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Reindeer meat classification and quality assessment: traditional and emerging technologies

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Reindeer (*Rangifer tarandus*) meat is a culturally and nutritionally significant product of Fennoscandian pastoralism. While the meat is available widely in the market in the producing countries, yet it lacks a species-specific quality classification system. The EUROP carcass grading framework, designed for cattle, is used instead, despite not fully suitable for cervids. Technologies, such as image based automated grading, also remain untested on reindeer. This review examines the current state of reindeer meat quality classification and evaluates the potential of hyperspectral imaging (HSI) to address the identified technological gaps. A comprehensive literature search was conducted across Web of Science, Scopus, and PubMed, supplemented by EU regulatory documents and published ethnographic sources on traditional Sámi knowledge systems. The review reveals that applying the EUROP system on reindeer meat requires oversimplification: fat scoring collapses into a single class owing to negligible subcutaneous fat, and conformation scoring reflects bovine muscularity benchmarks irrelevant to cervid anatomy. While this simplification works, some specific, important characters of reindeer meat might not be captured. Neither official veterinary inspection nor traditional Sámi assessment incorporates instrumental quality measurement, leaving ultimate pH, colour, and dark, firm, dry (DFD) status unmeasured. HSI has demonstrated strong predictive performance for these parameters in beef, pork, lamb, and farmed red deer venison, yet a systematic database search confirmed the complete absence of any HSI study on reindeer carcass and meat for grading purposes as of January 2026. This gap is significant because the quality parameters most critical to the reindeer industry are precisely those for which HSI has shown its strongest capability. A phased research roadmap is proposed, encompassing construction of a reindeer-specific spectral reference library, pilot deployment of portable snapshot HSI systems in remote slaughterhouses, and integration of instrumental quality indicators with traditional Sámi knowledge through participatory co-design. This methodological template is transferable to other underserved niche meat species worldwide.

KEYWORDS
carcass classification, DFD meat, EUROP grading, hyperspectral imaging, *Rangifer tarandus*, reindeer meat, video image analysis (VIA)

1 Introduction

Global meat production is governed by regulatory frameworks designed to safeguard animal welfare, ensure food safety, and establish quality standards throughout the supply chain (Jia et al., 2022; Henchion et al., 2014). In most countries, a government authority oversees these matters, for instance the Jordbruksverket (Swedish Board of Agriculture) in Sweden, the United States Department of Agriculture (USDA) in the US, and the Department for Environment, Food & Rural Affairs (Defra) in the UK. Within the European Union and associated countries, the EUROP carcass grading system serves as the primary classification framework for beef and sheep carcasses, assessing conformation and fatness to estimate meat yield (European Commission, 2017; Animalia, 2024; Nisbet et al., 2024b). The system was introduced in the early 1980s and remains the cornerstone of carcass pricing across EU member states (Kenny et al., 2020; Craigie et al., 2012). The EUROP grid, as illustrated in Figure 1, is a system developed in the 1980s, originally designed for grading cattle and lamb (European Commission, 2017). It evaluates each carcass on two axes: conformation (muscle) and fat cover, with green area indicating commercially desirable grade combinations and red area indicating less desirable grades. For commonly consumed species such as cow and sheep, classification procedures, validation protocols, and training standards for meat inspectors are well established and extensively documented.

While EUROP system is quite reliable for the whole carcass grading, mounting evidence indicates that EUROP scores are poor predictors of eating quality and marbling which are not homogeneous in a whole carcass body (Bonny et al., 2016; Liu et al., 2020; Santinello et al., 2024; Nogalski et al., 2019). Moreover for niche meat species that are produced only in specific regions, the regulatory infrastructure and supporting research base are inadequate. Reindeer (*Rangifer tarandus tarandus*) is one such species: economically and culturally significant in Fennoscandia (Sweden, Norway, and Finland), yet marginal in the global meat industry. Reindeer husbandry has been central to the livelihoods and cultural identity of the Sámi people for centuries (Salmi, 2023; Tyler et al., 2007), and reindeer meat remains a valued food product throughout the Nordic countries (Wiklund et al., 2014). Semi-domesticated reindeer graze freely on natural pastures across vast Arctic and sub-Arctic landscapes, following a seasonal cycle that includes calving in spring, mountain grazing in summer, gathering and slaughter from September to November, and winter foraging on lichen and other vegetation in forested lowlands (Renbiten AB, 2026). During the autumn gathering, animals are herded into enclosures where different owners separate their herds and selected animals, predominantly calves but also some older individuals, are directed to

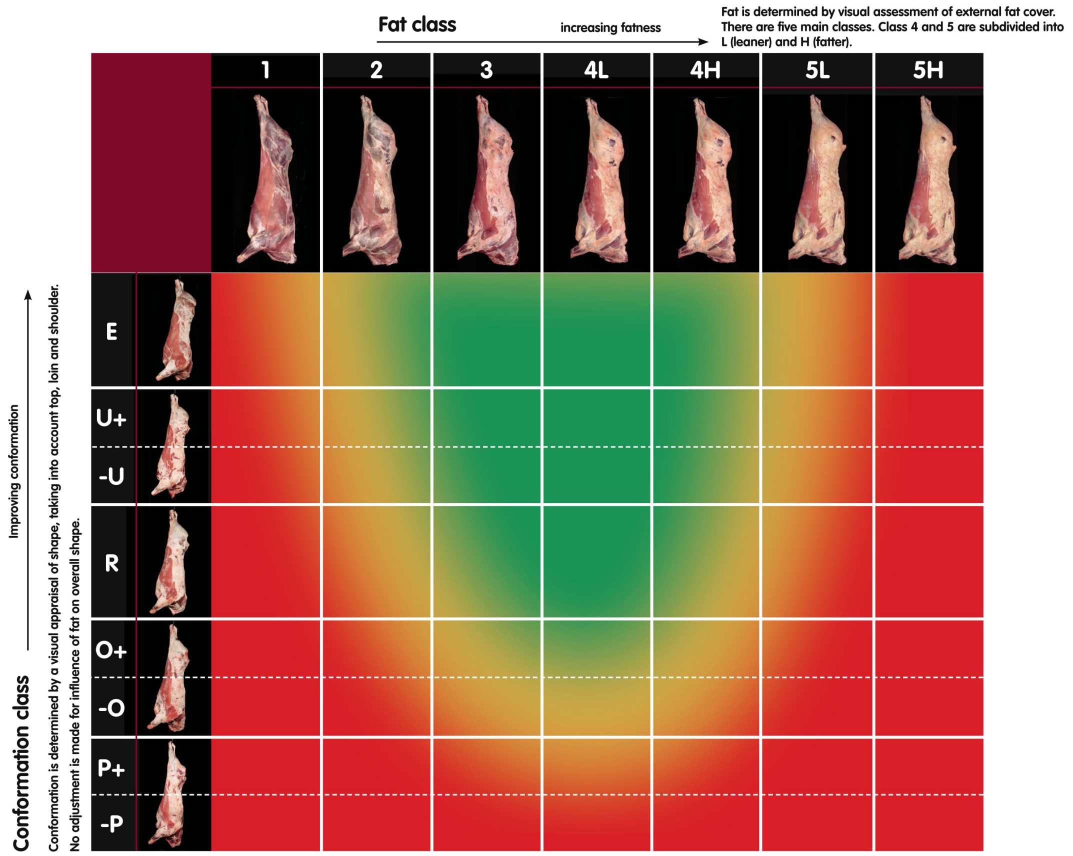

FIGURE 1
The EUROP carcass classification grid for beef, showing conformation classes (E to P, vertical axis) and fat cover classes (1 to 5, horizontal axis). Green indicates commercially desirable grade combinations; red indicates less desirable grades. Reindeer carcasses fall almost exclusively within fat classes 1–2 and conformation classes O–P (bottom-left corner), where discriminatory power is minimal. Adapted from AHDB (2017).

slaughter. This annual cycle of gathering, selection, and slaughter is deeply intertwined with Sámi traditions and ecological knowledge (Tyler et al., 2007). Nutritionally, reindeer meat is lean (approximately 2% total lipid), rich in iron, vitamin B12, and long-chain omega-3 fatty acids, and compares favourably with other red meats on multiple health-related indices (Triumf et al., 2012; Hassan et al., 2012; Dvoretsky et al., 2025; Wiklund et al., 2014). Despite this cultural significance and nutritional profile, the classification and grading of reindeer meat borrows almost entirely from systems designed for bovine carcasses. Specifically, reindeer carcasses in Sweden and Finland are assessed using an adapted simplified version of the EUROP grid.

The reliance on a bovine-derived classification system raises three interrelated challenges that motivate the present review. First, the EUROP criteria, calibrated for well-marbled beef cattle slaughtered at 12 to 24 months of age, may not accurately reflect reindeer carcass quality. Reindeer meat is significantly leaner than beef, with intramuscular fat content typically in the range of 1.5 to 3%, compared to 5 to 15% in beef, and exhibits higher protein content, higher iron concentrations, and a more favourable omega-3 to omega-6 fatty acid ratio (Wiklund et al., 2014; Triumf et al., 2012; Wiklund et al., 1995). Most reindeer in Fennoscandia are slaughtered as calves at just 6 to 9 months of age, yielding carcasses of 20 to 35 kg that overwhelmingly fall into the lowest EUROP fatness classes (1 and 2), effectively compressing the entire scoring range into a region where visual discrimination is unreliable (Wiklund et al., 1995). Swedish carcass records of autumn-slaughtered reindeer show that carcass weights are consistent with the lowest EUROP fatness and conformation classes (Olofsson et al., 2011). In Norway, carcass classification is required under national regulation as a condition for receiving the slaughter subsidy (Lovdata, 2011), though published data on the distribution of reindeer across EUROP classes remain scarce. Finland does not apply formal EUROP classification to reindeer, as discussed in Section 3. Given that EUROP conformation and fatness scores explain only a small proportion of the variance in marbling and bear no consistent relationship with sensory quality even in cattle (Bonny et al., 2016; Liu et al., 2020; Nogalski et al., 2019), the mismatch with ultra-lean reindeer carcasses is likely to be even more pronounced. Second, the scarcity of qualified inspectors in remote Arctic and sub-Arctic regions creates practical bottlenecks. Reindeer slaughterhouses are often located in sparsely populated areas with limited access to official veterinarians, and transport distances from grazing areas can exceed several hundred kilometres (Muuttoranta and Majuri, 2021; Kautto et al., 2023). These logistical constraints increase the risk of pre-slaughter stress, which can deplete muscle glycogen and elevate ultimate pH, resulting in dark, firm, and dry (DFD) meat (Wiklund et al., 1995; Ponnampalam et al., 2017; Hultgren et al., 2022). DFD is a quality defect that is disproportionately common in reindeer compared to cattle, owing to the semi-wild temperament of the animals and the prolonged handling chains typical of Arctic slaughter logistics (Wiklund et al., 1995). Third, evolving consumer demands for sustainability, traceability, and objective quality assurance are intensifying pressure on the reindeer meat industry to adopt transparent and verifiable grading methods (Jia et al., 2022; Henchion et al., 2014). Although reindeer meat production is modest in global terms, a significant and growing share is marketed through premium retail channels and exported to gourmet markets in continental Europe, where objective quality documentation is increasingly expected by retailers and consumers alike. Quality marks such as the Swedish "Renlycka" label, which requires O+ or better EUROP conformation and an ultimate pH below 5.8, represent an important step, but currently depend on manual assessment processes that are inherently subjective and difficult to standardise across facilities.

