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Review Article

Near-infrared and fourier-transform infrared spectroscopy for meat quality and safety assessment: A review

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Abstract

Meat quality and safety assessment demands analytical tools that are rapid, nondestructive, and capable of resolving a broad spectrum of physicochemical and microbiological parameters simultaneously. Near-infrared (NIR) and Fourier-transform infrared (FTIR) spectroscopy have emerged as two of the most promising technologies in this regard, offering complementary analytical capabilities rooted in distinct physical mechanisms of light-matter interaction. This review systematically examines the application of NIR and FTIR spectroscopy across the full scope of meat quality and safety evaluation, beginning with their contrasting physical and chemical principles as applied to muscle matrices, followed by a comprehensive mapping of spectral absorption bands to individual quality parameters including moisture, protein, fat, lipid oxidation, water-holding capacity, color, tenderness, and pH. Their utility in meat safety and authenticity assessment, encompassing microbial spoilage monitoring, species adulteration detection, exogenous adulterant identification, and halal authentication, is critically evaluated. Key methodological challenges including sample heterogeneity, water interference, calibration transferability, and model interpretability are discussed. Future directions emphasizing portable instrumentation, hyperspectral imaging, artificial intelligence integration, and open-access spectral databases are proposed. The evidence collectively supports a complementary dual-spectroscopic framework as the most comprehensive and practically deployable strategy for nondestructive meat quality governance across the supply chain.

Introduction

Meat is an essential component of a balanced human diet, valued for its rich nutritional profile and consumer acceptability. Global meat consumption is projected to rise considerably over the coming decade, driven by shifts in dietary preferences related to health and nutrition. According to the OECD/FAO (2019), a growth of approximately 1.2% in worldwide meat consumption is anticipated by 2028 relative to the base period of 2016 to 2018, with premium cuts such as beef and sheep meat expected to witness greater demand compared to other categories. To align with rising consumer expectations for safe, high quality, cost-effective, and sustainably produced meat, industry stakeholders and researchers are actively exploring improved approaches to ensure critical quality attributes while extending shelf life and storage stability (Grunert et al., 2004; Troy et al., 2016). Meat quality is conventionally assessed through a wide range of physicochemical properties, including color, tenderness, water-holding capacity, pH, moisture content, protein content, and fat content, all of which can be measured through laboratory-based instrumental analyses or trained sensory evaluation (Qian et al., 2021). While visible characteristics such as texture, appearance, and color are prominent determinants of consumer purchase decisions, the chemical composition and microbiological status of meat products play an equally important role in determining their eating quality and overall safety (Sarker et al., 2024; Herrero, 2008; Taheri-Garavand et al., 2019). Authenticity is also a critical quality dimension, ensuring that meat products conform to established regulatory criteria and compositional standards (Hashem et al., 2021 and 2022; Abbas et al., 2018).

Conventional approaches for assessing meat quality and safety encompass a broad range of techniques, including manual inspection by experienced personnel, microbiological enumeration methods, and an extensive array of mechanical, chemical, biochemical, immunological, and sensory assays (Sadakuzzaman et al., 2024; Mia et al., 2023; Torun et al., 2023; Troy et al., 2016; Xiong et al., 2017). Despite their reliability, these traditional methods are associated with several practical limitations, notably their time-intensive nature, destructive character, high operational cost, and the requirement for elaborate laboratory infrastructure and complex sample preparation procedures. These drawbacks have generated significant interest in rapid, nondestructive analytical alternatives that can enhance productivity and profitability across the meat supply chain while meeting growing consumer expectations for superior quality products (Miah et al., 2024; Wojnowski et al., 2017; Rahman et al., 2018; Giaretta et al., 2019).

Near-infrared (NIR) spectroscopy has been widely adopted for nondestructive quality evaluation of meat over the past several decades, owing to its non-invasive nature, minimal sample preparation requirements, and the speed with which measurements can be acquired. By capturing the absorption characteristics of hydrogen-containing functional groups across the NIR region, it enables reliable prediction of key compositional parameters in diverse meat matrices. The commercial expansion of NIR has been closely linked to advances in the miniaturization of spectrometer hardware and developments in chemometric modeling (Prieto et al., 2014; Andersen et al., 2018; Du et al., 2019; Candoğan et al., 2021).

Complementing this, Fourier-transform infrared (FTIR) spectroscopy has gained considerable attention as a rapid, reagent-free, and highly versatile analytical platform. By capturing molecular vibrational signatures across the mid-infrared region with high spectral resolution, FTIR enables simultaneous multi-analyte analysis and provides comprehensive biochemical information from a single measurement (Li-Chan et al., 2001; Severcan et al., 2012; Bureau et al., 2019). (Zheng et al., 2023) demonstrated that simple spectral dimension reduction strategies applied to NIR data could achieve prediction accuracy for lamb meat quality parameters comparable to complex wavelength selection algorithms, offering a practical basis for compact device development. (He and Zeng, 2025)

broadly reviewed vibrational spectroscopy techniques for food authentication across diverse matrices, highlighting advances in chemometrics, portable instrumentation, and hyperspectral imaging. Similarly, (Sarker et al., 2024b) reviewed the integration of artificial intelligence-driven approaches with NIR spectroscopy for meat quality and safety assessment, underscoring the growing role of machine learning in interpreting spectral data. However, these works lack a focused treatment of how NIR and FTIR are specifically applied to the simultaneous assessment of meat quality and safety, the systematic mapping of spectral bands to individual quality indices, and comparative evaluation of their utility for authenticity verification and spoilage monitoring. Methodological challenges specific to the meat matrix, including moisture interference, surface heterogeneity, and calibration transfer limitations, also remain insufficiently addressed.

Review Structure

The present review therefore aims to provide a comprehensive and focused account of the application of NIR and FTIR spectroscopy in meat quality assessment and safety evaluation. The discussion covers the fundamental physical and chemical principles underlying both techniques as applied to muscle matrices, a systematic mapping of spectral bands to specific meat quality parameters, their comparative utility in meat safety and authenticity assessment, and the key methodological challenges and limitations that must be addressed for broader industrial implementation, concluding with future research directions for the field. The overall scope and logical flow of this review, from the underlying spectroscopic principles through quality parameter mapping, safety and authenticity applications, and methodological challenges, to future directions, is summarized schematically in Figure 1.

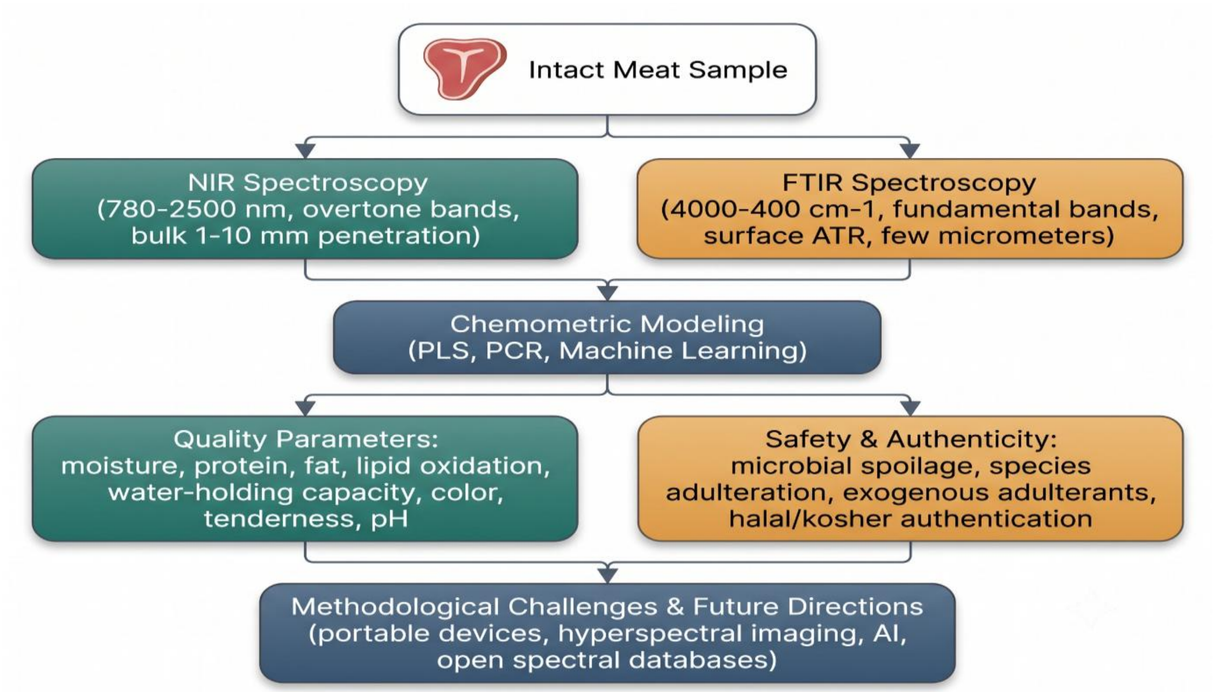

Figure 1. Schematic workflow of this review, showing how NIR and FTIR spectroscopy are applied to meat quality, safety, and authenticity assessment, and the challenges shaping their industrial adoption.

Physical and Chemical Principles: NIR vs. FTIR in Muscle Matrices

Spectroscopic analysis of meat relies fundamentally on the interaction between electromagnetic radiation and the molecular architecture of muscle tissue. While both NIR and FTIR spectroscopy exploit molecular vibrations to generate analytical information, they operate through distinct physical mechanisms, probe different tissue depths, and respond selectively to different categories of molecular motion. Understanding these differences is essential for selecting the appropriate technique or designing complementary analytical strategies for comprehensive meat quality assessment.

NIR Spectroscopy: Overtones and Combination Bands in Muscle Tissue

Near-infrared spectroscopy operates within the electromagnetic region spanning approximately 780 to 2500 nm, a spectral window defined not by fundamental molecular vibrations but by their overtones and combination bands (Alcalà et al., 2012). When a chemical bond absorbs NIR radiation, it undergoes transitions to higher-order vibrational energy states, producing weaker but detectable absorption features at wavelengths that are approximately integer multiples of the fundamental frequency (Weyer, 1985). In meat and muscle tissue, the dominant absorbing species are hydrogen-containing functional groups, specifically O-H bonds associated with water and hydroxyl-containing compounds, C-H bonds present in lipid chains and protein side chains, and N-H bonds found within peptide linkages and amino acid residues. These groups give rise to overlapping absorption features distributed broadly across the NIR region, with water overtones prominent near 970 nm and 1450 nm, lipid-related C-H combination bands appearing around 1720 nm and 2300 nm, and protein-associated N-H absorptions contributing across the 1500 to 2100 nm range (Manley, 2014; Bowker et al., 2014; Golovynskyi et al., 2023).

One of the most practically significant characteristics of NIR radiation in the context of meat analysis is its relatively deep tissue penetration. Depending on the optical density, water content, and structural organization of the tissue, NIR photons can penetrate from approximately 1 to 10 mm beneath the surface, making the technique inherently suitable for probing the bulk compositional properties of intact or minimally prepared meat samples (Prieto et al., 2017; Jiang et al., 2023). This penetration depth allows NIR to interrogate a representative volume of tissue, capturing information about moisture, fat, and protein content in a manner that reflects the average chemical composition rather than superficial surface conditions alone. Combined with the availability of robust diffuse reflectance sampling accessories and the increasing miniaturization of NIR hardware, this attribute positions NIR as a practical tool for rapid, at-line, or even online monitoring of meat quality throughout the processing chain. The broad and overlapping nature of NIR spectral features, however, means that meaningful quantitative information can only be extracted through the application of multivariate chemometric techniques such as partial least squares regression, principal component regression, or machine learning algorithms, which are capable of resolving the complex spectral mixtures characteristic of real meat matrices (Dixit et al., 2017a; Zheng et al., 2023; Feng et al., 2024).

