2022; Pabiou et al., 2011).

Addressing these challenges requires further research and improvements to ensure that both the Brazilian and European systems align with the evolving demands of the beef industry and the increasingly discerning expectations of consumers. A promising future solution could involve adapting and implementing a grading system similar to Meat Standards Australia (MSA), such as the Guaranteed Global Grading (3G) system currently under development in Europe (Bonny et al., 2018a; Ellies-Oury et al., 2020; Hocquette et al., 2020; Legrand et al., 2013; Liu et al., 2021; Liu et al., 2023b). By leveraging the successful experiences of other regions, this system could help address the gaps in both Brazilian and European frameworks, ultimately enhancing beef quality for consumers and better meeting market demands (Mendes et al., 2024a).

In Brazil, efforts are already underway to establish a comprehensive classification and grading system for bovine carcasses that incorporates key eating quality parameters, such as ultimate pH, marbling score, and meat color. The main challenge lies in developing a system that can be uniformly applied across the country, which features a wide range of production systems, climates, and cattle breeds (Nunes et al., 2024). Additionally, a small number of private companies in Brazil currently use USDA or AUS-MEAT standards to grade beef carcasses, providing specific grading criteria for certain brands marketed within the country (Nunes et al., 2024).

A promising future alternative is the adaptation and adoption of a grading system similar to MSA, such as the 3G system currently being developed in Europe. This approach would leverage the successful experiences and valuable insights gained by other regions, helping to address the gaps in both the Brazilian and European systems, ultimately leading to significant improvements in beef quality and market satisfaction (Mendes et al., 2024). Developing a grading scheme that considers all factors influencing beef eating quality is essential. Such a system should be firmly grounded in consumer-driven standards, ensuring that the real demands for beef quality are met (Liu et al., 2022).

4.4. The development of a beef classification system based on consumer quality according to MSA specifications in France and prospects in Brazil

Around the world, several beef grading schemes, such as MSA (Meat Standards Australia), USDA (United States Department of Agriculture), and JMGA (Japan Meat Grading Association), are used to evaluate beef eating quality. These systems assign quality grades based on consumer-driven eating quality or specific meat attributes, such as marbling. Studies indicate that quality grades are reliable predictors of consumer expectations and influence purchasing decisions. For example, Lyford et al. (2010) demonstrated that consumers from countries like Japan, Australia, the United States, and Ireland are willing to pay more for beef with higher quality grades. The MSA system, in particular, is noted for its accuracy in linking quality grades to the actual eating experience, ensuring consumer satisfaction. Unlike grading systems that rely on a single attribute, such as marbling, MSA prioritizes consumer-based quality metrics, which have proven more effective in predicting overall beef quality (Smith et al., 2008).

Over the last two decades, the MSA system has been successfully applied in multiple countries, including Ireland, the United States, South Korea, Japan, France, and Poland, among others. To meet the growing demand for a standardized, consumer-oriented beef grading system, the International Meat Research 3G Foundation was established, facilitating global research aligned with MSA standards across the beef supply chain. This platform has enhanced the industry's ability to meet consumer expectations through comprehensive data sharing and analysis (Hocquette et al., 2020).

Research by the 3G Foundation underscores that consumer expectations of beef eating quality are generally consistent across different regions, with only minor variations observed (Bonny et al., 2017, 2018a). These findings, supported by more recent studies (Hocquette et al., 2023; Liu et al., 2023a; Purslow, Zhang, 2022), reveal that consumers from countries such as Australia, Brazil, and European nations prioritize meat that is affordable, high in organoleptic, sanitary, and nutritional quality, and produced ethically (Hotzel, Vandresen, 2022).

In Europe, the diversity of production systems—including rearing and feeding practices, environmental conditions, breeds, and processing methods—adds variability to meat quality evaluation across different countries. To address this, there is a need for standardized principles for meat quality assessment to ensure consistency in both scientific research and industrial

applications (Hocquette et al., 2020). Developing an MSA-like grading scheme in Europe would be a promising approach, provided that factors such as breeding, production, pre-slaughter handling, processing, and value-adding strategies are considered throughout the beef sector.

Carcass grading, a key aspect of the MSA system, serves as a predictor of eating quality scores. In Australia, critical traits like marbling and rib fat thickness are evaluated at the ribeye muscle, typically located at the 10th thoracic vertebra. However, in Europe, where beef carcasses are traded in quarters, cutting at the 10th rib could lead to economic losses. Therefore, the 5th rib has been identified as a more practical site for grading. Liu et al. (2021) addressed this issue by demonstrating that marbling scores between the 5th and 10th ribs are comparable, ensuring accurate predictions of eating quality.