In the mainstream meat industry, some of the challenges in meat grading and classification have been addressed through technological innovation. Video image analysis (VIA) systems, which use digital cameras and automated software to predict EUROP grades from carcass images under controlled lighting conditions, now classify approximately 90% of beef carcasses in Ireland (AHDB, 2017; Craigie et al., 2012). VIA technology has shown to improve both the precision and accuracy of meat yield quality prediction compared with manual classification (Craigie et al., 2012; Negretti et al., 2022). Moreover, recent developments incorporating 3D imaging and machine learning have further extended its capabilities (Nisbet et al., 2024b, Nisbet et al., 2024a). More recently, hyperspectral imaging (HSI), which combines spatial imaging with spectroscopy to capture detailed chemical information across hundreds of contiguous wavelength bands, has demonstrated the ability to predict key quality attributes such as intramuscular fat, pH, moisture, and protein content across beef, pork, lamb, and poultry (Jo et al., 2024; Jia et al., 2022; Yi et al., 2025; Tang et al., 2023; Dixit et al., 2021a). HSI has also been explored for meat authentication and adulteration detection (Yu et al., 2025), and comprehensive reviews highlight its potential for factory-scale deployment within the framework of Food Industry 4.0 (Jia et al., 2022; Yi et al., 2025). Notably, Dixit et al. (2021a) developed a global calibration model for predicting intramuscular fat and pH across beef, lamb, and red deer venison (*Cervus elaphus*), using partial least squares regression (PLS-R) and deep convolutional neural networks (DCNN) trained on pooled hyperspectral data from all three species. The reported prediction coefficients ($R_p^2 = 0.86 - 0.89$) refer to continuous regression models validated on held-out samples, not to binary classification tasks. This demonstrated that global calibrations could accommodate the spectral variation across beef, lamb, and farmed red deer without species-specific sub-models, suggesting that HSI-based models can transfer across red meat species, including cervids. A subsequent pilot plant study confirmed the robustness of this approach under commercial-like conditions (Dixit et al., 2021b). Yet despite this proven cross-species applicability, no published study has applied HSI, or indeed any advanced imaging technology, to reindeer (*Rangifer tarandus*) meat quality assessment. The literature underpinning this review was identified through a structured search of three databases: Web of Science, Scopus, and PubMed. The primary search combined the terms "reindeer" OR "*Rangifer*" OR "caribou" with "meat quality" OR "carcass classification" OR "grading" OR "venison." A separate technology-focussed search combined "hyperspectral" OR "HSI" OR "VIS-NIR" OR "NIR imaging" OR "spectral imaging" OR "snapshot hyperspectral" with "meat" OR "carcass." No date or language restrictions were applied. In addition to peer-reviewed journal articles, the search encompassed EU regulatory documents, national legislation, published ethnographic sources on traditional Sámi knowledge, and grey literature including government reports and industry guidelines. Duplicate records were removed and the remaining titles and abstracts were screened for relevance to reindeer meat quality, cervid carcass classification, or imaging-based meat evaluation. This article provides a comprehensive collection of information about meat quality classification, focussing on reindeer meat, spanning the biological and compositional characteristics that distinguish reindeer from beef, current grading and inspection practices from both traditional Sámi assessment and official veterinary frameworks, and emerging imaging technologies with particular attention to HSI as an unexplored opportunity. The remainder of this paper is organised as follows. Section 2 introduces cervine animals and the venison production landscape in Fennoscandia and New Zealand. Section 3 examines the EUROP grading system and its adaptation to reindeer, highlighting the fundamental mismatches in fat scoring, age profiles, and colour benchmarks. Section 4 gathers information on current inspection practices, from traditional methods done by Sámi people through official veterinary procedures. Section 5 surveys technological approaches to carcass evaluation, including VIA and HSI, and formally establishes the complete absence of HSI research on reindeer as a critical gap in the literature. Section 6 discusses priorities for future research and proposes a phased roadmap for HSI deployment in the Fennoscandian reindeer industry. Section 7 concludes with a summary of findings and their broader implications for niche meat species worldwide.

2 Cervine animals and venison production

The family Cervidae comprises approximately 55 extant species of hoofed ruminants distributed across the Americas, Europe, and Asia, ranging in body mass from the diminutive pudú (approximately 9 kg) to the moose (*Alces alces*, up to 800 kg). Members of this family are commonly known as deer, and the adjective of relation is *cervine*, from the Latin *cervus*. The family is divided into two principal subfamilies: Cervinae (Old World deer, including red deer, fallow deer, and elk) and Capreolinae (New World deer, including reindeer, moose, roe deer, and white-tailed deer). Notably, reindeer (*Rangifer tarandus*) is the only cervid species in which both males and females bear antlers, and the only species to have been semi-domesticated on a large scale. The meat of cervid species is collectively referred to as "*venison*", a term derived from the Latin *venari* (to hunt), which historically encompassed all game meat but in modern usage is applied almost exclusively to deer meat; in North America, reindeer meat is also known as *caribou meat* (Wiklund et al., 2014).

Within the global venison market, two production systems dominate: the intensive farming of red deer (*Cervus elaphus*) in New Zealand, and the semi-domesticated reindeer herding practised across Fennoscandia and the Russian Federation. New Zealand is by far the world's largest exporter of farmed venison, with a national herd of approximately 800000 deer, of which around 85% are red deer and the remainder predominantly wapiti (*Cervus canadensis*) and their hybrids. The industry, established in the 1970s, generates approximately NZ$280 million per year in export revenue, with venison accounting for over 90% of total export volume. Red deer in New Zealand are pasture-fed, selectively bred for growth rate and carcass composition, and typically slaughtered at 12 to 18 months of age, yielding carcasses of 55 to 70 kg with a dressing-out percentage of 58 to 60% and a carcass fat content of 5 to 8%. The EUROP grading system is not used in New Zealand; instead, the industry has developed its own quality assurance programme (Cervena®) that specifies pasture-rearing, age limits, and processing standards.

In contrast, Fennoscandian reindeer production is based on semi-domesticated Eurasian tundra reindeer (*Rangifer tarandus tarandus*) that graze freely on natural pastures across vast Arctic and sub-Arctic landscapes. The combined numbers of winter herd across Norway, Sweden, and Finland are approximately 640,000 animals, managed by some 6,500 herders operating within 51 *sameby* (Sámi reindeer herding communities) in Sweden, 556 *siida* units in Norway, and 56 reindeer herding districts (*paliskunta*) in Finland (Figure 2) (Tryland and Buhler, 2025; Tyler et al., 2007). In Sweden and Norway, reindeer herding is legally reserved for the indigenous Sámi people, whereas in Finland any EU citizen residing within a designated herding district may own reindeer, although Sámi herders predominate in the northernmost districts (Tryland and Buhler, 2025). Annual slaughter in Sweden is in the order of 50,000 to 75,000 animals, of which nearly 70% are calves under one year of age, yielding an estimated 1,300 to 1,400 tonnes of meat per year (Kautto et al., 2017). In Finland, approximately 90,000 to 100,000 reindeers are slaughtered annually, producing roughly 2,000 tonnes of meat. Combined Fennoscandian production thus represents a fraction of the global beef or even New Zealand venison market, yet the per capita consumption of reindeer meat is substantial within herding communities and the wider Nordic population. Average national consumption has been estimated at approximately 400 g per person per year in Finland, 300 g in Norway, and 100 g in Sweden, though members of herding communities consume considerably more (Tryland and Buhler, 2025).

The two different venison production systems as described above extend well beyond scale. Red deer are farmed animals, bred and managed under controlled conditions with supplementary feeding, purpose-built handling facilities, and systematic genetic selection programmes. Reindeer, by contrast, are semi-wild animals that migrate between seasonal pastures, often covering distances of several hundred kilometres between summer mountain grazing and winter forest pastures (Tyler et al., 2007; Salmi, 2023). Sámi reindeer husbandry represents a pastoral tradition spanning millennia, intimately tied to indigenous identity, ecological knowledge, and customary law (Salmi, 2023; Tyler et al., 2007). The annual cycle of gathering, calf marking, selection, and slaughter follows rhythms dictated by season, snow conditions, and pasture availability rather than by optimised production schedules. These cultural and ecological dimensions distinguish reindeer herding from virtually all other modern livestock production systems and have direct implications for meat quality: the free-ranging lifestyle, natural forage

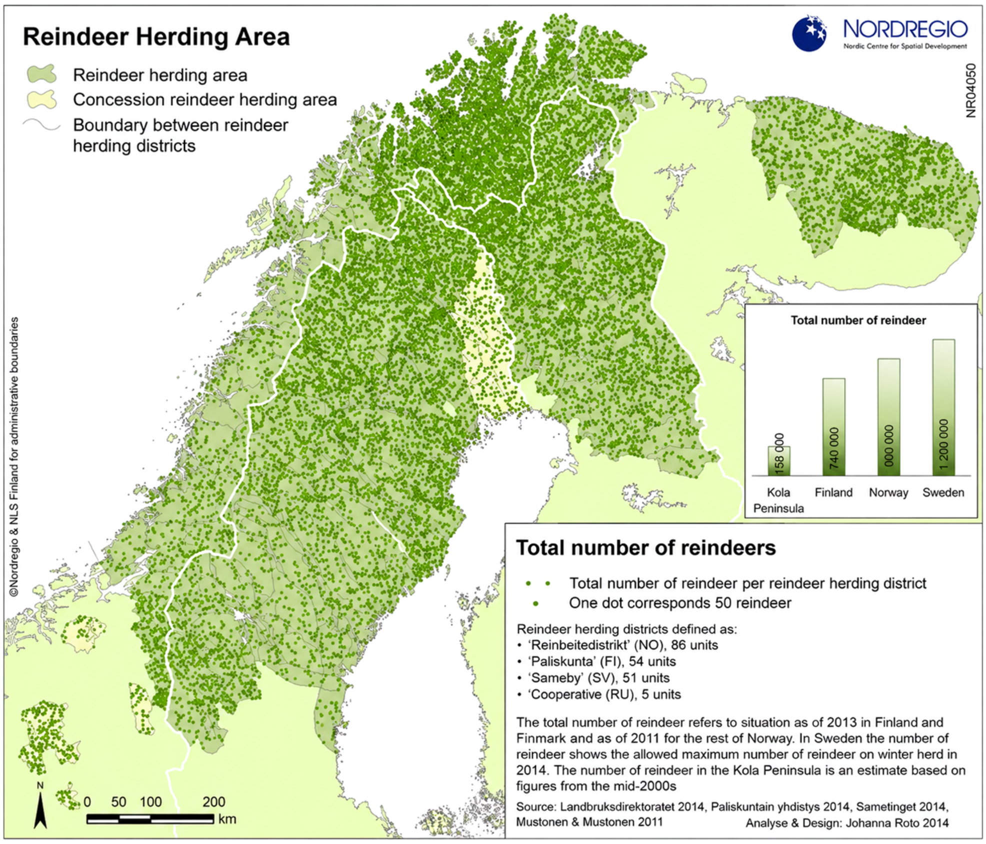

FIGURE 2
Reindeer herding area in Fennoscandia and the Kola Peninsula. Green dots represent the total number of reindeer per herding district (one dot corresponds to 50 reindeer). Herding districts are defined as *Reinbeitedistrikt* (Norway, 86 units), *Paliskunta* (Finland, 54 units), *Sameby* (Sweden, 51 units), and Cooperative (Russia, 5 units). Source: Nordregio, 2015. Map by Johanna Roto; reproduced under Nordregio's open-use policy.

diet, seasonal body condition fluctuations, and the stress associated with gathering and transport all influence carcass composition, fat deposition, and post-mortem pH development in ways that differ fundamentally from farmed red deer or cattle (Wiklund et al., 2003, Wiklund et al., 2014, Wiklund et al., 1995; Triumf et al., 2012). Indeed, reindeer grazed on natural pastures exhibit significantly higher ultimate pH values and distinct sensory profiles compared with animals fed commercial feed mixtures, demonstrating that nutritional management directly shapes both the biochemical and organoleptic properties of the meat (Wiklund et al., 2003).