FTIR Spectroscopy: Fundamental Vibrations and Surface Sensitivity

Fourier-transform infrared spectroscopy operates in the mid-infrared region, typically spanning 4000 to 400 cm^{-1}, where molecular bonds absorb radiation at frequencies that correspond directly to their fundamental vibrational modes (Parker et al., 2024). Unlike the overtone-driven absorptions of the NIR region, mid-infrared absorptions arise from primary stretching and bending transitions and are therefore considerably stronger and more structurally diagnostic (Yin et al., 2025). In the context of meat and muscle tissue, FTIR generates a rich and highly resolved spectral fingerprint in which individual molecular components produce narrow, well-defined absorption bands at characteristic wavenumbers (Candoğan et al., 2021; Al-Kelani and Buthelezi, 2024). The Amide I band, centered near 1650 cm^{-1} and arising primarily from C=O stretching of peptide bonds, is among the most analytically powerful features in meat spectra, as its precise position and shape are sensitive to protein secondary structure, denaturation state, and aggregation behavior (Yang et al., 2022). The Amide II band near 1550 cm^{-1}, resulting from a combination of N-H bending and C-N stretching, and the Amide III band in the 1200 to 1350 cm^{-1} region provide complementary structural information. Lipid-related absorptions appear prominently as carbonyl stretching bands near 1740 cm^{-1}, with additional contributions from C-H deformation modes around 1460 and 1370 cm^{-1}. Water, while giving a broad and intense O-H stretching absorption near 3300 cm^{-1} and a bending mode near 1640 cm^{-1}, can substantially interfere with protein bands in this region, representing one of the central analytical challenges in applying FTIR to high-moisture meat samples (Lozano et al., 2017; Schwaighofer et al., 2018; Sanden et al., 2019; Stani et al., 2020).

The tissue penetration depth of mid-infrared radiation is fundamentally limited by the strong absorption coefficients of the bands involved. Under attenuated total reflectance sampling conditions, which represent the dominant FTIR measurement mode in food and meat analysis, penetration into the sample extends only a few micrometers from the crystal interface (Mendes and Duarte, 2021). This surface sensitivity is both a limitation and an advantage: while it prevents FTIR from providing bulk compositional profiles in the manner of NIR, it renders the technique exquisitely responsive to surface-level biochemical changes, including the early stages of lipid oxidation, protein structural reorganization, microbial metabolite accumulation, and post-mortem biochemical modifications occurring at the tissue interface. The sharp, well-resolved nature of mid-infrared bands also facilitates direct spectral interpretation, enabling qualitative identification of specific molecular species without the extensive chemometric preprocessing required for NIR data analysis (Sanden et al., 2019; Lia et al., 2025).

The Complementary Matrix: Why Neither Technique Alone Is Sufficient

When considered independently, each technique leaves a meaningful analytical blind spot in the characterization of muscle tissue. NIR spectroscopy, by virtue of its deep penetration and sensitivity to bulk hydrogen-containing species, excels at rapid, nondestructive quantification of moisture, total fat, and crude protein across large sample volumes. However, its broad, overlapping spectral features are largely insensitive to the fine structural details of the tissue surface, including localized oxidative modifications, subtle protein conformational changes, and early-stage microbiological deterioration occurring at the cut surface or packaging interface. These are precisely the changes most relevant to freshness assessment and safety monitoring in retail and processing environments. FTIR spectroscopy, conversely, delivers unparalleled molecular specificity at the tissue surface. Its sharp fundamental bands are capable of resolving structural changes in individual protein classes, identifying specific lipid oxidation products, and detecting the biochemical signatures of spoilage-associated microbial activity. Yet the shallow penetration depth means that FTIR measurements of intact meat are inherently surface-weighted, potentially misrepresenting the bulk compositional status of thick cuts where the interior chemistry may differ substantially from the exposed surface. Additionally, the strong infrared absorption of water in the mid-infrared region complicates the analysis of high-moisture meat matrices, often requiring spectral subtraction, deconvolution, or careful ATR contact optimization to isolate meaningful biochemical information from the dominant water background. This contrast in tissue penetration and molecular sensitivity is illustrated schematically in Figure 2.

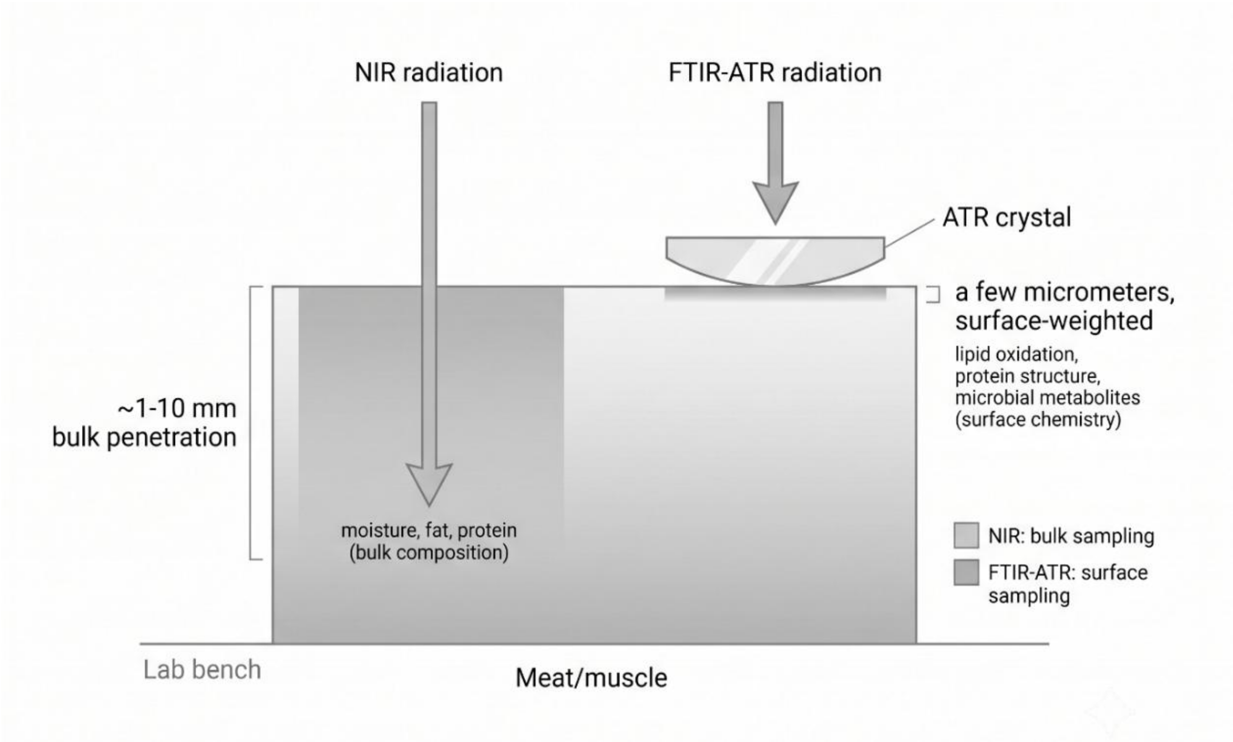

Figure 2. Cross-sectional schematic comparing NIR (~1–10 mm, bulk sampling) and FTIR-ATR (a few micrometers, surface-weighted) penetration depths in muscle tissue (Prieto et al., 2017; Jiang et al., 2023; Mendes and Duarte, 2021).

NIR and FTIR spectroscopy function as a complementary analytical pair whose combined deployment addresses the limitations inherent to each technique in isolation. NIR provides the broad, volumetric compositional overview necessary for bulk quality grading and composition prediction, while FTIR delivers the surface-level molecular resolution required for structural, oxidative, and microbiological characterization. A dual-spectroscopic strategy therefore offers a more complete picture of meat quality than either approach can achieve independently, making the integration of both modalities an increasingly attractive framework for comprehensive, nondestructive assessment across the meat supply chain.

Table 1. Comparative overview of near-infrared (NIR) and Fourier-transform infrared (FTIR) spectroscopy for meat analysis

Feature	NIR Spectroscopy	FTIR Spectroscopy	References
Spectral region	780–2500 nm	4000–400 cm^{-1} (mid-infrared)	(Beć et al., 2020; Candoğan et al., 2021)
Vibrational origin	Overtones and combination bands of C-H, O-H, and N-H bonds	Fundamental stretching and bending vibrations	(Beć et al., 2020; Candoğan et al., 2021)
Band character	Broad, overlapping absorptions	Sharp, well-resolved, chemically diagnostic bands	Beć et al., 2020; Candoğan et al., 2021)
Typical tissue penetration	~1–10 mm (bulk sampling)	A few micrometers under ATR (surface-weighted)	(Afara et al., 2021; Götz et al., 2020)
Common sampling mode	Diffuse reflectance / transmittance	Attenuated total reflectance (ATR)	(Dias et al., 2021; Candoğan et al., 2021)
Data interpretation	Requires multivariate chemometrics (PLS, PCR, machine learning)	Permits direct qualitative interpretation; chemometrics enhances quantification	(Beć et al., 2022; Candoğan et al., 2021)
Water interference	Overtone bands near 970, 1450 and 1940 nm can mask fat and protein signals	Strong O-H bands near 3300 and 1640 cm^{-1} overlap Amide I/II bands	(Yamada et al., 2024; Yang et al., 2022)
Principal analytical strength	Rapid, nondestructive bulk compositional quantification (moisture, fat, protein)	Molecular specificity for structural, oxidative and microbial changes	(Dias et al., 2021; Candoğan et al., 2021)
Principal limitation	Insensitive to fine surface or structural detail	Not representative of bulk composition in thick, intact cuts	(Afara et al., 2021; Götz et al., 2020)
Instrumentation maturity	Mature, widely available miniaturized/portable platforms	Increasingly portable but generally less field-mature than NIR	(Beć et al., 2022; Cebi et al., 2023)

Comprehensive Mapping of Spectral Bands to Meat Quality Parameters

The practical value of NIR and FTIR spectroscopy in meat science lies not only in their broad analytical capabilities but in their ability to resolve specific quality-defining parameters from the complex spectral landscape of muscle tissue. Each major meat quality attribute, whether compositional, structural, or biochemical, leaves a characteristic spectral signature within one or both of these regions. The following section systematically maps the key absorption features associated with each quality parameter and identifies which technique has demonstrated dominant analytical utility for its determination; a summary is provided in Table 2 and depicted visually in Figure 3.