Despite these advancements, implementing MSA principles in Europe presents additional challenges. For instance, measuring rib fat thickness at the 5th rib (instead of the 10th, as required in the MSA protocol) can result in less accurate predictions of eating quality. Rib fat thickness is a critical factor in determining whether a carcass qualifies for MSA grading (Polkinghorne et al., 2019). Further research is necessary to refine this process in the European context, ensuring that the MSA model remains a reliable predictor of beef quality across diverse production systems.

Liu et al. (2023b) identified a specific challenge with grass-fed Angus x Salers crossbred cattle, where the current MSA model has to be improved to accurately predict eating quality scores from consumer tests. This issue arose when the prediction model could not account for breed differences or non-compliance with grading standards. For successful MSA implementation in Europe, adjustments to the grading system may be required, alongside additional research on new genetic types and local livestock systems to improve model accuracy and robustness.

In Brazil, the introduction of an MSA-like system presents both challenges and opportunities. Efforts to establish a comprehensive grading system that includes essential parameters such as ultimate pH, marbling score, and meat color are underway. However, the main challenge lies in developing a system that can be uniformly applied across Brazil's diverse production systems, climates, and cattle breeds (Nunes et al., 2024). Some private companies in Brazil have already started using USDA or AUS-MEAT standards to grade beef, indicating a potential path toward a consumer-driven grading system like MSA (Nunes et al., 2024).

A significant development in Brazil is the work of Baldassini et al. (2023), who conducted a sensory analysis with untrained consumers using the MSA consumer test protocol to evaluate traits such as tenderness, flavor, juiciness, and overall liking. This initiative was supported by the startup Brazil Beef Quality (BBQ), which integrates quantitative and qualitative data from slaughterhouses. With backing from Fapesp and the EsalqTec incubator, BBQ developed a star rating system similar to the MSA and 3G systems, classifying over 100,000 carcasses in collaboration with companies such as VPJ, Barretto Steak, and the Beauvallet group (Brazil Beef Quality, 2024). Working with a company such as Beauvallet, which operates both in France and Brazil, opens up interesting perspectives for research and development. This international collaboration allows for a comparative analysis of beef quality across different production systems and market demands, leveraging the expertise from both regions to improve overall product quality.

The BBQ carcass classification system is based on 15 criteria for the prediction of beef eating quality. These include: sexual category (intact male, castrated male, heifer, cow, etc.), taurine blood content, chronological age (dentition), physiological age (ossification), hot carcass weight, fat finish, hanging method, hump height, meat color, fat color, marbling, ribeye area, subcutaneous fat thickness, pH, and meat maturation. Data from slaughtered animals are entered into the Beef registration web platform, which is interconnected with the Beef Score software. The algorithms process the information and provide real-time carcass scores. The data is sent to the Beef Report, which transforms it into graphs for analysis by interested parties. Depending on the score obtained (on a scale of 1 to 100), carcasses are either disqualified or receive the Brazil Beef Quality seal. If they pass the assessment, they can be classified into three categories: 3 stars (40 to 60 points, suitable for daily consumption), 4 stars (61 to 80 points, indicating very good meat), and 5 stars (over 80 points, indicating an excellent or premium quality standard). The certification training is conducted by the company's team, which hires professionals to oversee data collection during slaughter, including the analysis of ossification maturity following the methodology of the Australian certifying body, AUS-MEAT (Brazil Beef Quality, 2024).

In Brazil as in France, MSA-related initiatives have been primarily driven by academic research and startups, such as Brazil Beef Quality and the 3G grading scheme, often in partnership with universities. These startups, along with private enterprises, such as Beauvallet (which operates

in both France and Brazil), are having an increasing impact on the beef supply chain. However, government involvement in the adoption of these standards remains limited. Typically, government participation is focused on export quality management, where external auditors are engaged to validate beef quality for different markets, sometimes in alignment with MSA principles (Mendes et al., 2024a). Overall, similar academic research on beef quality is being applied in both countries, despite the differences in their beef supply chain structures (Nunes et al., 2024).