At the carcass level, the contrasts are equally stark. Red deer carcasses from New Zealand typically weigh 55 to 70 kg at 12 to 18 months of age, with intramuscular fat (IMF) contents of 1.5 to 4% depending on muscle and feeding regime (Triumf et al., 2012). Fennoscandian reindeer calves, slaughtered at 6 to 9 months, produce carcasses of only 20 to 35 kg, with IMF typically below 2% and minimal subcutaneous fat cover (Wiklund et al., 2014, Wiklund et al., 1995). Norwegian data confirm this leanness, reporting fat contents of only 0.5 to 1.6% in loin and topside muscles, alongside regional differences in proximate composition and antioxidant activity between animals from northern and mid-Norwegian herding areas (Mielnik et al., 2011). Adult reindeer carcasses are somewhat larger and heavier (35 to 55 kg) but remain substantially smaller and leaner than both red deer and beef carcasses. Comparable carcass composition has been reported for Alaskan reindeer steers, where dressing-out percentages of 52 to 55% and low subcutaneous fat depths confirm that leanness is a species-wide trait rather than a consequence of Fennoscandian management alone (Wiklund et al., 2008). These size and composition differences mean that carcass grading approaches developed for one species cannot simply be transferred to another: the morphological landmarks used to assess conformation, the expected range of fat cover, and the relationship between external fat and intramuscular fat all differ between red deer and reindeer. Despite this, both species in Fennoscandia are assessed using the simplification of the EUROP grid originally developed for cattle. However, this application induces mismatch as discussed in more detailed in Section 3.

3 The EUROP carcass classification system and its application to reindeer

The European carcass classification system, commonly known as the EUROP grid, was first introduced through European Economic Community Regulations (EEC) No. 1208/81 and No. 2930/81 and is currently governed by Regulation (EU) No. 1308/2013 (European Parliament and Council, 2013). Under this framework, the EUROP scale is compulsory for carcasses of bovine animals aged eight months or more and for pigs, whereas its application to sheep remains optional and at the discretion of individual Member States (European Commission, 2017). The system evaluates each carcass on two axes: conformation, assessed on a five-class scale from E (excellent, convex profiles with exceptional muscular development) through U, R, and O to P (poor, concave profiles with minimal musculature), and fat cover, scored from class 1 (low) to class 5 (very high). Several Member States further subdivide each class into low, medium, and high sub-classes, yielding a 15-point grid that can theoretically assign one of 225 unique grades (Allen and Finnerty, 2001).

In practice, the system was designed to predict saleable meat yield and to establish transparent, comparable market prices across the European Union; it was never intended to assess sensory quality, nutritional composition, or eating satisfaction. This yield-oriented philosophy has drawn sustained criticism from meat scientists, as explained earlier in Section 1. The disconnect between EUROP scores and consumer-relevant quality traits is now well documented: conformation scores show no consistent positive relationship with sensory attributes, and fat cover scores explain only a minor fraction of the variance in marbling (Bonny et al., 2016; Liu et al., 2020). Recognising these shortcomings, Monteils et al. (2017) proposed a supplementary set of five indicators, including marbling and meat colour, to better characterise carcass quality alongside the existing grid. More broadly, the evolution of eating-quality prediction in Europe has followed a fundamentally different trajectory from that of yield classification, with consumer-oriented systems such as the Meat Standards Australia (MSA) model gaining interest as complements to the EUROP framework (Farmer and Farrell, 2018). Nonetheless, the EUROP system remains the sole compulsory classification tool for carcasses in Europe, and no specific framework exists for cervid species.

The regulatory gap for cervids is not merely theoretical. It has direct practical consequences for the Fennoscandian reindeer industry. Although the EU classification regulations apply explicitly to bovine animals, pigs, and sheep, and do not cover reindeer as a species, both Sweden and Norway have established EUROP-based reindeer carcass classification at the national level. In Sweden, the Swedish Board of Agriculture's regulations on carcass classification require reindeer carcasses to be assessed for conformation and fat cover using the same five-class scales as cattle, with the resulting grades informing slaughterhouse payments to herders (Statens jordbruksverk, 2004). In Norway, carcass classification has been linked to a national slaughter subsidy of approximately 400 NOK per animal, with receipt of the subsidy contingent upon classification at the slaughterhouse and the filing of a slaughter record (*slaktejournal*) in accordance with the regulation *Forskrift om rapportering av slaktet rein og lagerbeholdning* (Lovdata, 2011). Finland, by contrast, has no formal carcass classification system for reindeer. In 2015, employees from a Finnish reindeer slaughterhouse participated in classification training organised in Seinäjoki, but implementation would have required supervision by an official veterinarian for which no regulatory basis existed, and the Finnish Ministry of Agriculture and Forestry did not support introducing new national regulations at a time when the legislative trend favoured deregulation. As a result, carcass classification is not used as a basis for pricing in the Finnish domestic reindeer meat market. However, regardless of national classification practices, the morphological assumptions underpinning the EUROP grid are fundamentally mismatched with reindeer anatomy. Reindeer calf carcasses, which comprise the majority of the annual slaughter, weigh only 20 to 55 kg and carry negligible subcutaneous fat, thus almost all carcasses fall within fat class 1 or, at most, the lower portion of class 2. By contrast, the EU reference standards for bovine carcasses target animals weighing 270 kg or more, where the fat score range from 1 to 5 is spread across a biologically meaningful gradient. The result is that, for reindeer, the fat axis of the EUROP grid has almost no discriminatory power, compressing the entire population's biological variation into a single class (Olofsson et al., 2011).

The conformation axis is similarly uninformative. The EUROP conformation classes were calibrated against bovine breeds ranging from lean dairy types (class P) to extreme double-muscled genotypes (class S or E), a spectrum driven by decades of genetic selection for muscularity. Reindeer have undergone no comparable artificial selection; their body conformation reflects adaptation to long-distance seasonal migration, energy conservation in sub-Arctic winters, and efficient foraging across tundra and boreal landscapes (Malmfors and Wiklund, 1996). In practice, reindeer carcasses cluster almost exclusively in classes O and P, with occasional R grades for well-nourished adult bulls, providing no useful quality differentiation for herders or processors. More critically, the EUROP grid cannot capture the factors that accurately determine reindeer meat quality, i.e. the animal's pre-slaughter nutritional status, the extent of glycogen depletion during gathering and transport, and ultimate muscle pH. The relationship between glycogen reserves and ultimate pH is particularly important in reindeer. Animals gathered over long distances or held in corrals for extended periods frequently exhibit depleted muscle glycogen and consequently elevated ultimate pH values well above the 5.8 threshold that defines DFD conditions in cattle (Wiklund et al., 1996a). Unlike in cattle, however, high-pH reindeer meat remains remarkably tender owing to rapid post-mortem proteolysis and small muscle fibre diameter, although colour stability, shelf life, and water-holding capacity are still adversely affected (Wiklund et al., 1997). The evidence for rapid tenderisation in reindeer comes from the study by Wiklund et al. (1997), which measured proteolysis and shear force in reindeer *longissimus thoracis* muscle across a range of ultimate pH values (5.65 to 6.38). Warner-Bratzler shear force values were uniformly low in both normal-pH and high-pH groups, ranging from 2.1 to 4.9 kg/cm^2 by 3 days post-mortem, with no significant difference between pH groups. Significant degradation of troponin T and concomitant appearance of a 30 kDa breakdown product were observed during storage, and mu-cal -pain activity was significantly higher in the high-pH group at 1 day post-mortem. The authors noted that reindeer *longissimus* muscle contains a large proportion of type IIB fibres, which are both highly glycolytic and remarkably oxidative, and hypothesised that the rapid post-mortem metabolism characteristic of this fibre type contributes to the fast tenderisation observed. These findings are specific to reindeer and cannot be assumed to generalise to other cervid species without further investigation. Reindeer meat is also naturally darker than beef due to a higher myoglobin concentration, thus the colour benchmarks implicitly assumed in beef-oriented classification are inappropriate for this species from the outset.

The EUROP classification system cannot be applied fully on reindeer carcasses. It requires simplification on both of its two primary axes (Table 1): fat cover scoring lacks the dynamic range to differentiate among carcasses, and conformation scoring reflects bovine muscularity benchmarks that are irrelevant to cervid anatomy. Furthermore, the system entirely omits the quality dimensions most pertinent to reindeer, including muscle pH, meat colour, glycogen status, and the nutritional condition of the animal at slaughter. These omissions mean that the primary tool available for communicating carcass value between slaughterhouses and herders provides virtually no actionable quality information. In the absence of species-specific grading indicators of the kind advocated for niche meat species more generally (Monteils et al., 2017; Farmer and Farrell, 2018), the reindeer industry continues to rely on a combination of carcass weight and informal visual assessment by experienced slaughterhouse staff, supplemented by the traditional knowledge of Sámi herders. This practical reality motivates the inspection practices discussed in Section 4.