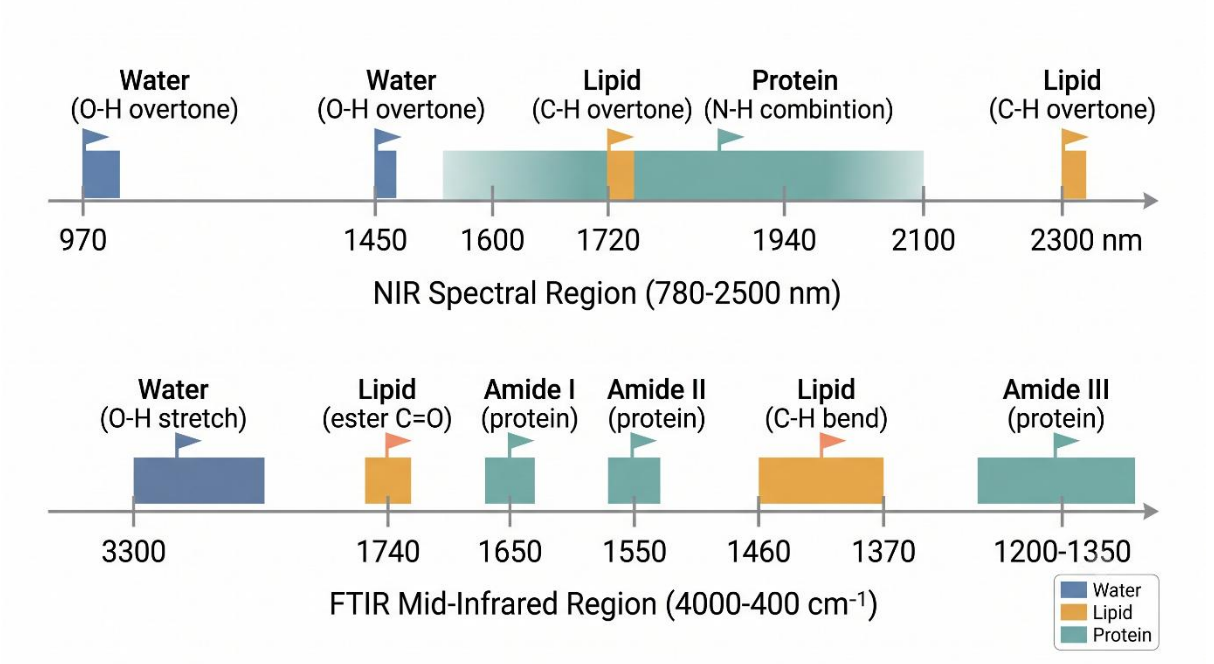

Figure 3. Annotated spectral map of NIR (780–2500 nm) and FTIR mid-infrared (4000–400 cm⁻¹) regions, showing principal absorption bands for water, protein (Amide I–III), and lipid. (Candoğan et al., 2021; Prieto et al., 2017; Talari et al., 2017; Yang et al., 2022).

Table 2. Summary of spectral band assignments and preferred spectroscopic technique for major meat quality parameters

Quality Parameter	Key NIR Bands	Key FTIR Bands	Preferred Technique	Representative Sources
Moisture content	970, 1450, 1940 nm (O-H overtones/combination)	~3300 cm^{-1} (O-H stretch); ~1640 cm^{-1} (H-O-H bend)	NIR	Zhang et al., 2023
Protein content and structure	1500–2100 nm (N-H combination/overtone)	Amide I ~1650, Amide II ~1550, Amide III 1200–1350 cm^{-1}	NIR (content); FTIR (structure)	Yang et al., 2022; Pongsetkul et al., 2023
Fat content and lipid composition	1720, 2300 nm (C-H overtones); 1600–2500 nm	~1740 cm^{-1} (ester C=O); 1460/1370 cm^{-1} (C-H bend); ~3010 cm^{-1} (C=C)	NIR (content); FTIR (fatty acid profiling)	Beriain et al., 2021; Rohman et al., 2020
Lipid oxidation	Broad, non-specific spectral variance	~3450 cm^{-1} (hydroperoxide O-H); 1700–1750 cm^{-1} (carbonyl)	FTIR	Lucarini et al., 2018
Water-holding capacity	Shifts in 970 and 1450 nm water bands	Amide I profile (myofibrillar protein conformation)	NIR	Geesink et al., 2003; Bertram et al., 2006
Meat color	505, 542, 555, 580, 630 nm (myoglobin redox forms)	Indirect only, via protein/heme oxidation markers	NIR/Visible	Suman et al., 2023; Arias et al., 2022
Tenderness and texture	Hyperspectral/NIR bands linked to myofibrillar and connective tissue	Better suited to ageing-stage discrimination than fine tenderness resolution	NIR (more consistent)	Beriain et al., 2022; ElMasry et al., 2012
pH	Water-band shifts; protein-related absorptions	Amide I shift linked to pH-driven denaturation	Both	Andersen et al., 2017
Post-mortem ageing/freshness	Global compositional shifts (water state, lipid oxidation)	Volatile fatty acids, protein denaturation, microbial metabolites	Both (complementary)	Sinelli et al., 2010

Moisture Content

Water is the most abundant component of fresh meat, typically constituting 65 to 80% of total tissue mass, and its quantification is fundamental to yield assessment, freshness monitoring, and compliance with regulatory compositional standards (Geletu et al., 2021). In the NIR region, water gives rise to well-characterized overtone and combination absorptions, with the most analytically prominent features appearing near 970 nm and 1450 nm, corresponding to the second and first overtones of the O-H stretching mode respectively, and a combination band near 1940 nm. The intensity and position of these bands are directly related to the total water content and its binding state within the muscle matrix, providing a reliable basis for predictive calibration models. Diffuse reflectance NIR has consistently demonstrated strong predictive performance for moisture across a range of meat species and cut types, and the technique's deep tissue penetration ensures that bulk water content rather than surface hydration alone is captured (Dias et al., 2021; Zhang et al., 2023).

In the FTIR mid-infrared region, water absorbs strongly at approximately 3300 cm^{-1} through O-H stretching and at 1640 cm^{-1} through H-O-H bending, producing intense, broad bands that can obscure neighboring protein features. While ATR-FTIR can detect moisture-related spectral changes, the strong water absorption frequently necessitates background subtraction or spectral processing steps that introduce additional uncertainty (Pedersen et al., 2003; Wang et al., 2026). NIR spectroscopy is therefore the dominant technique for moisture quantification in meat, offering robust, direct calibration against reference moisture values with minimal interference from sample preparation or surface effects (Zhang et al., 2023).

Protein Content and Structural Integrity

Protein constitutes approximately 15 to 23% of fresh meat by mass and represents one of the primary nutritional and functional quality determinants (Ahmad et al., 2018). Total crude protein content can be estimated by both NIR and FTIR, though the two techniques probe protein at fundamentally different levels of resolution. NIR quantification of protein relies primarily on N-H combination and overtone absorptions distributed across the 1500 to 2100 nm region, supplemented by contributions from C-H and C-N bonds within amino acid side chains. These broad features correlate well with total nitrogen content and form the basis of NIR-based protein prediction models that are now widely used in commercial meat grading and laboratory quality control settings (Jiang et al., 2023).

FTIR provides a deeper and more structurally specific view of the protein component. The Amide I band near 1650 cm^{-1}, dominated by C=O stretching of the peptide backbone, is exquisitely sensitive to protein secondary structure, with alpha-helical, beta-sheet, and random coil conformations producing subtly different band positions and shapes that can be resolved through second-derivative analysis or Fourier self-deconvolution. The Amide II band near 1550 cm^{-1} and Amide III features in the 1200 to 1350 cm^{-1} region provide complementary structural information (Pongsetkul et al., 2023; Li et al., 2025). These capabilities make FTIR the technique of choice not merely for estimating total protein content but for monitoring protein denaturation during thermal processing, structural changes associated with post-mortem aging, and myofibrillar protein integrity as a determinant of texture and water-holding capacity. For bulk protein quantification, NIR is preferred; for protein structural characterization, FTIR holds a clear advantage.

Fat and Lipid Content

Intramuscular fat, or marbling, is a critical determinant of eating quality in beef and other red meats, influencing tenderness, juiciness, flavor, and overall palatability (Lambe et al., 2021). Both NIR and FTIR are capable of predicting total fat content, but they differ in their sensitivity to lipid subcomponents and structural features. In the NIR region, lipid absorptions arise from C-H stretching overtones near 1720 nm and 2300 nm, and combination bands associated with methylene and methyl groups distributed broadly across the 1600 to 2500 nm range (Beriain et al., 2021). These features correlate with total fat content and, under appropriate chemometric treatment, can provide information about fatty acid chain length and degree of unsaturation, making NIR a practical tool for estimating fat content in intact carcasses or primal cuts (Parrini et al., 2023).

FTIR provides a more chemically resolved picture of the lipid fraction. The ester carbonyl stretching band near 1740 cm^{-1} is a diagnostic marker of triglyceride content and can be quantified independently of other absorbing species. C-H deformation bands near 1460 and 1370 cm^{-1} reflect methylene and methyl group contributions respectively, while the position of the C=C stretching band near 3010 cm^{-1} is sensitive to the proportion of unsaturated fatty acids (Rohman et al., 2020). ATR-FTIR has demonstrated particular utility in characterizing fatty acid profiles, detecting adulteration of fat fractions, and monitoring lipid oxidation through the progressive emergence of oxidation product bands in the carbonyl and hydroperoxide regions. For rapid total fat estimation in bulk samples, NIR is the dominant technique; for detailed fatty acid profiling and oxidative stability assessment, FTIR is the preferred modality.

Lipid Oxidation

Lipid oxidation is one of the primary mechanisms of quality deterioration in meat during storage, leading to the development of rancidity, off-flavors, and potentially harmful secondary oxidation products. Its spectroscopic detection demands sensitivity to low-concentration chemical species that emerge progressively against a background of dominant lipid signals, making it a challenging but analytically important target. FTIR spectroscopy is the dominant technique in this context, owing to its ability to resolve the sharp, diagnostic absorption bands of oxidation-related functional groups. The progressive formation of hydroperoxides, the primary products of lipid oxidation, generates a broad O-H stretching absorption near 3450 cm^{-1}, while secondary oxidation products such as aldehydes and ketones contribute absorptions in the carbonyl region between 1700 and 1750 cm^{-1}. Changes in the ratio of the ester carbonyl band at 1740 cm^{-1} to the C-H deformation bands at 1460 cm^{-1} have been used as semi-quantitative indicators of oxidative progression. ATR-FTIR applied to meat surface samples is therefore well suited to monitoring oxidative deterioration during refrigerated or modified-atmosphere storage (Lucarini et al., 2018).

NIR spectroscopy is less sensitive to lipid oxidation at early stages, as the spectral changes associated with oxidation product formation are subtle relative to the dominant lipid and water absorptions in this region. However, broad NIR calibrations incorporating oxidation-related spectral variance have been developed and can provide useful oxidation indices when paired with robust chemometric models (Prevolnik et al., 2005; Kombolo-Ngah et al., 2023).

Water Holding Capacity

Water-holding capacity, defined as the ability of muscle tissue to retain its inherent water against applied forces such as gravity, pressure, or heat, is a critical technological quality attribute that determines drip loss, cooking loss, and the visual appeal of fresh meat at retail. Its spectroscopic determination is mechanistically linked to the physical state of water within the tissue rather than its total quantity, requiring sensitivity to the hydrogen bonding environment and mobility of water molecules at the protein-water interface (Bao and Ertbjerg 2019). NIR spectroscopy is particularly well positioned for this measurement, as the precise wavelength position and shape of the water overtone bands near 970 and 1450 nm are influenced by the degree to which water molecules are bound to protein structures or exist in a free, mobile state. Shifts in band position and changes in spectral slope in these regions have been correlated with drip loss and cooking loss values across beef, pork, and poultry samples (Geesink et al., 2003; Zhang et al., 2023).