4.5. Non-destructive technologies for predicting beef quality

Beef quality can now be reliably predicted using emerging technologies without the need for destructive sample testing. These advanced technologies enable the direct prediction of eating quality based on animal, carcass, or beef characteristics within the framework of grading schemes like the MSA/3G systems, or indirectly through the prediction of factors such as marbling (Farmer, Farrell, 2018; Mendes et al., 2024a; Sanchez et al., 2022).

Numerous scientific articles have been published exploring the use of various sensing technologies to both quantitatively and qualitatively predict carcass composition and meat quality with promising results (Anderson et al., 2018; Beriain et al., 2021; Cama-Moncunill et al., 2020; Coombs et al., 2021; Stewart et al., 2021).

In order to meet the growing demands of the beef industry, extensive research has been conducted in Australia, particularly by the Meat and Livestock Australia (MLA) initiative, which has focused on calibrating these new non-destructive techniques. Studies by Stewart et al. (2021, 2024a, 2024b) have extensively utilized the MSA/3G grading scheme as a reference to calibrate technologies such as the Q-FOM™ Beef handheld camera. As part of my doctoral research, trials conducted in France demonstrated that marbling assessments made with the Q-FOM™ Beef handheld camera met acceptable standards for French slaughterhouses. Furthermore, both on-screen grading and in-chiller visual assessments of MSA marbling scores were found to be reliable for developing the Q-FOM™ marbling model ($R^2=0.78$, RMSEP=48.7).

Kombolo-Ngah et al (2023) investigated the use of handheld NIR spectrometers in the chiller for predicting marbling scores of intact meat muscles at slaughterhouses in France and Italy

with NIR measurements at different points on the *Longissimus thoracis*. Marbling was assessed according to the 3G (Global Grading Guaranteed) protocol ($R^2=0.46 - 0.59$). These results provide moderately predictive accuracy of the marbling scores with possible use by the European beef industry to predict classes of MSA marbling. These findings are expected to be expanded with further trials in Brazil, which are part of my thesis work. The research will apply similar non-invasive techniques to predict marbling in different breeds, such as Nellore and Angus crossbreeds. This expansion aims to validate the predictive accuracy of these technologies within the Brazilian beef industry, thereby contributing to a broader understanding of marbling assessment across diverse cattle breeds and production systems.

Studies have also highlighted the potential of infrared thermography as a valuable tool for the Brazilian beef industry. Ferreira et al. (2024) showed that this technology could be used not only to detect Dark, Firm, and Dry (DFD) meat but also to predict ultimate pH in carcasses, with improved results when combined with blood parameters. These developments underscore the significant role of infrared-based methods in improving meat quality predictions in Brazil. In addition to academic research, private sector initiatives in Brazil have made substantial strides in developing non-invasive technologies. Companies such as Brazil Beef Quality (BBQ) and DGT Brasil have been investing in innovative tools to enhance carcass evaluation and beef quality prediction (Mendes et al., 2024a). BBQ has been at the forefront of developing imaging-based technologies, such as Meat Image for carcass evaluation, Meat Score for tenderness prediction using spectral analysis, Yield Grade for deboning yield estimation, and Origin for cattle traceability. These tools are calibrated with MSA reference methodologies and supplemented by physico-chemical and rheological analyses to ensure accuracy and reliability (Brazil Beef Quality, 2024). Meanwhile, DGT Brasil has focused on developing its Bovine Image Analysis (BIA) software, which provides precise and unbiased interpretations of ultrasound images of cattle carcasses. While not directly calibrated with MSA methodologies, BIA has significantly improved data accuracy and consistency in carcass evaluation, offering an effective solution for the Brazilian beef industry (DGT Brasil, 2024).

A range of objective, non-destructive technologies is already in use, but many are limited by high costs, lack of portability, and reliance on reference methods (Scholz et al., 2015; Cheng et al., 2015). Overcoming these challenges requires the development of robust calibration models that better reflect industrial variability. The recent advent of portable handheld devices has made

large-scale application more feasible, allowing rapid data acquisition without the need for complex sampling or transporting samples to laboratories (Goi et al., 2022; Kademi et al., 2018).

To meet industry needs, both MSA in Australia and the 3G Foundation in France and Brazil are advancing devices that are calibrated with reference methodologies, supported by certified expert graders. The Q-FOM™ Beef handheld camera is one of the few tools approved by MSA/AUS-MEAT for use in commercial settings, accurately grading beef ribeye for marbling, intramuscular fat, eye muscle area, and other traits in seconds with just a single image (AUS-MEAT, 2023; Frontmatec, 2023; Stewart et al., 2024b). These tools not only increase efficiency but also assist certified graders in maintaining consistent and reliable grading standards.