4 Inspection practices: from traditional Sámi assessment to official veterinary controls

Long before modern food safety legislation reached the Arctic, Sámi reindeer herders had developed a sophisticated system for evaluating live animals and carcasses. This traditional assessment is embedded in the Sámi language itself. Herders employ at least 42 distinct concepts to describe reindeer meat quality, including more than ten terms for gradations of fat content alone (Oskal et al., 2024). At one extreme, the term *buoidi* denotes well-nourished, high-quality meat with ample fat reserves, while at the other, *cˇáhceváibbat* describes meat of such poor nutritional quality that it is considered unfit for human consumption. Between these extremes, terms such as *adˉdamíinˉ* and *jolážíin* capture intermediate states of fatness and condition that relate directly to the animal's seasonal foraging history, age, sex, and reproductive status (Oskal et al., 2024). The selection of animals for slaughter is itself a knowledge-intensive process: herders evaluate each animal's behaviour, body condition, role in the herd, and suitability for the intended food product, with castrated males (*spáillit*) and females without calves (*rotnu*) traditionally preferred for family consumption owing to their superior fat deposition (Sara and Mathiesen, 2020). This preslaughter assessment, transmitted across generations through the practice of *diida* (guidance principles embedded in herding pedagogy), represents a form of antemortem inspection that integrates animal welfare, herd management, and meat quality evaluation into a single, culturally embedded framework (Sara et al., 2022) (Table 2). The traditional slaughter method itself was designed to optimise both meat quality and full utilisation of the carcass. The Sámi practice known as *giehtadit* involved piercing the reindeer's heart through the chest cavity with a large knife, a technique performed close to the grazing herd to minimise pre-slaughter stress. This method maximised blood collection for food use and permitted complete utilisation of offal, sinew, hide, and bone (Sara et al., 2022). The practice of *bakkahit*, in which the rumen was deliberately left inside the carcass cavity during cold-weather slaughter, served as an indigenous tenderisation technique; the residual warmth and enzymatic activity from the rumen contents promoted favourable post-mortem pH decline in the surrounding muscles (Sara and Mathiesen, 2020).

Legislation mandating captive-bolt stunning before slaughter, first introduced in Scandinavia in 1929 and reinforced by EU

TABLE 1 **Comparison of key carcass and meat quality characteristics between beef cattle and semi-domesticated reindeer, illustrating the mismatch between the EUROP classification framework and reindeer biology.**

Parameter	Beef cattle	Reindeer
Typical slaughter age	12–24 months	6–9 months (calves); 1.5–5 years (adults)
Carcass weight (kg)	270–420	20–35 (calves); 35–55 (adults)
Intramuscular fat (%)	5–15	1–3
Subcutaneous fat cover	Moderate to high (fat classes 2– 5)	Negligible (fat class 1, occasionally 2)
EUROP fat class range used	1–5 (full scale)	1–2 (scale effectively collapsed)
EUROP conformation range used	P–E (full scale)	P–R (predominantly O and P)
Myoglobin concentration	Moderate	High (naturally darker meat)
Typical ultimate pH	5.4–5.7	5.5–6.5 (frequently >5.8)
DFD prevalence	Low (<5%)	High (common after prolonged gathering)
Tenderness of high-pH meat	Reduced	Preserved (rapid proteolysis, small fibre diameter)
Genetic selection for muscularity	Extensive (decades of selection)	None (adapted to migration and foraging)
Production system	Intensive or semi-intensive; supplementary feeding	Extensive; free-ranging on natural pastures

Data compiled from Wiklund et al. (2014); Wiklund et al. (1995); Triumf et al. (2012), and Malmfors and Wiklund (1996). DFD, dark, firm, and dry.

TABLE 2 Selected traditional Sámi terminology for reindeer meat quality assessment, illustrating the richness of indigenous knowledge systems for carcass and animal evaluation.

Sámi term	Quality dimension	Description
buoidi	Fat content/ overall quality	Well-nourished, high-quality meat with ample fat reserves
čáhceváibbat	Overall quality (negative)	Meat of such poor nutritional quality that it is considered unfit for human consumption
addamíin	Fat content (intermediate)	Intermediate fatness state reflecting seasonal foraging history
jolážíin	Body condition	Intermediate condition grade linked to age, sex, and reproductive status
spáillit	Animal selection	Castrated males, traditionally preferred for family consumption owing to superior fat deposition
rotnu	Animal selection	Females without calves, also preferred for consumption
diida	Knowledge transmission	Guidance principles embedded in herding pedagogy for quality assessment
giehtadit	Slaughter method	Traditional heart-piercing technique performed close to the herd to minimise pre-slaughter stress
bakkahit	Post-mortem treatment	Leaving the rumen inside the carcass cavity during cold-weather slaughter to promote tenderisation

Compiled from Oskal et al. (2024); Sara and Mathiesen (2020), and Sara et al. (2022). The Sámi lexicon contains at least 42 distinct concepts related to reindeer meat quality.

Council Regulation (EC) No. 1099/2009, has progressively displaced these traditional methods. In Norway, the Supreme Court ruled in 2008 that the *giehtadit* method without prior stunning was illegal, effectively criminalising a practice that herders had refined over centuries. The transition to centralised, EU-regulated slaughterhouses has thus not only changed the method of killing but has also disrupted the integrated quality assessment system that traditional slaughter practices supported (Sara et al., 2022). Under the current EU regulatory framework, meat inspection of reindeer follows the same general provisions that apply to domestic ungulates. Regulation (EU) 2017/625, the Official Controls Regulation, requires that all animals destined for slaughter undergo ante-mortem inspection by, or under the responsibility of, an official veterinarian, followed by post-mortem inspection of the carcass and viscera (European Parliament and Council, 2017).

In practice, the implementation of these requirements at Fennoscandian reindeer slaughterhouses faces a number of logistical challenges that distinguish reindeer from conventional livestock. Swedish reindeer are slaughtered at 11 to 12 small, often remote slaughterhouses during an intensive season from September to April, with a break during the October rutting period. Approximately 55000 reindeer pass through these facilities each winter, arriving in slaughter batches defined by their Sámi village of origin. Post-mortem findings are recorded at the batch level rather than for individual animals, and the most commonly identified conditions are parasitic infestations, particularly *Hypoderma tarandi* (reindeer warble fly), which has been documented at prevalences of 40 to 60 per cent of slaughtered animals in recent years (Hunka et al., 2024). Other recorded conditions include inflammatory processes, acute and chronic trauma, and emaciation, though these occur at much lower prevalences. The cost of on-site veterinary inspection at these remote, low-capacity facilities is disproportionately high relative to larger abattoirs, prompting recent research into remote ante-mortem inspection via video link as a means of improving both sustainability and continuity of official control (Kautto et al., 2023).

Finland operates a broadly similar inspection framework under the Finnish Food Authority (Ruokavirasto), with reindeer slaughterhouses concentrated in the northern provinces and subject to the same EU hygiene regulations. However, the implementation differs in important respects. In Swedish reindeer slaughterhouses, the official veterinarian or an authorised auxiliary performs visual and, where necessary, palpatory examination of carcasses and organs. In Finnish reindeer slaughterhouses, by contrast, auxiliary inspectors are not used; meat inspection is carried out exclusively by official veterinarians employed under a fee-based system, who perform the necessary incisions themselves. Only minor procedural differences distinguish reindeer inspection from domestic livestock inspection in Finland, such as the slaughterhouse worker splitting the heart. In both countries, inspectors look for signs of disease, parasitic infestation, contamination, and abnormal colour or odour. However, the inspection protocol does not include any systematic measurement of muscle pH, colour coordinates, or biochemical indicators of meat quality. The inspector's judgement of whether a carcass is fit for human consumption is fundamentally a food safety determination, not a quality assessment: a carcass may pass inspection and receive a health mark while still exhibiting elevated pH, atypical colour, or compromised water-holding capacity that would affect its commercial value and consumer acceptability. This gap between food safety clearance and quality characterisation is common across the EU meat inspection system but is particularly consequential for reindeer, where the prevalence of DFD-like conditions is substantially higher than in cattle due to the inherent stress of gathering semi-wild animals from extensive rangelands (Wiklund et al., 1996b). In Finland, the official meat inspection decision form additionally serves as a feedback instrument within the production chain, providing slaughterhouse-level data back to herders, although this mechanism does not extend to instrumental quality measurement. The result is a dual system in which traditional Sámi knowledge and modern veterinary inspection operate in parallel but largely without integration. Herders possess detailed, experiential knowledge of individual animal condition, seasonal variation, and the relationship between pre-slaughter management and meat quality, knowledge that is encoded in an extensive Sámi terminology but is not captured in any formal data system. Official inspectors, conversely, apply standardised protocols designed for food safety surveillance across all ungulate species, without species-specific quality indicators for reindeer. Neither system currently incorporates objective instrumental measurements of the kind that could bridge this gap, such as pH meters, colorimeters, or imaging technologies. The potential for such technologies to complement both traditional assessment and official inspection, providing objective, rapid, and non-destructive quality data at the point of slaughter, is the subject of Section 5.

5 Technological approaches to carcass evaluation: from video image analysis to hyperspectral imaging

The limitations of subjective classification documented in Section 3 have spurred the development of objective, instrument-based technologies for carcass evaluation. The most widely adopted of these is video image analysis (VIA), a camera-based approach in which digital images of hanging carcasses are processed by purpose-built software to extract dimensional, shape, and colour data. Since the first EU approval of a VIA system for commercial bovine classification in 2003, several platforms have been deployed in beef and sheep abattoirs across Europe and Australasia, including two-dimensional systems such as VIAscan and VBS2000 and, more recently, three-dimensional systems that use structured light to reconstruct full carcass geometry. In the United Kingdom, a direct comparison of VIA against the Meat and Livestock Commission's EUROP-based scoring scheme demonstrated that VIA was, on average, two percentage points more accurate and 12% more precise in predicting primal joint weights for 443 commercial lamb carcasses (Rius-Vilarrasa et al., 2009). Comparable results were obtained under Icelandic conditions, where VIAscan predicted overall lean meat yield more accurately than the EUROP system and replicated expert conformation scores with 82% agreement across 862 lamb carcasses (Einarsson et al., 2014). Despite these achievements, that VIA has been developed and validated exclusively for cattle, sheep, and pigs, no VIA system has been calibrated for cervid carcasses of any species. Table 3 summarises the capabilities and limitations of the principal technologies currently available or under development for objective carcass and meat quality evaluation, ranging from simple point instruments through camera-based systems to full hyperspectral platforms.