FTIR can also contribute information on water-holding capacity through the analysis of protein structural changes that govern water binding, particularly through the Amide I band profile, which reflects the conformational state of myofibrillar proteins. Denaturation or structural disruption of myosin and actin, detectable through shifts in Amide I peak position and changes in secondary structure proportions, correlates with reduced water retention in heat-treated or post-mortem aged samples (Pedersen et al., 2003; Bertram et al., 2006). For direct, rapid prediction of drip loss and related water-holding metrics in fresh meat, NIR spectroscopy remains the more practically deployable technique.

Meat Color

Color is the primary visual quality cue used by consumers to assess the freshness and desirability of fresh meat at the point of purchase, and it is governed principally by the concentration and oxidation state of myoglobin and its derivatives, including oxymyoglobin and metmyoglobin (Mostafa et al., 2025; Suman et al., 2023; Tushar et al., 2023). The spectroscopic assessment of meat color naturally falls within the visible and short-wave NIR regions, where myoglobin species produce distinct and well-characterized absorption bands. Deoxymyoglobin absorbs maximally near 555 nm, producing the characteristic purplish-red color of freshly cut meat. Oxymyoglobin, formed upon oxygen exposure, exhibits a double absorption peak near 542 and 580 nm and is associated with the bright cherry-red color preferred by consumers. Metmyoglobin, the oxidized form responsible for undesirable browning, absorbs near 505 and 630 nm (Arias et al., 2022). Measurement of reflectance in these spectral windows, combined with ratios between key wavelengths, provides a reliable non-contact basis for monitoring the myoglobin redox status and predicting instrumental color values such as CIE L*, a*, and b* (Shohiduzjaman et al., 2024; Piao et al., 2022; Rong et al., 2023).

FTIR does not directly capture the electronic transitions responsible for meat color and therefore offers limited utility for direct colorimetric assessment. However, FTIR monitoring of protein oxidation and structural changes in the heme environment can provide indirect information about metmyoglobin formation and surface discoloration mechanisms (Dias et al., 2024; Bhandari et al., 2025).

Tenderness and Texture

Tenderness is widely regarded as the most important eating quality attribute of beef and other red meats, and its objective determination remains one of the most challenging analytical targets for spectroscopic methods due to the complexity of the structural factors that govern textural perception. Tenderness is determined by a combination of myofibrillar protein integrity, connective tissue content, sarcomere length, and post-mortem proteolytic activity, each of which leaves a distinct but overlapping spectral signature (Naganathan et al., 2008; Soji, 2021). Post-mortem ageing generally improves tenderness, in part through degradation of myofibrillar proteins such as desmin and troponin-T, although the rate and extent of tenderization differ across muscles and production contexts (Phelps et al., 2016; Moloney et al., 2020). Recent work integrating histomorphological and gene expression analyses of muscle fibers across primal cuts has further elucidated the biological basis of these tenderness differences, providing complementary mechanistic context for spectroscopic tenderness prediction models (Sarker et al., 2024a). Spectroscopic methods have shown potential for non-destructive tenderness assessment, especially when combined with chemometric models, but prediction accuracy is inconsistent across studies and tends to depend on sample set, ageing stage, instrument design, and whether the goal is regression or classification (Savoia et al., 2021). Within this evidence set, NIR and hyperspectral approaches appear more consistently supported than FTIR-MIR for direct tenderness prediction, while FTIR-MIR appears more useful for distinguishing early from late ageing stages than for accurately resolving intermediate tenderness differences (El Masry et al., 2012).

4.8 pH

Post-mortem muscle pH is a key determinant of meat quality, governing water-holding capacity, color development, texture, and microbial shelf life, with pH, color, and tenderness closely interrelated through their shared dependence on post-mortem glycolysis and protein denaturation (Sristi et al., 2025). The decline of pH from approximately 7.2 at slaughter to an ultimate value near 5.5 in normal beef, driven by anaerobic glycolysis and lactic acid accumulation, can deviate significantly in cases of dark, firm, and dry meat or pale, soft, and exudative conditions, both of which represent economically significant quality defects (Khatri and Huff-Lonergan, 2023). The spectroscopic determination of pH is indirect, relying on the correlated changes in water state, protein conformation, and myoglobin chemistry that accompany pH variation in post-mortem muscle. NIR spectroscopy has been successfully applied to pH prediction by exploiting water band shifts associated with changes in the protonation state and hydrogen bonding environment of tissue water, as well as protein-related absorptions that reflect conformational responses to acidification (Qu et al., 2018; Sahar et al., 2019). FTIR complements this by providing direct evidence of structural changes in myofibrillar proteins linked to pH-driven denaturation, particularly through alterations in Amide I band shape and position. Both techniques have demonstrated acceptable predictive accuracy for pH in multiple meat species, with NIR generally favored for rapid at-line measurements and FTIR offering greater mechanistic insight into the biochemical consequences of pH variation (Andersen et al., 2017).

Post-Mortem Aging and Freshness Assessment

The biochemical and structural changes that occur in muscle tissue during post-mortem aging, including proteolytic degradation of myofibrillar proteins, accumulation of biogenic amines, changes in nucleotide catabolism products, and progressive lipid and protein oxidation, collectively determine the evolution of meat tenderness, flavor, and microbial safety over time (Bischof et al., 2024). Both NIR and FTIR have been investigated

as tools for monitoring freshness-related changes during storage, with each offering distinct advantages depending on the specific marker of interest (Sinelli et al., 2010; Alexandrakis et al., 2012). NIR spectroscopy captures broad compositional shifts, including changes in water state, protein-water interactions, and accumulating lipid oxidation products, providing a global freshness index that integrates multiple quality-relevant changes simultaneously (Peyvasteh et al., 2020; Chen et al., 2026). FTIR, with its higher molecular specificity, can resolve individual markers of deterioration more precisely, including the emergence of volatile fatty acid absorptions, changes in protein denaturation state, and the spectral signatures of microbial metabolites accumulating at the meat surface. ATR-FTIR is particularly suited to detecting early-stage spoilage at the surface level, where microbial activity is most pronounced (Ellis et al., 2002), while NIR provides a complementary volumetric assessment of internal quality changes that may lag behind surface deterioration. Machine learning-based classification models integrating NIR spectral data with laboratory reference metrics have further improved the discrimination of fresh versus frozen-thawed meat, offering a dual analytical framework for freshness verification (Mia and Hashem, 2026). To situate these mechanistic and application-level observations within the quantitative literature, Tables 4 and 5 compile representative, non-exhaustive examples of published NIR and FTIR calibration performance for compositional and technological/safety-related meat quality parameters, respectively, reporting the coefficient of determination (R^2), calibration or prediction error, and residual predictive deviation (RPD) as given by the original authors.

Table 4. Representative NIR and FTIR calibration performance for compositional parameters in meat and meat products

Meat/Product	Technique	Parameter	R^2 (or r)	Error (SEP/RMSEP)	RPD	Reference
Beef, minced sausage meat	NIR	Fat / Moisture / Protein	0.98 / 0.98 / 0.93	SEP 1.38 / 1.00 / 0.83 %	—	Dixit et al. (2016)
Beef, homogenised sausage meat	NIR	Fat / Moisture / Protein	0.99 / 0.98 / 0.93	SEP 0.94 / 0.76 / 0.87 %	—	Dixit et al. (2016)
Chicken hamburger	NIR (iSPA-PLS)	Fat content	r = 0.94	RMSEP 1.59 %	3.02	Krepper et al. (2018)
Beef, intramuscular fat	FT-MIR	α-Linolenic acid (18:3 n-3)	0.96 (CV)	—	—	Beriain et al. (2021)
Beef, intramuscular fat	FT-MIR	n-3 PUFA	0.93 (CV)	—	—	Beriain et al. (2021)
Soy-sauce stewed meat	Dual-band NIR	Fat content	$R_P = 0.81$	RMSEP 2.01 g kg^{-1}	1.67	Jiang et al. (2023)
Soy-sauce stewed meat	Dual-band NIR	Protein content	$R_P = 0.86$	RMSEP 3.37 g kg^{-1}	1.86	Jiang et al. (2023)

Note: R^2, coefficient of determination (calibration, cross-validation [CV], or prediction [R_P] as reported by the original authors); SEP, standard error of prediction; RMSEP, root mean square error of prediction; RPD, ratio of standard deviation to prediction error; PUFA, polyunsaturated fatty acids. Values are reproduced as reported in the cited sources; dashes indicate that the statistic was not reported.

Table 5. Representative NIR and FTIR calibration performance for technological and safety-related quality attributes in meat

Meat/Product	Technique	Parameter/Attribute	Reported Performance	Reference
Pork	FT-IR + low-field NMR	Water-holding capacity	r = 0.76 between the extramyofibrillar water (T22) population and WHC	Bertram et al. (2006)
Beef, minced	FTIR (ATR)	Spoilage (total viable count) / pH	$R^2 = 0.80$ (TVC); $R^2 = 0.92$ (pH)	Ammor et al. (2009)
Pork, MAP-packaged	Portable Vis-NIR	Colour (L*, a*, C*, h*) and microbial counts	R^2val > 0.72; RPDval > 2	Arias et al. (2022)
Beef, lamb, pork, chicken	Handheld Vis-NIR / NIR	Halal (pork) speciation	95–100 % correct classification (OCC); 93.4–94.7 % (SVM, Vis-NIR)	Dashti et al. (2021)

Note: WHC, water-holding capacity; ATR, attenuated total reflectance; MAP, modified atmosphere packaging; TVC, total viable count; OCC, one-class classification; SVM, support vector machine.

Meat Safety and Authenticity Assessment

Beyond compositional quality, the application of NIR and FTIR spectroscopy to meat safety and authenticity represents one of the most practically consequential and rapidly expanding domains within the field. The economic incentives for meat fraud, combined with the potential public health consequences of undisclosed species substitution, microbial contamination, and illegal additive use, have created strong regulatory and commercial demand for rapid, reliable, and nondestructive screening tools capable of operating across the meat supply chain. Both NIR and FTIR spectroscopy, by virtue of their sensitivity to the molecular fingerprint of muscle tissue, offer powerful capabilities in this area, with FTIR generally favored for its superior chemical specificity at the molecular level and NIR preferred where speed, portability, and bulk sampling are prioritized. Table 3 summarizes the principal applications and their associated spectral markers.