4.6. Guarantees of beef quality from quality labels and MSA specifications

In both Brazil and France, quality labels and certifications play a pivotal role in shaping the value and image of beef products. These labels contribute not only to consumer perceptions of quality but also to the competitiveness of beef in both domestic and international markets. The Label Rouge in France and other certification programs in Brazil highlight different aspects of beef production, including sustainability, traceability, and sensory quality, while aiming to meet the increasingly sophisticated demands of consumers (Mendes et al., 2024).

In France, the Label Rouge stands as one of the most recognized certifications for superior beef quality. This label, regulated by French authorities, signifies that the beef meets higher standards of palatability and credibility, reflecting consumer-driven attributes such as taste, tenderness, and overall eating satisfaction (Hocquette et al., 2014). The Or Rouge brand, which focuses on premium Limousin beef, is a prime example of how intrinsic (eating quality) and extrinsic (image value) quality traits are combined to meet consumer expectations. By leveraging the Label Rouge system and emphasizing grass-fed systems, Or Rouge aligns itself with the high standards of the French beef industry, focusing on intrinsic qualities such as marbling and color that are essential for superior meat (Raulet et al., 2021).

One key aspect of the Label Rouge certification is its emphasis on breed-specific quality, particularly focusing on breeds such as Limousin, Charolaise, and Salers. Production practices on farms, like mandatory grazing periods or grass-feeding for at least five months, and also 10

days of ageing (a minimum which is compulsory) further enhance the quality of the beef produced under this label (Raulet et al., 2021). However, despite the strength of these certifications, concerns have been raised about how well they align with comprehensive grading systems such as the MSA, which prioritizes consumer-driven eating quality. During my thesis, I had the opportunity to participate in analyses applying the MSA methodology and utilizing various innovative technologies, including SCIO, Meat@ppli, the Q-FOMTM camera, and IndiGo, to predict beef quality. Around 1,000 carcasses were graded according to MSA specifications at the Beauvallet CV Plainemaison chiller, the company behind the Or Rouge brand. This approach demonstrated the advantages of integrating local breed-specific characteristics with the MSA's focus on consumer satisfaction (Liu et al., 2021). Moreover, Or Rouge, a brand of Limousin beef from C.V Plainemaison - Beauvallet, ensures high-quality beef through the use of Limousin cattle raised under specific grazing and production systems, along with efficient carcass management and quality control techniques. In addition to carcass grading, innovative management practices like the Tenderstretch method were adopted to enhance the tenderness of loin and hindquarter cuts (Bonny et al., 2018; Legrand et al., 2021). The OR Rouge brand specifies a minimum amount of marbling. This additional requirement aligns with the broader French national strategy, proposed during the "États Généraux de l'Alimentation" (French Food Conference) in 2018, which recommended incorporating marbling into the French beef grading system to further elevate quality standards (Liu et al., 2020).

In Brazil, the focus on beef quality is shaped by different priorities, with a strong emphasis on sustainability and traceability. Certifications such as Carne Sustentável do Pantanal and Carbon Neutral Brazilian Beef focus on environmentally responsible production, integrating sustainable practices into the beef supply chain (Embrapa, 2024). Programs such as the Green Sign Pact and Early Beef Program aim to improve carcass classification and herd management, contributing to the overall quality of Brazilian beef. However, despite the work of the Brazil Beef Quality startup, Brazil currently lacks a national grading system focused solely on eating quality, unlike the national MSA programme in Australia, which integrates consumer satisfaction into its grading criteria (Mendes et al., 2024a; Nunes et al., 2024). While private companies in Brazil have begun using USDA or AUS-MEAT standards for specific beef brands, these systems do not fully account for consumer-based eating quality, which is the cornerstone

of the MSA system (Nunes et al., 2024). The development of a comprehensive system that includes key parameters such as pH, marbling, and tenderness would align Brazil more closely with global quality standards and ensure that the country's beef products meet both domestic and international consumer expectations (Nunes et al., 2024).