Moreover, VIA is inherently limited to information that can be extracted from external carcass surfaces: shape, dimensional proportions, surface colour, and subcutaneous fat coverage. It cannot directly assess the chemical composition, muscle pH, water-holding capacity, or tenderness that collectively determine eating quality, nor can it detect the metabolic signatures of pre-slaughter stress. Near-infrared (NIR) spectroscopy partially addresses this limitation by exploiting the absorption of electromagnetic radiation in the 750 to 2500 nm range, where overtones and combination bands of O–H, C–H, and N–H functional groups encode information about moisture, protein, and lipid content. Over the past three decades, NIR spectroscopy has been applied extensively to beef, pork, and lamb, with reliable prediction of proximate composition and moderate success for pH and colour parameters, although predictions of sensory attributes remain less consistent (Prieto et al., 2017). However, conventional NIR spectroscopy acquires spectra from a single point or small area on the sample surface, providing no information about the spatial distribution of quality parameters within or across the muscle. This restriction motivated the development of hyperspectral imaging (HSI), a technology that merges the chemical specificity of spectroscopy with the spatial resolution of digital imaging by capturing a three-dimensional data cube in which every pixel carries a continuous reflectance spectrum spanning hundreds of narrow, contiguous wavelength bands (Figure 3). It should be noted that individual quality parameters such as pH and colour can be measured using simple, low-cost instruments: a portable pH meter with a glass electrode can determine ultimate pH at a cost of a few hundred euros, and a handheld tristimulus colorimeter can quantify CIE $L^*a^*b^*$ coordinates in seconds. These point-measurement devices are well established in meat science and are routinely used as reference methods in research settings (Prieto et al., 2009). However, they share two fundamental limitations. First, they acquire data from a single insertion point or a small surface area (typically 8 to 25 mm diameter), providing no information about the spatial heterogeneity of pH, colour, or composition within or across a muscle. Given that quality parameters are not uniformly distributed across a carcass, point measurements may not represent the whole cut. Second, pH measurement is invasive, requiring electrode insertion into the muscle, which damages the sample surface and is impractical for whole-carcass screening at line speed. A colorimeter, while non-destructive, still measures only one spot per reading. By contrast, hyperspectral imaging acquires spatially resolved spectral information from the entire visible surface simultaneously, enabling prediction of multiple quality parameters, including pH, colour, moisture, and intramuscular fat, in a single non-contact acquisition. This capacity for simultaneous, spatially comprehensive, non-destructive multi-parameter assessment is the principal advantage that distinguishes HSI from conventional point instruments, and it is particularly relevant for on-line carcass sorting where speed and full-surface coverage are essential. Hyperspectral imaging has been applied to

TABLE 3 **Comparison of technologies for objective meat quality assessment, showing the quality parameters accessible to each method, its spatial coverage, destructiveness, line-speed capability, and current species validation status.**

Technology	Parameters measured	Spatial coverage	Destructive?	Line-speed capable?	Species validated
pH meter (electrode)	Ultimate pH	Single point	Yes	No	Beef, pork, lamb, reindeer (research only)
Colorimeter	CIE $L^*a^*b^*$	Single spot (8–25 mm)	No	No	Beef, pork, lamb
VIA (2D/3D camera)	Shape, dimensions, surface colour, fat cover	Whole carcass surface	No	Yes	Beef, lamb, pigs
NIR spectroscopy	Moisture, protein, fat, pH	Single point or small area	No	Partial	Beef, pork, lamb
Hyperspectral imaging	pH, colour, moisture, fat, tenderness, microbial load, adulteration	Whole visible surface, spatially resolved	No	Yes (prototype)	Beef, pork, lamb, chicken, red deer; no reindeer

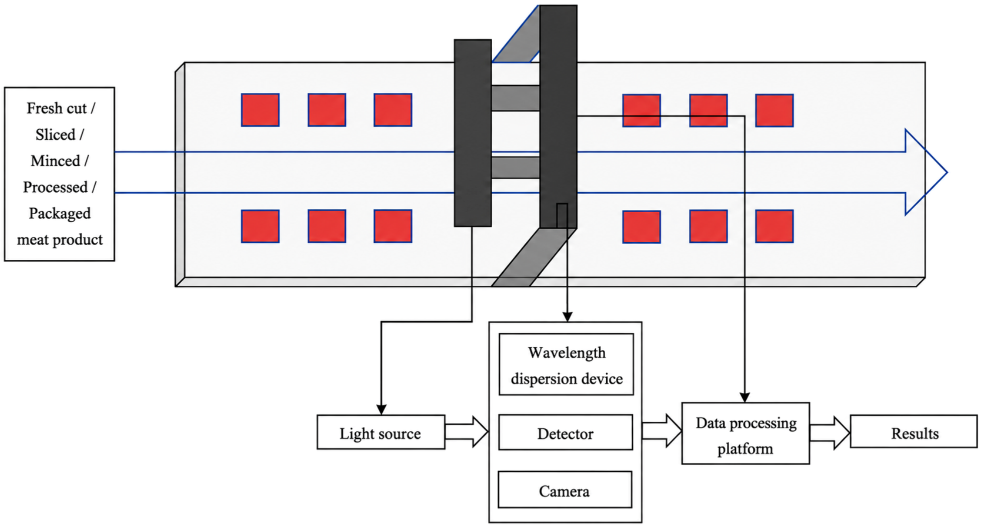

FIGURE 3
Schematic of a hyperspectral imaging (HSI) system integrated into a meat production line. Meat samples (fresh cut, sliced, minced, processed, or packaged) pass through an illuminated imaging zone where a wavelength dispersion device separates reflected light into narrow spectral bands. The detector and camera capture spatial and spectral information simultaneously, which is processed via a data processing platform to yield quality predictions. Reproduced from Jia et al. (2022) under Creative Commons CC BY-NC-ND 4.0 licence.

meat quality evaluation with increasing frequency over the past two decades. Early reviews established the feasibility of HSI for simultaneously quantifying colour, marbling, texture, and chemical constituents in beef and pork, noting that the technology could measure multiple quality attributes without destructive sample preparation (ElMasry et al., 2012). Subsequent work extended HSI to lamb, chicken, and processed meat products, with demonstrated prediction performance for moisture, intramuscular fat, pH, tenderness, water-holding capacity, and microbial contamination, as well as the detection of adulteration and species substitution. A comprehensive review of non-destructive techniques for fresh meat found that most published studies involved pork and beef samples, followed by lamb and chicken, with only isolated investigations on rabbit and duck and no studies on any cervid species (Antequera et al., 2021). More recently, HSI has been extended to fish and seafood for freshness prediction and microbial spoilage detection (Cheng and Sun, 2015). Nevertheless, these applications remain concentrated on spoilage assessment rather than on carcass-level quality classification, and no HSI-based grading system has been developed for any niche meat species. The most recent synthesis of the field, encompassing literature through 2025, confirms that HSI has matured substantially: deep learning architectures and data fusion strategies now routinely achieve prediction accuracies exceeding $R^2 = 0.90$ for multiple quality parameters in beef and pork, and prototype industrial scale systems demonstrate the feasibility of on-line deployment at commercial processing speeds (Yi et al., 2025). Nevertheless, the species coverage of HSI research remains heavily concentrated on the same domesticated livestock that dominate global meat production (Table 4).

Within the cervid family, published HSI work is confined to farmed red deer (*Cervus elaphus*) venison from New Zealand, which has been included in multi-species global data sets for prediction of intramuscular fat and pH alongside beef and lamb. Those studies demonstrated that HSI prediction models could be extended beyond

TABLE 4 **Summary of hyperspectral imaging prediction performance for key meat quality parameters across species.**

Quality parameter	Beef	Pork	Lamb	Chicken	Red deer	Reindeer
Ultimate pH	0.72–0.86	0.60–0.70	0.65–0.85	—	0.89[a]	—
Intramuscular fat	0.77–0.93	0.88–0.93	0.86–0.88	—	0.86[a]	—
Colour (CIE $L^*a^*b^*$)	0.85–0.91	0.78–0.89	0.88–0.91	—	—	—
Moisture	0.89–0.95	0.92–0.95	0.88	0.70–0.82	—	—
Tenderness (WBSF)	0.50–0.75	0.55–0.68	—	—	—	—
DFD/PSE detection	detected	96%	—	—	—	—
Microbial load	0.86–0.89	0.86–0.92	—	0.80–0.88	—	—
Adulteration	>94%	>94%	>94%	—	—	—

[a]Obtained from multi-species global calibration models including beef, lamb, and New Zealand farmed red deer venison (Dixit et al., 2021a). Representative R^2 ranges compiled from ElMasry et al. (2012); Antequera et al. (2021), and Yi et al. (2025). WBSF, Warner–Bratzler shear force; DFD, dark, firm, and dry; PSE, pale, soft, and exudative.
Values indicate representative coefficients of determination (R^2) or classification accuracy (%) reported in the literature; a dash indicates no published study.

a single species, achieving reasonable accuracy ($R_p^2 = 0.86 - 0.89$ across both parameters) when trained on pooled data from multiple slaughter seasons and detection environments. However, New Zealand red deer are intensively farmed animals processed in modern high-throughput plants conditions that differ fundamentally from those of semi-domesticated reindeer (*Rangifer tarandus*) slaughtered in small, seasonal facilities across the Fennoscandian Arctic. The technology-focussed search described in Section 1, using the terms "hyperspectral" OR "HSI" OR "VIS-NIR" OR "NIR imaging" OR "spectral imaging" OR "snapshot hyperspectral," each combined with "reindeer," "*Rangifer*," or "caribou," returned no results as of January 2026. This complete absence of HSI research on reindeer constitutes the central gap identified by this review.

The gap is not merely an oversight of academic interest; it has direct practical significance. Reindeer meat presents a distinctive spectral profile that differs markedly from the beef and lamb matrices on which existing HSI calibration models have been built. Intramuscular fat content is typically below two per cent, subcutaneous fat is negligible in calves, and the dominant myoglobin concentration produces a naturally darker baseline colour than in cattle or sheep. Furthermore, the high prevalence of glycogen depletion and consequently elevated ultimate pH values, arising from the extended gathering, herding, and transport that precede slaughter, generates a DFD-like condition whose spectral signature in the visible and near-infrared regions has never been characterised for reindeer muscle. Paradoxically, these very characteristics make reindeer an especially compelling candidate for HSI-based quality assessment: the quality parameters of greatest importance to the industry pH, colour stability, and DFD detection are precisely those for which HSI has demonstrated its strongest predictive performance in other species. The small carcass size of reindeer calves (20 to 35 kg) is advantageous for camera field-of-view design, and the emergence of compact, portable HSI systems offers a realistic pathway for deployment in the remote, low-throughput slaughterhouses that characterise the Fennoscandian reindeer industry. A direct comparison of a portable Vis-NIR system (400 to 1000 nm) against a laboratory-grade snapscan SWIR camera for meat authentication demonstrated that the portable device achieved classification accuracies of 94 to 96% using support vector machine and artificial neural network models, matching or exceeding the benchtop system's performance and confirming that field-deployable instruments need not sacrifice analytical capability (Dashti et al., 2023). It should be acknowledged that the predictive performance of HSI in meat applications is subject to several practical constraints that the literature does not always emphasise. Measurement depth is limited to the surface and near-surface layers of the muscle (typically the uppermost 1 to 3 mm depending on wavelength), meaning that HSI captures superficial composition rather than bulk properties. Surface moisture, which varies with time post-mortem, drip loss rate, and ambient humidity, can alter reflectance spectra and introduce noise. Surface roughness arising from different cutting angles or muscle fibre orientation similarly affects light scattering and spectral consistency. Sample temperature at the time of acquisition influences both the physical state of the tissue and the spectral response of water and lipid bands, yet many published models are developed at a single controlled temperature and may not transfer directly to warm carcasses measured shortly after slaughter. Instrument-specific factors, including detector type, spectral resolution, illumination geo -metry, and the wavelength range covered (visible, NIR, or SWIR), also constrain the parameters that can be predicted and the accuracy achievable. Finally, robust calibration requires reference measurements of known accuracy; for pH prediction in particular, the model can only be as reliable as the electrode-based pH values used for training, and care must be taken to avoid circular reasoning in which model performance appears strong simply because the reference method has low variance within the calibration set. These practical considerations underscore the need for rigorous, species-specific validation under operational slaughterhouse conditions, as proposed in the research roadmap of Section 6. It is important to note that HSI is not proposed as a replacement for simple point-measurement instruments such as pH meters or colorimeters, which remain valuable as reference methods. Rather, HSI addresses a fundamentally different operational need: the ability to screen entire carcass surfaces non-destructively and simultaneously for multiple quality parameters at line speed, without requiring electrode insertion or trained laboratory personnel. In the context of remote, seasonally operating reindeer slaughterhouses where neither pH measurement nor colour assessment is currently performed, the barrier to adoption is not the cost of a single instrument but the absence of any integrated, rapid, and operator-friendly quality screening system. HSI offers a pathway to fill that gap. These opportunities, together with the research priorities they imply, are elaborated in the roadmap presented in Section 6.