Table 6. Applications of NIR and FTIR spectroscopy in meat safety and authenticity assessment

Application	Target Marker/Analyte	Spectral Technique and Key Features	Representative Sources
Microbial spoilage monitoring	Total volatile basic nitrogen, biogenic amines, lactic acid	FTIR: N-H bands ~3300 and 1400–1600 cm^{-1}; C-O/C=O bands near 1125/1720 cm^{-1}; ATR surface sensitivity matches spoilage-metabolite accumulation	Bekhit et al., 2021; Uhlig et al., 2024
Species adulteration and economic fraud	Species-specific fatty acid and protein fingerprints	FTIR: lipid fingerprint region 1000–1500 cm^{-1} with LDA/PLS-DA/SVM classification; NIR: bulk compositional and myoglobin-based discrimination	Valand et al., 2020; Mortas et al., 2022
Exogenous adulterant detection	Injected water, phosphate/carrageenan plumping, plant protein fillers	NIR: shifts in 970/1450 nm water-band shape; FTIR: P-O ~1000–1100 cm^{-1}, sulfate ester ~1250 cm^{-1}, Amide I/II shifts	Nunes et al., 2019; Rodriguez-Saona and Allendorf 2011
Veterinary drug/chemical residue screening	Antibiotic classes, e.g., tetracyclines and sulfonamides	FTIR: carbonyl, amine, aromatic and heteroaromatic signatures; micro-ATR for surface-level screening	Mesfin et al., 2024
Halal and kosher authentication	Porcine-derived fat and tissue in certified products	FTIR: lipid fingerprint (oleic/linoleic ratio) with ATR + chemometrics, ~1% detection limit; NIR: rapid screening of intact or processed samples	Dashti et al., 2021; Airin et al., 2025

Microbial Spoilage Monitoring

The microbiological deterioration of meat during refrigerated storage is driven by the progressive proliferation of spoilage-associated bacterial communities on the tissue surface, accompanied by the accumulation of characteristic metabolic byproducts that alter the chemical composition of the meat matrix in measurable ways (Bekhit et al., 2021). Total volatile basic nitrogen, comprising ammonia, trimethylamine, and dimethylamine released through bacterial proteolysis and amino acid catabolism, is among the most widely used chemical indicators of microbial spoilage and correlates well with total viable bacterial counts and sensory rejection thresholds (Uhlig et al., 2024). FTIR spectroscopy is particularly well suited to monitoring these changes, as the N-H stretching and bending absorptions of volatile basic nitrogen compounds contribute detectable features in the 3300 cm^{-1} and 1400 to 1600 cm^{-1} regions of the mid-infrared spectrum. The surface sensitivity of ATR-FTIR sampling makes it ideally matched to the detection of spoilage metabolites that accumulate preferentially at the tissue surface and packaging interface, where bacterial colonization is most active (Ammor et al., 2009; Papadopoulou et al., 2011).

Biogenic amines, including histamine, putrescine, cadaverine, tyramine, and spermidine, formed through the decarboxylation of free amino acids by specific spoilage bacteria, represent both quality markers and food safety concerns, particularly in the context of histamine toxicity in certain species (Spyrelli et al., 2021). Their characteristic N-H and C-N vibrational signatures are detectable by FTIR, and multivariate calibration models built on mid-infrared spectral data have demonstrated the ability to predict biogenic amine concentrations with reasonable accuracy in refrigerated meat and fish samples. Lactic acid, accumulating as a product of facultative anaerobic bacterial metabolism under modified-atmosphere packaging conditions, contributes a distinctive C-O stretching absorption near 1125 cm^{-1} and a carbonyl band near 1720 cm^{-1}, both of which can be monitored by FTIR as indicators of anaerobic spoilage progression. NIR spectroscopy has also been applied to spoilage monitoring, primarily through broad chemometric models trained to detect the cumulative spectral changes associated with bacterial growth and metabolite accumulation, though its lower molecular specificity relative to FTIR means that it generally functions as a screening tool rather than a mechanistically resolved monitoring platform (Spyrelli et al., 2021; Candoğan et al., 2021). Hyperspectral NIR imaging has shown additional promise for spatially mapping the distribution of spoilage-related spectral changes across meat surfaces, enabling the detection of heterogeneous spoilage patterns that point-based measurements would miss (Jin et al., 2023; Chen et al., 2026).

Species Adulteration and Economic Fraud

The substitution or undisclosed blending of low-value meat species into products sold or labeled as higher-value alternatives represents one of the most prevalent and economically significant forms of food fraud globally (Valand et al., 2020). High-profile adulteration incidents involving the inclusion of horsemeat in beef products, pork in halal-certified meat, and poultry in premium minced beef have demonstrated both the scale of the problem and the inadequacy of conventional inspection methods for its detection (Hashem et al., 2024a, 2024b and 2023a; Mortas et al., 2022). NIR and FTIR spectroscopy offer complementary approaches to species authentication, exploiting the subtle but consistent differences in the molecular composition of muscle tissue from different animal species to generate species-specific spectral fingerprints.

FTIR spectroscopy has demonstrated particular utility in species adulteration detection, as the mid-infrared spectrum of meat reflects the precise fatty acid composition, protein secondary structure distribution, and glycogen content of the tissue, all of which vary in characteristic ways between species. (Siddiqui et al., 2021). The lipid fingerprint region between 1000 and 1500 cm^{-1}, encompassing C-H deformation, C-O stretching, and ester-related absorptions, is especially informative for species discrimination, as the fatty acid profiles of different animal species differ in chain length distribution and degree of unsaturation in ways that produce measurable band position and intensity differences (Mortas et al., 2022). ATR-FTIR combined with linear discriminant analysis, partial least squares discriminant analysis, or support vector machine classification has achieved high classification accuracies for binary and multi-species discrimination tasks, including the detection of pork adulteration in beef, poultry adulteration in minced lamb, and horsemeat inclusion in beef products at levels as low as a few percent by mass (Lia et al., 2025).

NIR spectroscopy approaches species authentication from a complementary angle, utilizing the broad compositional differences between species in terms of moisture, fat, and protein content, as well as species-specific differences in myoglobin content reflected in the visible and short-wave NIR region, to construct discriminant models capable of identifying adulterated products (Zuo et al., 2024; St John et al., 2025). The availability of portable and handheld NIR devices makes this approach particularly attractive for rapid screening at points of receipt in processing facilities or at retail, where laboratory-based confirmation methods may not be immediately accessible. Raman spectroscopy has also emerged as a valuable complementary tool in this context, with its sensitivity to lipid unsaturation and protein structural features providing discriminatory information that reinforces NIR and FTIR-based classification (Saleem et al., 2025). NIR spectroscopy coupled with machine learning algorithms has further demonstrated the ability to authenticate fresh and frozen meat across multiple species by referencing physicochemical and bioactive markers (Mia et al., 2025), as well as to discriminate cooked poultry meat of different species such as broiler and duck (Bristy et al., 2025; Khatun et al., 2022).

The challenge of detecting adulteration in processed, heat-treated, or highly comminuted meat products is substantially greater than in fresh meat, as thermal processing denatures proteins, redistributes water, and alters the lipid matrix in ways that reduce species-specific spectral contrast. Addressing this limitation has required the development of spectral libraries encompassing processed meat products and the application of more sophisticated chemometric approaches, including transfer learning and ensemble modeling strategies, capable of generalizing across the wider spectral variability introduced by processing.

Exogenous Adulterant Detection

Beyond species fraud, meat products are subject to a range of adulteration practices involving the addition of exogenous substances intended to increase product weight, improve visual appearance, or reduce production costs while deceiving consumers and evading regulatory inspection. Two categories of exogenous adulteration are of particular concern: illegal water injection through brining or phosphate-based plumping, and the incorporation of non-meat protein fillers such as soy protein isolates, wheat gluten, or other plant-derived proteins (Nunes et al., 2019; Kosek et al., 2019).

Water injection, achieved by infusing meat cuts with saline solutions, phosphate buffers, or carrageenan-based water-retention formulations, artificially inflates the weight of the product while diluting its true nutritional value (Nunes et al., 2016). The spectroscopic detection of this practice relies on the ability to distinguish between naturally bound tissue water and exogenously added free water, a distinction that is accessible through NIR spectroscopy by virtue of the sensitivity of water overtone band shapes and positions to the hydrogen bonding environment. Free water introduced through injection is less tightly bound to protein structures than native tissue water, producing subtle but detectable shifts in the 970 and 1450 nm water overtone features (Li et al., 2020). Additionally, the presence of phosphate salts introduces characteristic P-O stretching absorptions in the FTIR mid-infrared region near 1000 to 1100 cm^{-1}, providing a direct chemical marker of phosphate-based plumping that can be detected by ATR-FTIR even at relatively low concentrations. Carrageenan, used as a gelling agent in some water-retention formulations, contributes distinctive sulfate ester absorptions near 1250 cm^{-1} and glycosidic linkage bands near 1070 cm^{-1} that are readily identifiable in FTIR spectra (Rodriguez-Saona and Allendorf, 2011).

The detection of non-meat protein fillers presents a different spectroscopic challenge, requiring the identification of plant-derived protein signatures against the dominant animal protein background of the meat matrix. Soy protein isolates contain phenylalanine-rich proteins whose spectral contributions differ from those of myofibrillar proteins in the Amide I region, and soy-specific isoflavone absorptions in the 1600 to 1650 cm^{-1} region can serve as chemical markers of soy adulteration detectable by FTIR. Wheat gluten, characterized by its high glutamine and proline content, produces Amide I and Amide II band profiles that differ measurably from those of meat proteins, and its presence at substitution levels above a few percent can be detected through multivariate analysis of ATR-FTIR spectra (Nunes et al., 2019; Candoğan et al., 2021). NIR spectroscopy has also been applied to plant protein filler detection, exploiting differences in the N-H combination band region associated with the distinct amino acid compositions of plant versus animal proteins, as well as carbohydrate-related absorptions introduced by starch fillers that have no counterpart in pure meat spectra (Rady and Adedeji, 2018; Jia et al., 2024a).

Veterinary Drug and Chemical Residue Detection

The presence of veterinary drug residues, including antibiotic compounds, hormonal growth promoters, and anti-inflammatory agents, in meat intended for human consumption represents a significant food safety concern with direct implications for public health and international trade (Mesfin et al., 2024). While chromatographic and immunochemical methods remain the gold standard for residue detection at regulatory action levels, NIR and FTIR spectroscopy have been investigated as complementary screening tools capable of flagging suspect samples for confirmatory analysis. FTIR spectroscopy is particularly relevant in this context, as many veterinary drug classes possess characteristic mid-infrared absorption signatures arising from their carbonyl, amine, aromatic, and heteroaromatic functional groups. Surface-enhanced techniques and micro-ATR approaches have improved the sensitivity of FTIR-based residue detection, enabling the identification of specific antibiotic classes including tetracyclines and sulfonamides in meat extracts and, in some cases, directly on meat surfaces (de Freitas et al., 2021; Lee et al., 2026).

Halal Authentication

Religious dietary compliance represents a globally significant meat authenticity concern, with the halal and kosher meat markets collectively representing hundreds of billions of dollars in annual trade (Hashem et al., 2023b and 2023c; Airin et al., 2025). The spectroscopic verification of halal and kosher status centers primarily on the detection of forbidden species, particularly porcine-derived tissues and fats, in products certified or labeled as compliant. Porcine fat possesses a distinctive fatty acid composition, characterized by relatively high proportions of oleic and linoleic acids compared to ruminant fats, which produces measurable differences in the lipid fingerprint region of FTIR spectra (Mortas et al., 2022). ATR-FTIR combined with chemometric classification has been widely applied to pork lard detection in beef, lamb, and poultry matrices, achieving detection thresholds of approximately 1% by mass in binary fat mixtures, well within the sensitivity range required for regulatory screening purposes (Dashti et al., 2021). NIR spectroscopy offers a complementary rapid screening capability, particularly for intact or minimally prepared samples where ATR contact may be impractical, and has demonstrated useful classification accuracy for halal authentication in processed meat products where the lipid signature remains sufficiently preserved despite thermal treatment (Nurani et al., 2024; Airin et al., 2025).