A significant development in Brazil is the work of Baldassini et al. (2023), who conducted a sensory analysis with untrained consumers using the MSA consumer test protocol to evaluate traits such as tenderness, flavor, juiciness, and overall liking. This initiative was supported by the startup Brazil Beef Quality (BBQ), which integrates quantitative and qualitative data from slaughterhouses. With backing from Fapesp and the EsalqTec incubator, BBQ developed a star rating system similar to the MSA and 3G systems, classifying over 100,000 carcasses in collaboration with companies such as VPJ, Barretto Steak, and the Beauvallet group (Brazil Beef Quality, 2024). Working with a company such as Beauvallet, which operates both in France and Brazil, opens up interesting perspectives for research and development. This international collaboration allows for a comparative analysis of beef quality across different production systems and market demands, leveraging the expertise from both regions to improve overall product quality.

The Beauvallet group has designed a new premium beef brand called OR Rouge developed by this group in France, based on specifications for French farmers. The primary objective of OR Rouge is to provide tender, healthy, and flavorful beef to consumers. The superior quality of Or Rouge beef product is guaranteed using taurine cows reared using particular grazing and production practices along with efficient carcass management. Beauvallet was the first company in Brazil to utilize the pelvic suspension technique, which not only enhances tenderness but also assists in the meat maturation process. Certification for this brand is provided by Brazil Beef Quality, a startup that relies on the methodologies of USDA and MSA (Beauvallet, 2024). During my thesis, I worked in this field under the Or Rouge brand and implemented the MSA methodology. Additionally, this brand uses the BBQ specifications, which are also adopted by the Or Rouge brand, along with the instrumental methods developed by BBQ, such as Meat Image, Meat Score and Score Yield Grade.

The integration of MSA principles into both Brazilian and French quality systems offers a promising path forward. For France, incorporating consumer-based eating quality assessments into labels like Label Rouge and Or Rouge could further enhance their reputations for superior

eating quality. For Brazil, the adoption of a grading system focused on eating quality, similar to the MSA, would address current gaps in the certification process and ensure that Brazilian beef remains competitive in the global market.

Both countries can benefit from a hybrid approach, combining local production practices with the MSA's focus on consumer satisfaction. By doing so, they would not only improve the intrinsic quality of their beef products but also enhance their extrinsic value, ensuring that their beef is not only palatable but also aligned with consumer expectations for sustainable and ethically produced food (Bonny et al., 2018a; Liu et al., 2023b; Mendes et al., 2024a).

4.7. Future prospects for this study

- **Building an ontology**

One of the key challenges in the beef industry is the lack of standardization and interoperability between different grading systems and data sources (Barro et al., 2024). For example, while the BBQ system in Brazil and the 3G Foundation in France both aim to ensure high standards of beef quality, their methodologies and data are not fully aligned. This creates barriers to effective data integration and comparison across different regions and systems. Addressing this gap is essential for advancing research and improving industrial applications in the beef sector.

As highlighted by Kombolo-Ngah et al. (2022), the meat thesaurus serves as a valuable semantic resource that can promote the interoperability and findability of data within the meat sector. Leveraging this resource as a foundation, we propose the development of a beef quality ontology. An ontology would provide a formal, structured representation of domain-specific knowledge, enabling the organization, structuring, and sharing of data between systems like BBQ and 3G. By defining and modeling the characteristics, relationships, and quality metrics of beef in a consistent and unified framework, this ontology could facilitate advanced reasoning and prediction of meat quality, benefiting both research and industrial practices (Kombolo-Ngah et al., 2022).

- **Creation of a unified grading system**

In the current global meat industry, several grading systems such as MSA and USDA coexist, each with its own criteria and methodology for assessing meat quality. While these systems are highly valuable within their respective regions, the lack of a unified reference standard complicates the comparison of meat quality across countries. Establishing a universal grading framework would not only facilitate cross-border trade but also allow for a more consistent evaluation of quality traits globally. This unified approach would help mitigate discrepancies that arise from regional variations in meat classification and ensure a common language in the international meat sector.

- **Development of devices for routine and non-invasive assessments**

As part of my thesis, this study demonstrated that the Q-FOM™ Beef camera can reliably predict MSA marbling scores in beef carcasses quartered between the 5th and 6th ribs, a common practice in Europe. The results showed strong correlations between the camera's predictions and expert grader assessments, meeting the accreditation criteria established by AUS-MEAT in Australia. Both in-chiller and on-screen evaluations proved effective for developing a calibration model, confirming the camera's potential to enhance the consistency and accuracy of marbling assessments in the French beef industry.