6 Future research priorities and a roadmap for HSI deployment

The absence of hyperspectral imaging research on reindeer meat, as raised in Section 5, defines a clear starting point for future work. Before any predictive model can be deployed, a reindeer-specific spectral reference library must be constructed. This library should encompass the full range of biological variation encountered in the Fennoscandian slaughter population: calves and adults of both sexes, animals in varying nutritional condition from well-nourished autumn calves to lean late-winter adults, and crucially, carcasses spanning the entire gradient of ultimate pH values from normal post-mortem acidification through borderline to fully DFD muscle. Acquiring such a library requires coordinated sampling across multiple slaughter seasons and at least two to three geographically dispersed slaughterhouses in Sweden and Finland, so that variation attributable to herd management, lichen versus supplementary feeding regimes, and gathering distance is adequately represented. Each sample should be accompanied by reference measurements of pH, CIE L*a*b* colour coordinates, Warner–Bratzler shear force, proximate composition, and drip loss, following the protocols established for beef and lamb calibration studies (Prieto et al., 2009). This foundational data set would serve as the common calibration resource from which all subsequent models are derived.

With a spectral library in hand, the first modelling priority should be the prediction of ultimate pH and DFD classification, because these are the quality parameters of greatest practical and economic significance to the reindeer industry. Elevated pH shortens shelf life, darkens colour, and reduces consumer acceptance, yet it is currently unmeasured at slaughter. A hyperspectral model capable of discriminating normal from DFD reindeer carcasses online would, for the first time, allow slaughterhouses to sort carcasses by quality grade rather than weight alone, enabling value-based marketing and targeted product channelling. It is important to clarify what "DFD detection by HSI" means in operational terms. In the existing literature, two distinct approaches have been employed. The first is pH regression, in which a chemometric model (typically partial least squares regression) predicts ultimate pH as a continuous variable from the spectral data, and a threshold (commonly pH 5.8 or 6.0) is then applied to classify carcasses as normal or DFD. The second is direct spectral classification, in which labelled samples (DFD versus normal, defined by reference pH measurement) are used to train a discriminant model (such as PLS-DA, SVM, or a neural network) that assigns a binary class label directly from the spectrum. Both approaches ultimately depend on reference pH measurements for model training, and care must be taken to ensure that the ground-truth pH values are measured consistently and with sufficient accuracy to avoid circular reasoning. The spectral features most commonly associated with pH variation in meat lie in the visible region (540 to 630 nm), where changes in myoglobin redox state alter reflectance, and in the NIR region (ox950 to 1,050 nm and 1,400 to 1,450 nm), where water absorption bands shift with changes in water-holding capacity. For the proposed reindeer work, both regression and classification approaches should be evaluated, with the choice of operational method guided by the distribution of pH values in the calibration population and the practical decision thresholds required by the industry. The second priority is colour stability prediction, given that reindeer meat is inherently darker than beef and that colour deterioration during retail display is a key driver of waste. Existing HSI models for beef colour have achieved coefficients of determination in the range of R^2 =0.85 to 0.91 for CIE L* and a* values; whether comparable performance is attainable for the narrower colour range of reindeer muscle is an empirical question that only species-specific calibration can answer. A third, longer-term objective is the prediction of intramuscular fat and fatty acid profiles, which are relevant both to eating quality and to the marketing of reindeer meat as a nutritionally distinctive product rich in polyunsaturated fatty acids. However, it should be acknowledged that at the very low intramuscular fat levels typical of reindeer meat (below 2 to 3%), the fatty acid composition is dominated by structural membrane phospholipids rather than by triacylglycerols in visible fat depots. This limits the magnitude of spectral variation available for discrimination and may reduce the predictive performance of HSI for fatty acid profiling compared with fattier species. Consequently, fatty acid prediction should be regarded as an exploratory objective whose feasibility in reindeer remains to be empirically demonstrated, rather than as a primary justification for HSI deployment.

It is legitimate to ask whether an objective quality grading system is warranted for an industry whose annual output is modest by global standards and whose product is consumed largely within the producing region. Several considerations suggest that it is. First, even at current production volumes, the economic losses associated with undetected DFD meat are substantial: carcasses with elevated pH have shorter shelf life, darker colour, and reduced consumer acceptance, yet are currently sold at the same price as normal-pH carcasses because no sorting mechanism exists. Objective quality-based sorting would allow slaughterhouses to channel DFD carcasses toward processed products where colour and shelf life are less critical, while directing premium-quality carcasses toward fresh retail, thereby capturing value that is currently lost. Second, the reindeer meat market is not purely local. A growing share of Fennoscandian reindeer meat is marketed through premium retail channels, exported to gourmet markets in continental Europe, and sold under quality labels such as the Swedish "Renlycka" brand that already require pH thresholds. These market segments demand objective, traceable quality documentation that manual assessment alone cannot provide. Third, unlike cattle or sheep grading, the purpose of an HSI-based system for reindeer would not be to reward genetic superiority for muscularity, since no structured breeding programme exists for reindeer, but rather to detect the effects of pre-slaughter management, particularly glycogen depletion and stress-induced DFD (Wiklund et al., 1995), that are the dominant sources of quality variation in this species. The objective is therefore not to replicate the EUROP yield-classification model but to provide a quality-assurance tool tailored to the specific risk factors of reindeer production. From a logistical perspective, a portable HSI device could be operated by existing slaughterhouse staff with minimal training, reducing the dependence on scarce qualified classifiers in remote Arctic locations and complementing recent initiatives for remote veterinary inspection (Kautto et al., 2023).

The deployment of HSI technology in the reindeer industry cannot follow the model established for large-scale beef or lamb processing, where line-scan systems operating at 400 to 1000 carcasses per hour are permanently integrated into high-throughput kill floors. Reindeer slaughter in Fennoscandia takes place in eleven to twelve small, often remote facilities that operate seasonally, processing roughly 50 to 200 animals per day during the autumn–winter campaign. This operational context demands a fundamentally different hardware strategy. Compact, portable snapshot hyperspectral cameras, which acquire the entire spectral–spatial data cube in a single exposure without the need for a conveyor or linear translation stage, offer a realistic pathway for these conditions.

Recent work has demonstrated that snapshot HSI devices coupled with three-dimensional convolutional neural networks can classify red meat species with accuracies exceeding 96 per cent, at video-rate acquisition speeds and with a form factor suitable for handheld or tripod-mounted operation (Al-Sarayreh et al., 2020). The research agenda outlined in this section is being initiated through the Innovative Arctic Food Quality Control for SMEs (InAFQual) project (InAFQual, 2025), a cross-border collaboration between Luleå University of Technology (Sweden), Seiniäjoki University of Applied Sciences (Finland), and Novia University of Applied Sciences (Finland), funded by the European Union Interreg Aurora programme.

A critical technical question for the pilot phase is whether existing calibration models developed on beef and lamb can be transferred to reindeer through domain adaptation, or whether entirely new models must be trained from scratch. The multi-species global data sets constructed for red meat pH and intramuscular fat prediction have shown that pooling spectral data across beef, lamb, and venison can yield robust models, but this work used New Zealand farmed red deer, whose spectral characteristics may differ from those of semi-domesticated reindeer owing to differences in myoglobin concentration, subcutaneous fat thickness, and muscle fibre architecture. Transfer learning and domain adaptation techniques, including piecewise direct standardisation and adversarial neural network approaches, have shown promise for bridging spectral shifts between different HSI instruments and sample populations in agricultural applications (Sun et al., 2024). Applying these methods to adapt beef–lamb models to a small initial reindeer data set could substantially reduce the sample sizes required for acceptable prediction accuracy, a practical advantage given the logistical difficulty of collecting large reference data sets from remote Arctic slaughterhouses.

Finally, any research programme on reindeer meat quality must be designed in genuine partnership with the Sámi herding communities whose livelihoods depend on the industry. The traditional knowledge systems documented in Section 4 encode a rich, experientially derived understanding of meat quality that is complementary to instrumental measurement. A participatory co-design approach, in which herders contribute to the definition of quality grades, the selection of slaughter events for sampling, and the interpretation of model outputs, is essential both for ethical reasons and for practical adoption. Technology that is perceived as externally imposed or that conflicts with established assessment practices is unlikely to gain acceptance, regardless of its predictive accuracy. Conversely, a system that integrates HSI-derived quality indicators with herders' experiential judgements could strengthen the value chain by providing objective, traceable quality documentation while respecting the cultural context in which reindeer husbandry operates (Turi, 2016). The roadmap outlined here, from spectral library construction through calibration model development, pilot deployment, and community-integrated co-design, represents the first concerted effort to apply hyperspectral imaging technology to reindeer meat quality assessment, and the InAFQual project provides the cross-border infrastructure to initiate this work within a three-year horizon.

7 Conclusion

This review has examined the current state of reindeer meat quality classification from multiple perspectives, spanning biological, regulatory, cultural, and technological dimensions, and has identified hyperspectral imaging as a critical yet entirely unexplored opportunity for this niche species. Several key findings emerge from the analysis.

First, reindeer meat occupies a distinctive position among red meats. Its characteristically low intramuscular fat content, negligible subcutaneous fat cover, naturally dark colour driven by high myoglobin concentration, and susceptibility to glycogen depletion and elevated ultimate pH collectively define a quality profile that differs fundamentally from those of beef and lamb. These differences are not merely academic: they render the standard tools and benchmarks of mainstream meat science inapplicable to reindeer without species-specific adaptation.

Second, the EUROP carcass classification system, the sole compulsory grading framework in the European Union, cannot be applied comprehensively when applied to reindeer. The fat scoring axis collapses into a single class for virtually all carcasses, the conformation axis reflects bovine muscularity benchmarks that are irrelevant to cervid anatomy, and the system omits entirely the quality dimensions, including pH, colour, glycogen status, and nutritional condition, that matter most for reindeer meat. The result is that the primary instrument for communicating carcass value between slaughterhouses and herders provides no actionable quality information.