Methodological Challenges and Limitations

Despite the considerable analytical promise demonstrated by NIR and FTIR spectroscopy in meat quality assessment, safety monitoring, and authenticity verification, their translation from controlled research settings into routine industrial deployment remains constrained by several persistent methodological challenges. The inherent complexity and heterogeneity of meat as an analytical matrix is perhaps the most fundamental of these. Fresh muscle tissue is a structurally anisotropic, biochemically dynamic material whose optical properties vary with fiber orientation, intramuscular fat distribution, myoglobin oxidation state, surface moisture, post-mortem age, and temperature, all of which introduce spectral variability unrelated to the quality parameter of interest. Scatter correction algorithms such as standard normal variate transformation and multiplicative scatter correction can partially address these effects but cannot fully compensate for the extreme sample-to-sample variability encountered in intact whole-muscle cuts (Jia et al., 2024b; Dai et al., 2026).

Water, as the dominant absorbing species in fresh meat, poses an acute challenge for both techniques. In NIR, intense water overtone bands near 970, 1450, and 1940 nm can mask weaker absorptions of protein and fat, reducing calibration sensitivity (Kaur et al., 2025). In FTIR, strong O-H absorptions overlap directly with protein Amide bands in the 1600 to 1700 cm^{-1} region, complicating structural interpretation and requiring careful spectral subtraction procedures (Kassem et al., 2023). Neither technique fully resolves water interference in high-moisture meat matrices without preprocessing, and the trade-off between analytical throughput and correction rigor remains an unresolved practical tension. Calibration model development represents a further critical bottleneck. Robust calibration requires large, diverse sample sets spanning variation across breeds, feeding regimes, slaughter ages, post-mortem handling conditions, and geographic origins, the assembly of which is expensive and logistically demanding. Many published studies rely on narrow sample populations that generalize poorly beyond their specific production context, and overfitting to limited datasets remains a persistent risk insufficiently addressed by cross-validation alone (Biancolillo et al., 2020; Tarapoulouzi et al., 2026; Dai et al., 2026).

Calibration transfer between instruments presents an additional barrier to standardized industrial deployment. Even nominally identical instruments from the same manufacturer can differ sufficiently in detector response, optical alignment, and wavelength accuracy to render a calibration developed on one system inaccurate on another. Transfer algorithms such as piecewise direct standardization can partially compensate for these differences but introduce their own uncertainty, and the challenge is compounded further when transferring models between benchtop and portable platforms (Tarapoulouzi et al., 2026; Dai et al., 2026). Portable NIR and FTIR devices, while offering operational flexibility, typically exhibit lower spectral resolution, reduced signal-to-noise ratios, and narrower wavelength ranges than benchtop systems, compromising predictive accuracy for quality parameters with subtle spectral signatures. Their physical robustness under the temperature, humidity, and contamination conditions of meat processing environments is also not always adequate for sustained routine use (Beć et al., 2022).

For NIR reflectance measurements, probe-to-sample distance, illumination angle, and sample temperature all influence spectral output in ways difficult to control on a production floor. For ATR-FTIR, inconsistent crystal contact pressure and surface contamination from fatty or proteinaceous residues between measurements can significantly degrade spectral quality and model performance (Dixit et al., 2017b; Candoğan et al., 2021). The absence of universally standardized spectral databases and validated reference methods further constrains both cross-laboratory comparison and regulatory acceptance of spectroscopic approaches. Without shared libraries of authenticated meat species, adulterated products, and quality-defect categories, establishing the method equivalence and reproducibility that regulatory bodies require remains difficult. Finally, the interpretability of complex chemometric and machine learning models built on high-dimensional spectral data raises legitimate concerns about scientific rigor and regulatory transparency. Models based on partial least squares or deep learning architectures can deliver impressive predictive performance while providing limited mechanistic justification for their outputs, a deficiency that is particularly consequential in food safety and authenticity contexts where false-negative results carry serious implications. Developing more interpretable model architectures and robust uncertainty quantification frameworks therefore remains an important priority as these techniques advance toward broader regulatory acceptance.

Conclusions and Future Research

NIR and FTIR spectroscopy have collectively established themselves as powerful and complementary analytical tools for the nondestructive assessment of meat quality, safety, and authenticity. NIR spectroscopy delivers rapid, volumetric assessment of bulk compositional parameters including moisture, protein, fat, and water-holding capacity, with versatility spanning laboratory benchtops to portable handheld devices. FTIR complements this with superior molecular specificity at the tissue surface, resolving protein structural changes, lipid oxidation products, microbial metabolite accumulation, and species-specific biochemical fingerprints with a precision that bulk NIR measurements cannot match. Their combined deployment addresses the full analytical range from gross compositional quality to molecular-level authenticity verification, representing a more robust framework for meat quality governance than either technique provides in isolation.

The miniaturization of portable spectroscopic devices will progressively close the performance gap with laboratory-grade systems, enabling reliable quality assessment at every node of the supply chain. Integration with hyperspectral imaging will add spatial resolution to spectral measurements, while artificial intelligence and deep learning approaches offer substantial promise for automating feature extraction and generalizing calibration models across instruments and production environments. The establishment of open-access, curated spectral databases encompassing authenticated meat samples across species, breeds, and processing conditions would represent a transformative advance, enabling cross-laboratory validation and regulatory harmonization. Data fusion strategies combining NIR and FTIR with complementary modalities such as electronic nose arrays and fluorescence spectroscopy offer further potential for capturing complex quality attributes beyond the reach of either technique alone. Ultimately, continued advances in instrumentation, chemometrics, and regulatory frameworks will be essential for transitioning NIR and FTIR spectroscopy from research tools into the backbone of a more transparent and scientifically rigorous global meat quality assurance system.

References

Abbas O, Zadravec M, Baeten V, Mikuš T, Lešić T, Vulić A, Prpić J, Jemeršić L, Pleadin J. 2018. Analytical methods used for the authentication of food of animal origin. Food Chemistry, 246: 6–17. https://doi.org/10.1016/j.foodchem.2017.11.007.

Afara IO, Shaikh R, Nippolainen E, Querido W, Torniainen J, Sarin JK, Kandel S, Pleshko N, Töyräs J. 2021. Characterization of connective tissues using near-infrared spectroscopy and imaging. Nature Protocols, 16(2): 1297–1329. https://doi.org/10.1038/s41596-020-00468-z.

Ahmad RS, Imran A, Hussain MB. 2018. Nutritional composition of meat. In Meat Science and Nutrition. InTech. https://doi.org/10.5772/intechopen.77045.

Airin CM, Budikafa MJ, Erwanto Y, Sudjadi S, Astuti P, Sarmin S, Windarsih A, Rohman A. 2025. Fingerprinting using vibrational spectroscopy and chemometrics for determining the presence of non-halal meats in food products. Applied Food Research, 5(1), 100982. https://doi.org/10.1016/j.afres.2025.100982.

Alcalà M, Blanco M, Menezes JC, Felizardo PM, Garrido A, Pérez D, Zamora E, Pasquini C, Romañach RJ. 2012. Near-infrared spectroscopy in laboratory and process analysis. In Encyclopedia of Analytical Chemistry. Wiley. https://doi.org/10.1002/9780470027318.a9361.

Alexandrakis D, Downey G, Scannell AGM. 2012. Rapid non-destructive detection of spoilage of intact chicken breast muscle using near-infrared and Fourier transform mid-infrared spectroscopy and multivariate statistics. Food and Bioprocess Technology, 5(1): 338–347. https://doi.org/10.1007/s11947-009-0298-4.

Al-Kelani M, Buthelezi N. 2024. Advancements in medical research: Exploring Fourier transform infrared (FTIR) spectroscopy for tissue, cell, and hair sample analysis. Skin Research and Technology, 30(6). https://doi.org/10.1111/srt.13733.

Ammor MS, Argyri A, Nychas G-JE. 2009. Rapid monitoring of the spoilage of minced beef stored under conventionally and active packaging conditions using Fourier transform infrared spectroscopy in tandem with chemometrics. Meat Science, 81(3): 507–514. https://doi.org/10.1016/j.meatsci.2008.10.015.

Andersen PV, Veiseth-Kent E, Wold JP. 2017. Analyzing pH-induced changes in a myofibril model system with vibrational and fluorescence spectroscopy. Meat Science, 125: 1–9. https://doi.org/10.1016/j.meatsci.2016.11.005.

Andersen PV, Wold JP, Gjerlaug-Enger E, Veiseth-Kent E. 2018. Predicting post-mortem meat quality in porcine longissimus lumborum using Raman, near infrared and fluorescence spectroscopy. Meat Science, 145: 94–100. https://doi.org/10.1016/j.meatsci.2018.06.016.

Arias E, Sierra V, Prado N, González P, Fiorentini G, Díaz J, Oliván M. 2022. Development of a portable near-infrared spectroscopy tool for detecting freshness of commercial packaged pork. Foods, 11(23), 3808. https://doi.org/10.3390/foods11233808.

Bao Y, Ertbjerg P. 2019. Effects of protein oxidation on the texture and water-holding of meat: A review. Critical Reviews in Food Science and Nutrition, 59(22): 3564–3578. https://doi.org/10.1080/10408398.2018.1498444.

Beć KB, Grabska J, Huck CW. 2022. Miniaturized NIR spectroscopy in food analysis and quality control: Promises, challenges, and perspectives. Foods, 11(10), 1465. https://doi.org/10.3390/foods11101465.

Beć KB, Grabska J, Huck CW. 2020. Near-infrared spectroscopy in bio-applications. Molecules, 25(12), 2948. https://doi.org/10.3390/molecules25122948.

Bekhit AE-DA, Holman BWB, Giteru SG, Hopkins DL. 2021. Total volatile basic nitrogen (TVB-N) and its role in meat spoilage: A review. Trends in Food Science & Technology, 109: 280–302. https://doi.org/10.1016/j.tifs.2021.01.006.

Beriain MJ, Ibañez FC, Beruete E, Gómez I, Beruete M. 2021. Estimation of fatty acids in intramuscular fat of beef by FT-MIR spectroscopy. Foods, 10(1), 155. https://doi.org/10.3390/foods10010155.

Beriain MJ, Lozano M, Echeverría J, Murillo-Arbizu MT, Insausti K, Beruete M. 2022. Tenderness of PGI "Ternera de Navarra" beef samples determined by FTIR-MIR spectroscopy. Foods, 11(21), 3426. https://doi.org/10.3390/foods11213426.

Bertram HC, Kohler A, Böcker U, Ofstad R, Andersen HJ. 2006. Heat-induced changes in myofibrillar protein structures and myowater of two pork qualities. A combined FT-IR spectroscopy and low-field NMR relaxometry study. Journal of Agricultural and Food Chemistry, 54(5): 1740–1746. https://doi.org/10.1021/jf0514726.

Bhandari S, A Devage S, Kumar R, Ramanathan R, Krishnan S. 2025. Electrochemical measurement of freeze-thaw cycle impact on sarcoplasmic oxidation in beef. ACS Measurement Science Au, 5(3): 287–293. https://doi.org/10.1021/acsmeasuresciau.4c00095.