Using reference methods such as a grid for marbling assessment can be subjective, which highlights the importance of developing algorithms that establish a direct relationship with the intramuscular fat percentage (IMF%). As described by Stewart et al. (2024a), models were developed and validated to use chemical IMF% to find equivalent MSA marbling scores and AUS-MEAT marbling grades. Consequently, IMF% can serve as a proxy for MSA marbling when comparing results across studies. Furthermore, this research focuses on the feasibility of the Q-FOM™ Beef camera in predicting MSA marbling in French cattle breeds, which exhibit a limited marbling range compared to breeds commonly found in Australia.

Given these promising results, it is crucial to continue advancing research in this area. In response to the technological demands of the Brazilian beef industry, BBQ has developed the Score Yield Grade (SYG) project and the Meat Image system, aiming to create a platform capable of predicting both carcasses yield before deboning and carcass quality at the 5th and 6th ribs. SYG uses advanced machine learning algorithms and artificial intelligence to analyze

carcass characteristics such as subcutaneous fat thickness and ribeye area. However, although this technique currently focuses on carcass evaluation between the 10th and 13th ribs, following the Australian standards of the MSA methodology, adjustments are needed to adapt it to the Brazilian context, where the typical carcass cut is made between the 5th and 6th ribs. This adaptation will allow the development of regression equations to more accurately predict meat yield, optimize production efficiency, and reduce waste on the production line.

BBQ's innovative Meat Image system, integrated into the SYG platform, represents a significant technological advancement, aligning carcass evaluation technology with the 5th and 6th rib positions commonly used in Brazilian slaughterhouses. This adaptation not only ensures more accurate and consistent measurements but also positions BBQ to expand its market presence in Brazil and internationally, including countries such as France, which also use carcass cuts at the 5th and 6th ribs.

Additionally, future studies will be conducted in Brazil and France to verify whether devices or tools, such as the Q-FOM™ camera, Meat Image and SYG function identically in both regions, ensuring that data can be merged. These actions are pivotal in achieving a globally harmonized system that fosters transparency and objectivity in meat quality assessment, ultimately enhancing the efficiency and profitability of the global beef industry.

Conclusion

This thesis highlights the importance of continued advancements in beef production across Brazil and France, two key players on the global stage. Both countries must constantly strive to maintain technical and economic superiority within their respective beef supply chains. While consumer preferences for beef quality in Brazil and France are quite similar, demanding affordable meat with excellent organoleptic, nutritional, and ethical qualities, the implementation of the MSA/3G methodology and non-destructive technologies could bring significant added value to both markets. The adoption of these approaches would allow for the identification and selection of genetic criteria that enhance sensory quality, ultimately improving the profitability of producers and processors, as has already been achieved in Australia. Therefore, it is essential for Brazil and France to continue investing in research and innovation to ensure their beef products remain competitive in the international marketplace.

In the study conducted at Beauvallet Inhumas, Brazil, we observed that transport distance and time had little impact on the quality of beef from Nellore cattle. This finding aligns with the physical resilience of the Nellore breed and the operational strategy of limiting transportation to a maximum of 300 kilometers or 8 hours, which complies with market requirements. The results reinforce the need for further research on stress indicators, such as cortisol and creatine kinase levels, to provide a more detailed understanding of how transportation affects beef quality and animal welfare.

Similarly, a study at Beauvallet Limoges, France, showed that transportation had negligible effects on the ultimate pH of Limousin cull cows. Variability in potential eating quality was observed between producers, but the distance traveled and time in transit were not significant factors. The use of MSA protocols for grading carcasses could further improve the consistency and quality of beef in France.

The findings from this thesis also confirmed that the Q-FOM™ Beef grading camera, tested in the French slaughterhouse at Beauvallet CV Plainemaison, accurately predicts MSA marbling scores using the MSA grading scheme. This technology demonstrated its reliability in the European context, where marbling scores are generally lower than in countries like Australia. The camera provided consistent results and represented a significant step forward in improving marbling evaluation accuracy within the French beef industry.

Future studies will be developed in Brazil and France to achieve the following key steps: (1) aligning and clearly defining the MSA traits measured in Brazil and those measured in Europe, (2) ensuring that carcass graders assess these MSA traits consistently across different countries, as cultural factors may introduce bias into the assessment, and (3) verifying whether devices or tools, such as the Q-FOM™ camera, work identically in both regions to guarantee that data can be merged. These actions are pivotal in achieving a globally harmonized system that fosters transparency and objectivity in meat quality assessment.

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