Third, two parallel inspection systems currently operate in the Fennoscandian reindeer industry, neither of which incorporates instrumental quality measurement. Official veterinary inspection, governed by EU Regulation 2017/625, focuses on food safety through ante-mortem and post-mortem examination but does not assess eating quality or detect DFD conditions. Traditional Sámi assessment, grounded in an extensive vocabulary of meat quality concepts and centuries of experiential knowledge, provides a sophisticated qualitative framework but lacks the standardisation and traceability that modern supply chains require. These two systems coexist without formal integration, leaving a measurement vacuum between food safety assurance and quality-based value differentiation.

Fourth, the technological landscape for objective carcass evaluation has advanced considerably over the past two decades, yet its benefits have not reached the reindeer sector. Video image analysis has improved yield prediction for cattle and sheep but cannot assess chemical composition or metabolic quality indicators. Near-infrared spectroscopy provides chemical specificity but lacks spatial resolution. Hyperspectral imaging combines the strengths of both approaches, offering simultaneous, non-destructive, spatially resolved prediction of multiple quality parameters including pH, colour, moisture, intramuscular fat, and microbial contamination. Despite this capability, and despite the demonstrated extension of HSI to New Zealand farmed red deer venison, no published study has applied hyperspectral imaging to reindeer meat in any form. This gap constitutes the central finding of this review.

Fifth, the characteristics that make reindeer meat challenging for conventional grading systems are precisely those that make it a compelling candidate for HSI-based assessment. The quality parameters of greatest practical importance, namely ultimate pH, DFD detection, and colour stability, are among the attributes for which HSI has demonstrated its strongest predictive performance in other species. The small carcass size is advantageous for camera field-of-view design, and the emergence of compact, portable snapshot hyperspectral cameras offers a realistic hardware solution for the remote, low-throughput slaughterhouses that characterise the industry. A phased research programme, progressing from spectral library construction through pilot deployment to community-integrated quality grading, could transform the evidential basis for reindeer meat classification within a five- to ten-year horizon.

The implications of this work extend beyond reindeer to the broader challenge of quality classification for niche and underserved meat species worldwide. Yak, water buffalo, camel, alpaca, and numerous wild-harvested game species face analogous problems: grading systems designed for mainstream livestock, a scarcity of species-specific calibration data, and processing environments that preclude the adoption of high-throughput industrial technologies. The methodological template proposed here, encompassing systematic gap identification, species-specific spectral library construction, portable HSI deployment, transfer learning from existing models, and participatory co-design with producer communities, is directly transferable to these contexts. As consumer demand for sustainably produced, culturally distinctive, and nutritionally differentiated meat products continues to grow, the development of fit-for-purpose quality assessment tools for niche species is no longer a peripheral concern but a practical necessity for equitable market access and fair producer remuneration.

Author contributions

MS: Conceptualization, Writing – original draft, Methodology, Writing – review & editing, Formal analysis, Investigation, Validation, Data curation, Resources. AE: Writing – review & editing. MO: Writing – review & editing. JK: Writing – review & editing. DL: Formal analysis, Supervision, Data curation, Validation, Methodology, Writing – review & editing, Funding acquisition, Resources, Conceptualization, Writing – original draft, Investigation, Project administration.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

AHDB (2017). "Using the EUROP grid in beef carcase classification," in *Industry guide, agriculture and horticulture development board*. (Coventry: Agriculture and Horticulture Development Board (AHDB).

Allen, P., and Finnerty, N. (2001). "Mechanical grading of beef carcasses," in *The national food centre research report*. (Dublin: Teagasc / The National Food Centre).

Al-Sarayreh, M., Reis, M. M., Yan, W. Q., and Klette, R. (2020). Potential of deep learning and snapshot hyperspectral imaging for classification of species in meat. *Food Control* 117, 107332. doi:10.1016/j.foodcont.2020.107332

Animalia (2024). *Utdypende informasjon om klassifisering og kalkyleskjæring av slakt*. Available online at: https://www.animalia.no/no/ravare-og-foredling/klassifisering/utdypende-informasjon-omklassifisering-og-kalkyleskjaring-av-slakt/ (Accessed January 15, 2026).

Antequera, T., Caballero, D., Grassi, S., Uttaro, B., and Pérez-Palacios, T. (2021). Evaluation of fresh meat quality by hyperspectral imaging (HSI), nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI): a review. *Meat Sci.* 172, 108340. doi:10.1016/j.meatsci.2020.108340

Bonny, S. P. F., Pethick, D. W., Legrand, I., Wierzbicki, J., Allen, P., Farmer, L. J., et al. (2016). European conformation and fat scores have no relationship with eating quality. *Animal* 10, 996–1006. doi:10.1017/S1751731115002839

Cheng, J.-H., and Sun, D.-W. (2015). Recent applications of spectroscopic and hyperspectral imaging techniques with chemometric analysis for rapid inspection of microbial spoilage in muscle foods. *Compr. Rev. Food Sci. Food Saf.* 14, 478–490. doi:10.1111/1541-4337.12141

Craigie, C. R., Navajas, E. A., Purchas, R. W., Maltin, C. A., Bünger, L., Hoskin, S. O., et al. (2012). A review of the development and use of video image analysis (VIA) for beef carcass evaluation as an alternative to the current EUROP system and other subjective systems. *Meat Sci.* 92, 307–318. doi:10.1016/j.meatsci.2012.05.028

Dashti, A., Müller-Maatsch, J., Roetgerink, E., Wijtten, M., Weesepoel, Y., Parastar, H., et al. (2023). Comparison of a portable Vis-NIR hyperspectral imaging and a snapscan SWIR hyperspectral imaging for evaluation of meat authenticity. *Food. Chemistry: X* 18, 100667. doi:10.1016/j.fochx.2023.100667

Dixit, Y., Al-Sarayreh, M., Craigie, C. R., and Reis, M. M. (2021a). A global calibration model for prediction of intramuscular fat and pH in red meat using hyperspectral imaging. *Meat Sci.* 181, 108405. doi:10.1016/j.meatsci.2020.108405

Dixit, Y., Hitchman, S., Hicks, T. M., Lim, P., Wong, C. K., Holibar, L., et al. (2021b). Non-invasive spectroscopic and imaging systems for prediction of beef quality in a meat processing pilot plant. *Meat Sci.* 181, 108410. doi:10.1016/j.meatsci.2020.108410

Dvoretsky, A. G., Bichkaeva, F. A., Nesterova, E. V., Shengof, B. A., and Dvoretsky, V. G. (2025). Fatty acids in the meat and by-products of reindeer from northwestern Siberia, Russia. *J. Food Compos. Anal.* 139, 107104. doi:10.1016/j.jfca.2024.107104

Einarsson, E., Eythórsdóttir, E., Smith, C. R., and Jónmundsson, J. V. (2014). The ability of video image analysis to predict lean meat yield and EUROP score of lamb carcasses. *animal* 8, 1170–1177. doi:10.1017/S1751731114000962

ElMasry, G., Barbin, D. F., Sun, D.-W., and Allen, P. (2012). Meat quality evaluation by hyperspectral imaging technique: an overview. *Crit. Rev. Food Sci. Nutr.* 52, 689–711. doi:10.1080/10408398.2010.507908

European Commission (2017). *Commission Delegated Regulation (EU) 2017/1182 of 20 April 2017 supplementing Regulation (EU) No 1308/2013 as regards the Union scales for the classification of beef, pig and sheep carcasses.* Available online at: https://eur-lex.europa.eu/eli/reg_del/2017/1182/oj/eng (Accessed January 15, 2026).

European Parliament and Council (2013). "Regulation (EU) No 1308/2013 of 17 December 2013 establishing a common organisation of the markets in agricultural products," in *OJ L 347, 20.12.2013*, 671–854. (Luxembourg: Publications Office of the European Union).

European Parliament and Council (2017). "Regulation (EU) 2017/625 of 15 March 2017 on official controls and other official activities performed to ensure the application of food and feed law," in *OJ L 95, 7.4.2017*, 1–142. (Luxembourg: Publications Office of the European Union).

Farmer, L. J., and Farrell, D. T. (2018). Review: Beef-eating quality: a European journey. *Animal* 12, 2424–2433. doi:10.1017/S1751731118001672

Hassan, A. A., Sandanger, T. M., and Brustad, M. (2012). Selected vitamins and essential elements in meat from semi-domesticated reindeer (Rangifer tarandus tarandus L.) in mid- and northern Norway: Geographical variations and effect of animal population density. *Nutrients* 4, 724–739. doi:10.3390/nu4070724

Henchion, M., McCarthy, M., Resconi, V. C., and Troy, D. (2014). Meat consumption: Trends and quality matters. *Meat Sci.* 98, 561–568. doi:10.1016/j.meatsci.2014.06.007

Hultgren, J., Arvidsson Segerkvist, K., Berg, C., Karlsson, A. H., Öhgren, C., and Algers, B. (2022). Preslaughter stress and beef quality in relation to slaughter transport of cattle. *Livest. Sci.* 264, 105073. doi:10.1016/j.livsci.2022.105073

Hunka, A. D., Vanacore, E., Medin, I., Gjona, E., and Kautto, A. H. (2024). Official control in slaughter and game handling: expectations and prerequisites for implementation of remote meat inspection in Sweden. *J. Food Prot.* 87, 100196. doi:10.1016/j.jfp.2023.100196

InAFQual (2025). *Innovative arctic food quality control for smes*. Available online at: https://inafqual.eu/ (Accessed January 15, 2026).

Jia, W., van Ruth, S., Scollan, N., and Koidis, A. (2022). Hyperspectral imaging (HSI) for meat quality evaluation across the supply chain: Current and future trends. *Curr. Res. Food Sci.* 5, 1017–1027. doi:10.1016/j.crfs.2022.05.016

Jo, K., Lee, S., Jeong, S-K-C., Lee, D.-H., Jeon, H., and Jung, S. (2024). Hyperspectral imaging-based assessment of fresh meat quality: Progress and applications. *Microchem. J.* 197, 109785. doi:10.1016/j.microc.2023.109785

Kautto, A. H., Medin, I., Almqvist, V., Boqvist, S., and Vågsholm, I. (2023). Remote ante mortem inspection – possibilities for improved sustainability in low-capacity slaughter. *Food Control* 153, 109967. doi:10.1016/j.foodcont.2023.109967

Kautto, A. H., Vågsholm, I., and Niskanen, R. (2017). Meat inspection of reindeer – a rich source of data for monitoring food safety and animal and environmental health in Sweden. *Infection Ecol. Epidemiol.* 7, 1340695. doi:10.1080/20008686.2017.1340695

Kenny, D., Murphy, C. P., Sleator, R. D., Judge, M. M., Evans, R. D., and Berry, D. P. (2020). Animal-level factors associated with the achievement of desirable specifications in Irish beef carcasses graded using the EUROP classification system. *J. Anim. Sci.* 98, skaa191. doi:10.1093/jas/skaa191

Liu, J., Chriki, S., Ellies-Oury, M.-P., Legrand, I., Pogorzelski, G., Wierzbicki, J., et al. (2020). European conformation and fat scores of bovine carcasses are not good indicators of marbling. *Meat Sci.* 170, 108233. doi:10.1016/j.meatsci.2020.108233

Lovdata (2011). *Forskrift om rapportering av slaktet rein og lagerbeholdning*. Available online at: https://lovdata.no/dokument/SF/forskrift/2011-06-21-617 (Accessed January 15, 2026).