Biancolillo A, Marini F, Ruckebusch C, Vitale R. 2020. Chemometric strategies for spectroscopy-based food authentication. Applied Sciences, 10(18), 6544. https://doi.org/10.3390/app10186544.

Bischof G, Witte F, Terjung N, Heinz V, Juadjur A, Gibis M. 2024. Metabolic, proteomic and microbial changes postmortem and during beef aging. Critical Reviews in Food Science and Nutrition, 64(4): 1076–1109. https://doi.org/10.1080/10408398.2022.2113362.

Bowker B, Hawkins S, Zhuang H. 2014. Measurement of water-holding capacity in raw and freeze-dried broiler breast meat with visible and near-infrared spectroscopy. Poultry Science, 93(7): 1834–1841. https://doi.org/10.3382/ps.2013-03651.

Bristy KK, Ghosh D, Hashem MA. 2025. NIRS and machine learning algorithms as a non-invasive technique to discriminate and classify cooked broiler and duck meat. Applied Food Research, 5(1), 100984. https://doi.org/10.1016/j.afres.2025.100984.

Bureau S, Cozzolino D, Clark CJ. 2019. Contributions of Fourier-transform mid infrared (FT-MIR) spectroscopy to the study of fruit and vegetables: A review. Postharvest Biology and Technology, 148: 1–14. https://doi.org/10.1016/j.postharvbio.2018.10.003.

Candoğan K, Altuntas EG, İğci N. 2021. Authentication and quality assessment of meat products by Fourier-transform infrared (FTIR) spectroscopy. Food Engineering Reviews, 13(1): 66–91. https://doi.org/10.1007/s12393-020-09251-y.

Cebi N, Bekiroglu H, Erarslan A, Rodriguez-Saona L. 2023. Rapid sensing: Hand-held and portable FTIR applications for on-site food quality control from farm to fork. Molecules, 28(9), 3727. https://doi.org/10.3390/molecules28093727.

Chen R, Ning W, Xie X, Bi J, Zhang G, Hou H. 2026. Non-destructive assessment of beef freshness using visible and near-infrared spectroscopy with interpretable machine learning. Foods, 15(4), 728. https://doi.org/10.3390/foods15040728.

Dai L, Luo D, Zhang J, Chen Y, Li C. 2026. Near-infrared spectroscopy in food analysis: Applications, chemometric strategies, and technological advances. Foods, 15(10), 1814. https://doi.org/10.3390/foods15101814.

Dashti A, Müller-Maatsch J, Weesepoel Y, Parastar H, Kobarfard F, Daraei B, AliAbadi MHS, Yazdanpanah H. 2021. The feasibility of two handheld spectrometers for meat speciation combined with chemometric methods and its application for halal certification. Foods, 11(1), 71. https://doi.org/10.3390/foods11010071.

de Freitas AGM, Minho LAC, de Magalhães BEA, dos Santos WNL, Santos LS, de Albuquerque Fernandes SA. 2021. Infrared spectroscopy combined with random forest to determine tylosin residues in powdered milk. Food Chemistry, 365, 130477. https://doi.org/10.1016/j.foodchem.2021.130477.

Dias CSAM, Nunes HP, Melo TMMV, Rosa HJD, Silva CCG, Borba AES. 2021. Application of near infrared reflectance (NIR) spectroscopy to predict the moisture, protein, and fat content of beef for gourmet hamburger preparation. Livestock Science, 254, 104772. https://doi.org/10.1016/j.livsci.2021.104772.

Dias Kasthuri SB, Bhandari S, Devage SA, Avery JA, Kumar R, Ramanathan R, Krishnan S. 2024. Discovery of electrochemical indicators upon sarcoplasmic meat discoloration. Journal of the American Chemical Society, 146(45): 30728–30732. https://doi.org/10.1021/jacs.4c09375.

Dixit Y, Casado-Gavalda MP, Cama-Moncunill R, Cama-Moncunill X, Jacoby F, Cullen PJ, Sullivan C. 2016. Multipoint NIR spectrometry and collimated light for predicting the composition of meat samples with high standoff distances. Journal of Food Engineering, 175: 58–64.

Dixit Y, Casado-Gavalda MP, Cama-Moncunill R, Cama-Moncunill X, Markiewicz-Keszycka M, Cullen PJ, Sullivan C. 2017. Developments and challenges in online NIR spectroscopy for meat processing. Comprehensive Reviews in Food Science and Food Safety, 16(6): 1172–1187. https://doi.org/10.1111/1541-4337.12295.

Dixit Y, Casado-Gavalda MP, Cama-Moncunill R, Cullen PJ, Sullivan C. 2017. Challenges in model development for meat composition using multipoint NIR spectroscopy from at-line to in-line monitoring. Journal of Food Science, 82(7): 1557–1562. https://doi.org/10.1111/1750-3841.13770.

Du S, You SH, Bao J, Gegentu, Jia YS, Cai YM. 2019. Evaluation of the growth performance and meat quality of Mongolian lamb fed grass, hay or pellets of Inner Mongolian native grass. Small Ruminant Research, 181: 34–38. https://doi.org/10.1016/j.smallrumres.2019.10.008.

Ellis DI, Broadhurst D, Kell DB, Rowland JJ, Goodacre R. 2002. Rapid and quantitative detection of the microbial spoilage of meat by Fourier transform infrared spectroscopy and machine learning. Applied and Environmental Microbiology, 68(6): 2822–2828. https://doi.org/10.1128/AEM.68.6.2822-2828.2002.

ElMasry G, Barbin DF, Sun D-W, Allen P. 2012. Meat quality evaluation by hyperspectral imaging technique: An overview. Critical Reviews in Food Science and Nutrition, 52(8): 689–711. https://doi.org/10.1080/10408398.2010.507908.

Feng Y, Wang Y, Beykal B, Xiao Z, Luo Y. 2024. Machine learning supported ground beef freshness monitoring based on near-infrared and paper chromogenic array. Food Frontiers, 5(5): 2199–2210. https://doi.org/10.1002/fft2.438.

Geesink GH, Schreutelkamp FH, Frankhuizen R, Vedder HW, Faber NM, Kranen RW, Gerritzen MA. 2003. Prediction of pork quality attributes from near infrared reflectance spectra. Meat Science, 65(1): 661–668. https://doi.org/10.1016/S0309-1740(02)00269-3.

Geletu US, Usmael MA, Mummed YY, Ibrahim AM. 2021. Quality of cattle meat and its compositional constituents. Veterinary Medicine International, 2021: 1–9. https://doi.org/10.1155/2021/7340495.

Giaretta E, Mordenti A, Palmonari A, Brogna N, Canestrari G, Belloni P, Cavallini D, Mammi L, Cabbri R, Formigoni A. 2019. NIRs calibration models for chemical composition and fatty acid families of raw and freeze-dried beef: A comparison. Journal of Food Composition and Analysis, 83, 103257. https://doi.org/10.1016/j.jfca.2019.103257.

Golovynskyi S, Golovynska I, Roganova O, Golovynskyi A, Qu J, Ohulchanskyy TY. 2023. Hyperspectral imaging of lipids in biological tissues using near-infrared and shortwave infrared transmission mode: A pilot study. Journal of Biophotonics, 16(7). https://doi.org/10.1002/jbio.202300018.

Götz A, Nikzad-Langerodi R, Staedler Y, Bellaire A, Saukel J. 2020. Apparent penetration depth in attenuated total reflection Fourier-transform infrared (ATR-FTIR) spectroscopy of Allium cepa L. epidermis and cuticle. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 224, 117460. https://doi.org/10.1016/j.saa.2019.117460.

Grunert KG, Bredahl L, Brunsø K. 2004. Consumer perception of meat quality and implications for product development in the meat sector-a review. Meat Science, 66(2): 259–272. https://doi.org/10.1016/S0309-1740(03)00130-X.

Hashem MA, Akter R, Ahmmed A, Billah MM, Rahman MM. 2024a. Detection of adulteration of cattle and buffalo meat through NIRS and chemometric analysis. Meat Research, 4: 3, Article 95. https://doi.org/10.55002/mr.4.3.95

Hashem MA, Ambia J, Mia N, Ali MH, Rahman MM, Ali MS. 2024b. Detection of adulteration of goat and sheep meat through NIRS and chemometric analysis. Meat Research, 4: 2, Article 86.

Hashem MA, Islam SM, Tushar ZH, Rahaman MH, Akhter S. 2023a. Can live and dead broiler meat be identified through sensory and physicochemical attributes? Meat Research, 3 (5).

Hashem MA, Rahman MF, Mustari A, Goswami PK, Hasan MM, Rahman MM. 2023b. Predict the quality and safety of chicken sausage through computer vision technology. Meat Research, 3: 1, Article 47.

Hashem MA, Rahman MF, Mustari A, Goswami PK, Hasan MM, Rahman MM. 2023c. Predict the quality and safety of chicken sausage through computer vision technology. Meat Research, 3: 1, Article 47.

Hashem MA, Morshed MM, Khan M, Rahman MM, Al Noman MA, Mustari A, Goswami PK. 2022. Prediction of chicken meatball quality through NIR spectroscopy and multivariate analysis. Meat Research, 2: 5, Article 34.

Hashem MA, Tule SA, Khan M, Rahman MM, Azad MAK, Ali MS. 2021. Prediction of beef quality traits through mini NIR spectrophotometer and multivariate analyses. Meat Research, 1: 1, Article 6.

He W, Zeng Q. 2025. Non-invasive food authentication using vibrational spectroscopy techniques for low-resolution food fingerprinting. Applied Sciences, 15(11), 5948. https://doi.org/10.3390/app15115948.

Herrero AM. 2008. Raman spectroscopy a promising technique for quality assessment of meat and fish: A review. Food Chemistry, 107(4): 1642–1651. https://doi.org/10.1016/j.foodchem.2007.10.014.

Jia W, Ferragina A, Hamill R, Koidis A. 2024. Modelling and numerical methods for identifying low-level adulteration in ground beef using near-infrared hyperspectral imaging (NIR-HSI). Talanta, 276, 126199. https://doi.org/10.1016/j.talanta.2024.126199.

Jia W, Georgouli K, Martinez-Del Rincon J, Koidis A. 2024. Challenges in the use of AI-driven non-destructive spectroscopic tools for rapid food analysis. Foods, 13(6), 846. https://doi.org/10.3390/foods13060846.

Jiang H, Zhou Y, Zhang C, Yuan W, Zhou H. 2023. Evaluation of dual-band near-infrared spectroscopy and chemometric analysis for rapid quantification of multi-quality parameters of soy sauce stewed meat. Foods, 12(15), 2882. https://doi.org/10.3390/foods12152882.

Jin P, Fu Y, Niu R, Zhang Q, Zhang M, Li Z, Zhang X. 2023. Non-destructive detection of the freshness of air-modified mutton based on near-infrared spectroscopy. Foods, 12(14), 2756. https://doi.org/10.3390/foods12142756.

Kassem A, Abbas L, Coutinho O, Opara S, Najaf H, Kasperek D, Pokhrel K, Li X, Tiquia-Arashiro S. 2023. Applications of Fourier transform-infrared spectroscopy in microbial cell biology and environmental microbiology: Advances, challenges, and future perspectives. Frontiers in Microbiology, 14. https://doi.org/10.3389/fmicb.2023.1304081.