Malmfors, G., and Wiklund, E. (1996). Pre-slaughter handling of reindeer – effects on meat quality. *Meat Sci.* 43, S257–S264. doi:10.1016/0309-1740(96)00070-8

Mielnik, M. B., Rzeszutek, A., Triumf, E. C., and Egelandsdal, B. (2011). Antioxidant and other quality properties of reindeer muscle from two different Norwegian regions. *Meat Sci.* 89, 526–532. doi:10.1016/j.meatsci.2011.05.021

Monteils, V., Sibra, C., Ellies-Oury, M.-P., Botreau, R., De la Torre, A., and Laurent, C. (2017). A set of indicators to better characterize beef carcasses at the slaughterhouse level in addition to the EUROP system. *Livest. Sci.* 202, 44–51. doi:10.1016/j.livsci.2017.05.017

Muuttoranta, K., and Majuri, K. 2021). "Good practices in reindeer slaughtering – slaughtering at a slaughterhouse," in *No. D 3/2021 in publications of lapland university of applied sciences*. (Rovaniemi: Lapland University of Applied Sciences).

Negretti, P., Bianconi, G., Cannata, G., Catillo, G., Steri, R., Barrasso, R., et al. (2022). Visual image analysis for a new classification method of bovine carcasses according to EU legislation criteria. *Meat Sci.* 183, 108654. doi:10.1016/j.meatsci.2021.108654

Nisbet, H., Lambe, N., Miller, G. A., Doeschl-Wilson, A., Barclay, D., Wheaton, A., et al. (2024a). Machine learning algorithms for the prediction of EUROP classification grade and carcass weight, using 3-dimensional measurements of beef carcasses. *Front. Anim. Sci.* 5, 1383371. doi:10.3389/fanim.2024.1383371

Nisbet, H., Lambe, N., Miller, G. A., Doeschl-Wilson, A., Barclay, D., Wheaton, A., et al. (2024b). Using in-abattoir 3-dimensional measurements from images of beef carcasses for the prediction of EUROP classification grade and carcass weight. *Meat Sci.* 209, 109391. doi:10.1016/j.meatsci.2023.109391

Nogalski, Z., Pogorzelska-Przybyłek, P., Sobczuk-Szul, M., and Purwin, C. (2019). The effect of carcase conformation and fat cover scores (EUROP system) on the quality of meat from young bulls. *Ital. J. Anim. Sci.* 18, 615–620. doi:10.1080/1828051X.2018.1549513

Nordregio (2015). Reindeer Herding Area in the Nordic Countries. (Stockholm, Sweden: Nordregio). Available online at: https://nordregio.org/maps/reindeer-herding-area-in-the-nordic-countries/ (Accessed January 15, 2026).

Olofsson, A., Danell, Ö., Åhman, B., and Forslund, P. (2011). Carcass records of autumnslaughtered reindeer as indicator of long-term changes in animal condition. *Rangifer* 31, 7–20. doi:10.7557/2.31.1.1830

Oskal, A., Sara, R. B. M. E., Krarup-Hansen, K., Smuk, I. A., and Mathiesen, S. D. (2024). "Reindeer herders' food knowledge systems," in *Reindeer husbandry*. Eds. S. D. Mathiesen, I. M. G. Eira, E. I. Turi, A. Oskal, M. Pogodaev and M. Tonkopeeva (Springer, Cham). Springer Polar Sciences. doi:10.1007/978-3-031-42289-8_6

Ponnampalam, E. N., Hopkins, D. L., Bruce, H., Li, D., Baldi, G., and Bekhit, A. E.-D. (2017). Causes and contributing factors to "dark cutting" meat: Current trends and future directions: A review. *Compr. Rev. Food Sci. Food Saf.* 16, 400–430. doi:10.1111/1541-4337.12258

Prieto, N., Pawluczyk, O., Dugan, M. E. R., and Aalhus, J. L. (2017). A review of the principles and applications of near-infrared spectroscopy to characterize meat, fat, and meat products. *Appl. Spectrosc.* 71, 1403–1426. doi:10.1177/0003702817709299

Prieto, N., Roehe, R., Lavín, P., Batten, G., and Andrés, S. (2009). Application of near infrared reflectance spectroscopy to predict meat and meat products quality: a review. *Meat Sci.* 83, 175–186. doi:10.1016/j.meatsci.2009.04.016

Renbiten AB (2026). *Processing and production*. Available online at: https://renbiten.se/en/processing-and-production (Accessed January 15, 2026).

Rius-Vilarrasa, E., Bünger, L., Maltin, C., Matthews, K. R., and Roehe, R. (2009). Evaluation of video image analysis (VIA) technology to predict meat yield of sheep carcasses on-line under UK abattoir conditions. *Meat Sci.* 82, 94–100. doi:10.1016/j.meatsci.2008.12.009

Salmi, A.-K. (2023). The archaeology of reindeer domestication and herding practices in northern Fennoscandia. *J. Archaeol. Res.* 31, 617–660. doi:10.1007/s10814-022-09182-8

Santinello, M., Penasa, M., Goi, A., Rampado, N., Hocquette, J.-F., and De Marchi, M. (2024). Relationships between European carcass evaluation and Meat Standards Australia grading scheme applied to young beef cattle. *Meat Sci.* 216, 109575. doi:10.1016/j.meatsci.2024.109575

Sara, R. B. M. E., Lykke, K. V., and Mathiesen, S. D. (2022). Precious blood and nourishing offal: past and present slaughtering perspectives in Sámi reindeer pastoralism. *Pastoralism: Research Policy Pract.* 12, 20. doi:10.1186/s13570-021-00224-2

Sara, R. B. M. E., and Mathiesen, S. D. (2020). Sámi gastronomy: The role of traditional knowledge. *J. Gastronomy Tourism* 5, 33–49. doi:10.3727/216929720X15968961037890

Statens jordbruksverk (2004). Föreskrifter om ändring i Statens jordbruksverks föreskrifter (SJVFS 1998:127) om klassificering av slaktkroppar SJVFS 2004:88. *Statens jordbruksverks*. (SJVFS 2004:88), 1–17.

Sun, D.-W., Pu, H., and Yu, J. (2024). Applications of hyperspectral imaging technology in the food industry. *Nat. Rev. Electrical Eng.* 1, 251–263. doi:10.1038/s44287-024-00033-w

Tang, X., Rao, L., Xie, L., Yan, M., Chen, Z., Liu, S., et al. (2023). Quantification and visualization of meat quality traits in pork using hyperspectral imaging. *Meat Sci.* 196, 109052. doi:10.1016/j.meatsci.2022.109052

Triumf, E. C., Purchas, R. W., Mielnik, M., Maehre, H. K., Elvevoll, E., Slinde, E., et al. (2012). Composition and some quality characteristics of the longissimus muscle of reindeer in Norway compared to farmed New Zealand red deer. *Meat Sci.* 90, 122–129. doi:10.1016/j.meatsci.2011.06.011

Tryland, M., and Buhler, K. J. (2025). Zoonotic infections in semi-domesticated Eurasian tundra reindeer (Rangifer tarandus tarandus) in Fennoscandia – a review. *One Health Outlook* 7, 18. doi:10.1186/s42522-025-00140-0

Turi, E. I. (2016). *State steering and traditional ecological knowledge in reindeer-herding governance: cases from western finnmark, Norway and yamal, Russia* (Umeå, Sweden: Umeå University). Ph.D. thesis.

Tyler, N. J. C., Turi, J. M., Sundset, M. A., Bull, K. S., Sara, M. N., Reinert, E., et al. (2007). Saami reindeer pastoralism under climate change: Applying a generalized framework for vulnerability studies to a sub-Arctic social–ecological system. *Global Environ. Change* 17, 191–206. doi:10.1016/j.gloenvcha.2006.06.001

Wiklund, E., Andersson, A., Malmfors, G., and Lundström, K. (1996a). Muscle glycogen levels and blood metabolites in reindeer (Rangifer tarandus tarandus L.) after transport and lairage. *Meat Sci.* 42, 133–144. doi:10.1016/0309-1740(95)00035-6

Wiklund, E., Andersson, A., Malmfors, G., Lundström, K., and Danell, Ö. (1995). Ultimate pH values in reindeer meat with particular regard to animal sex and age, muscle and transport distance. *Rangifer* 15, 47–54. doi:10.7557/2.15.2.1166

Wiklund, E., Barnier, V. M. H., Smulders, F. J. M., Lundström, K., and Malmfors, G. (1997). Proteolysis and tenderisation in reindeer (Rangifer tarandus tarandus L.) bull longissimus thoracis muscle of varying ultimate pH. *Meat Sci.* 46, 33–43. doi:10.1016/S0309-1740(97)00015-6

Wiklund, E., Farouk, M., and Finstad, G. (2014). Venison: Meat from red deer (Cervus elaphus) and reindeer (Rangifer tarandus tarandus). *Anim. Front.* 4, 55–61. doi:10.2527/af.2014-0034

Wiklund, E., Finstad, G., Johansson, L., Aguiar, G., and Bechtel, P. J. (2008). Carcass composition and yield of Alaskan reindeer (Rangifer tarandus tarandus) steers and effects of electrical stimulation applied during field slaughter on meat quality. *Meat Sci.* 78, 185–193. doi:10.1016/j.meatsci.2007.06.004

Wiklund, E., Johansson, L., and Malmfors, G. (2003). Sensory meat quality, ultimate pH values, blood parameters and carcass characteristics in reindeer (Rangifer tarandus tarandus L.) grazed on natural pastures or fed a commercial feed mixture. *Food Qual. Preference* 14, 573–581. doi:10.1016/S0950-3293(02)00151-9

Wiklund, E., Malmfors, G., Lundström, K., and Rehbinder, C. (1996b). Pre-slaughter handling of reindeer bulls (Rangifer tarandus tarandus L.) – effects on technological and sensory meat quality, blood metabolites and muscular and abomasal lesions. *Rangifer* 16, 109–117. doi:10.7557/2.16.3.1204

Yi, X., Li, W., Li, Y., Ren, J., Zhang, J., Li, B., et al. (2025). Decoding the spectrum of meat quality: Advances in hyperspectral imaging for multi-attribute analysis. *Food Chem.* 496, 146912. doi:10.1016/j.foodchem.2025.146912

Yu, Y., Chen, W., Zhao, D., Zhang, H., Chen, W., Liu, R., et al. (2025). Meat species authentication using portable hyperspectral imaging. *Front. Nutr.* 12, 1577642. doi:10.3389/fnut.2025.1577642