Kaur P, Chauhan A, Singh A. 2025. Navigating fishery advancements with Fourier transform infrared spectroscopy (FTIR). Journal of Advances in Biology & Biotechnology, 28(2): 702–723. https://doi.org/10.9734/jabb/2025/v28i22031.

Khatri Y, Huff-Lonergan E. 2023. Effect of postmortem pH on the physical, biochemical, and sensory characteristics of bovine longissimus thoracis at lumborum muscle. Food Science & Nutrition, 11(4): 2002–2011. https://doi.org/10.1002/fsn3.3235.

Khatun MM, Hossain MA, Ali MS, Rahman MM, Azad MAK, Hashem MA. 2022. Formulation of value-added chicken nuggets using carrot and ginger as a source of dietary fiber and natural antioxidant. SAARC J. Agric., 20 (1): 185-196.

Kombolo-Ngah M, Goi A, Santinello M, Rampado N, Atanassova S, Liu J, Faure P, Thoumy L, Neveu A, Andueza D, De Marchi M, Hocquette J-F. 2023. Across countries implementation of handheld near-infrared spectrometer for the on-line prediction of beef marbling in slaughterhouse. Meat Science, 200, 109169. https://doi.org/10.1016/j.meatsci.2023.109169.

Kosek V, Uttl L, Jírů M, Black C, Chevallier O, Tomaniová M, Elliott CT, Hajšlová J. 2019. Ambient mass spectrometry based on REIMS for the rapid detection of adulteration of minced meats by the use of a range of additives. Food Control, 104: 50–56. https://doi.org/10.1016/j.foodcont.2018.10.029.

Krepper G, Romeo F, de Sousa Fernandes DD, Diniz PHGD, de Araújo MCU, Di Nezio MS, Pistonesi MF, Centurión ME. 2018. Determination of fat content in chicken hamburgers using NIR spectroscopy and the successive projections algorithm for interval selection in PLS regression (iSPA-PLS). Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 189: 300–306. https://doi.org/10.1016/j.saa.2017.08.046.

Lambe NR, Clelland N, Draper J, Smith EM, Yates J, Bunger L. 2021. Prediction of intramuscular fat in lamb by visible and near-infrared spectroscopy in an abattoir environment. Meat Science, 171, 108286. https://doi.org/10.1016/j.meatsci.2020.108286.

Lee I, Park SJ, Jung D-H, Kim H-Y. 2026. Non-destructive detection and classification of antibiotic residues in pork using hyperspectral imaging with an attention-guided matrix interference reduction. Food Chemistry, 504, 147907. https://doi.org/10.1016/j.foodchem.2026.147907.

Li H, Li C, Shoaib M, Zhang W, Murugesan A. 2025. Advances in non-thermal processing of meat and monitoring meat protein gels through vibrational spectroscopy. Foods, 14(11), 1929. https://doi.org/10.3390/foods14111929.

Li Y, Liu S, Meng F, Liu D, Zhang Y, Wang W, Zhang J. 2020. Comparative review and the recent progress in detection technologies of meat product adulteration. Comprehensive Reviews in Food Science and Food Safety, 19(4): 2256–2296. https://doi.org/10.1111/1541-4337.12579.

Lia F, Caffari M, Borg M, Attard K. 2025. Authentication of Maltese pork meat unveiling insights through ATR-FTIR and chemometric analysis. Foods, 14(20), 3510. https://doi.org/10.3390/foods14203510.

Li-Chan ECY, Ismail AA, Sedman J, van de Voort FR. 2001. Vibrational spectroscopy of food and food products. In Handbook of Vibrational Spectroscopy. Wiley. https://doi.org/10.1002/0470027320.s6501.

Lozano M, Rodríguez-Ulibarri P, Echeverría JC, Beruete M, Sorolla M, Beriain MJ. 2017. Mid-infrared spectroscopy (MIR) for simultaneous determination of fat and protein content in meat of several animal species. Food Analytical Methods, 10(10): 3462–3470. https://doi.org/10.1007/s12161-017-0879-1.

Lucarini M, Durazzo A, Sánchez del Pulgar J, Gabrielli P, Lombardi-Boccia G. 2018. Determination of fatty acid content in meat and meat products: The FTIR-ATR approach. Food Chemistry, 267: 223–230. https://doi.org/10.1016/j.foodchem.2017.11.042.

Manley M. 2014. Near-infrared spectroscopy and hyperspectral imaging: Non-destructive analysis of biological materials. Chem. Soc. Rev., 43(24): 8200–8214. https://doi.org/10.1039/C4CS00062E.

Mendes E, Duarte N. 2021. Mid-infrared spectroscopy as a valuable tool to tackle food analysis: A literature review on coffee, dairies, honey, olive oil and wine. Foods, 10(2), 477. https://doi.org/10.3390/foods10020477.

Mesfin YM, Mitiku BA, TamratAdmasu H. 2024. Veterinary drug residues in food products of animal origin and their public health consequences: A review. Veterinary Medicine and Science, 10(6). https://doi.org/10.1002/vms3.70049.

Mia N, Hashem MA. 2026. Machine learning versus laboratory metrics: A dual approach to fresh and frozen lamb meat assessment. Journal of Food Composition and Analysis: 108869. https://doi.org/10.1016/j.jfca.2026.108869.

Mia N, Hashem MA, Yang HS, Seo JK. 2025. AI-driven rapid non-destructive authentication of fresh and frozen meat from multiple species using NIR spectroscopy with reference to physicochemical and bioactive markers. Food Control: 111921. https://doi.org/10.1016/j.foodcont.2025.111921.

Mia N, Rahman MM, Hashem MA. 2023. Effect of heat stress on meat quality: A review. Meat Research. 3 (6): Article No. 73.

Miah MR, Mia N, Khan M, Rahman MM, Hashem MA. 2024. Prediction of chemical compositions of crushed maize used in meat animal ration using near infrared spectroscopy and multivariate analysis. Meat Research, 4 (1). Article No. 81. https://doi.org/10.55002/mr.4.1.81
Moloney AP, Picard B, Moran L. 2020. The effect of extended post-mortem ageing on the Warner--Brazlershear force of longissimus thoracis from beef heifers from two sire breeds, slaughtered at 20 or 25 mo of age. Irish Journal of Agricultural and Food Research, 59(1). https://doi.org/10.15212/ijafr-2020-0116.
Mortas M, Awad N, Ayvaz H. 2022. Adulteration detection technologies used for halal/kosher food products: An overview. Discover Food, 2(1), 15. https://doi.org/10.1007/s44187-022-00015-7.
Mostafa MS, Tushar ZH, Hashem MA, Rahman MM. 2025. Role of natural antioxidants on active packaging of meat and meat products: A review. Applied Food Research. 5, 101437, https://doi.org/10.1016/j.afres.2025.101
Naganathan GK, Grimes LM, Subbiah J, Calkins CR, Samal A, Meyer GE. 2008. Visible/near-infrared hyperspectral imaging for beef tenderness prediction. Computers and Electronics in Agriculture, 64(2): 225–233. https://doi.org/10.1016/j.compag.2008.05.020.
Nunes KM, Andrade MVO, Almeida MR, Fantini C, Sena MM. 2019. Raman spectroscopy and discriminant analysis applied to the detection of frauds in bovine meat by the addition of salts and carrageenan. Microchemical Journal, 147: 582–589. https://doi.org/10.1016/j.microc.2019.03.076.
Nunes KM, Andrade MVO, Santos Filho AMP, Lasmar MC, Sena MM. 2016. Detection and characterisation of frauds in bovine meat in natura by non-meat ingredient additions using data fusion of chemical parameters and ATR-FTIR spectroscopy. Food Chemistry, 205: 14–22. https://doi.org/10.1016/j.foodchem.2016.02.158.
Nurani LH, Guntarti A, Lestari D, Wirnawati, Rohman A, Windarsih A. 2024. The application of FTIR spectra coupled with chemometrics for analysis of lard in food products for halal authentication: A mini review. Food Research, 8(3): 73–83. https://doi.org/10.26656/fr.2017.8(3).489.
OECD/FAO. 2019. OECD-FAO agricultural outlook 2019-2028. OECD Publishing. https://doi.org/10.1787/agr_outlook-2019-en.
Papadopoulou O, Panagou EZ, Tassou CC, Nychas G-JE. 2011. Contribution of Fourier transform infrared (FTIR) spectroscopy data on the quantitative determination of minced pork meat spoilage. Food Research International, 44(10): 3264–3271. https://doi.org/10.1016/j.foodres.2011.09.012.
Parker T, Zhang D, Bugallo D, Shevchuk K, Downes M, Valurouthu G, Inman A, Chacon B, Zhang T, Shuck CE, Hu Y-J, Gogotsi Y. 2024. Fourier-transform infrared spectral library of MXenes. Chemistry of Materials, 36(17): 8437–8446. https://doi.org/10.1021/acs.chemmater.4c01536.
Parrini S, Sirtori F, Čandek-Potokar M, Charneca R, Crovetti A, Kušec ID, Sanchez EG, Cebrian MMI, Garcia AH, Karolyi D, Lebret B, Ortiz A, Panella-Riera N, Petig M, Jesus da Costa Pires P, Tejerina D, Razmaite V, Aquilani C, Bozzi R. 2023. Prediction of fatty acid composition in intact and minced fat of European autochthonous pigs breeds by near infrared spectroscopy. Scientific Reports, 13(1), 7874. https://doi.org/10.1038/s41598-023-34996-x.
Pedersen DK, Morel S, Andersen HJ, Balling Engelsen S. 2003. Early prediction of water-holding capacity in meat by multivariate vibrational spectroscopy. Meat Science, 65(1): 581–592. https://doi.org/10.1016/S0309-1740(02)00251-6.
Peyvasteh M, Popov A, Bykov A, Meglinski I. 2020. Meat freshness revealed by visible to near-infrared spectroscopy and principal component analysis. Journal of Physics Communications, 4(9), 095011. https://doi.org/10.1088/2399-6528/abb322.
Phelps KJ, Drouillard JS, Silva MB, Miranda LDF, Ebarb SM, Van Bibber-Krueger CL, O'Quinn TG, Gonzalez JM. 2016. Effect of extended postmortem aging and steak location on myofibrillar protein degradation and Warner-Bratzlershear force of beef M. Semitendinosus steaks1. Journal of Animal Science, 94(1): 412–423. https://doi.org/10.2527/jas.2015-9862.
Piao D, Denzer ML, Mafi G, Ramanathan R. 2022. Daily quantification of myoglobin forms on beef longissimus lumborum steaks over 7 days of display by near-infrared diffuse reflectance spectroscopy. Meat and Muscle Biology, 5(1). https://doi.org/10.22175/mmb.12562.
Pongsetkul J, Siriwong S, Thumanu K, Boonanuntanasarn S, Yongsawatdigul J. 2023. Investigating the effect of various sous-vide cooking conditions on protein structure and texture characteristics of tilapia fillet using synchrotron radiation-based FTIR. Foods, 12(3), 568. https://doi.org/10.3390/foods12030568.
Prevolnik M, Čandek-Potokar M, Škorjanc D, Velikonja-Bolta Š, Škrlep M, Žnidaršic T, Babnik D. 2005. Predicting intramuscular fat content in pork and beef by near infrared spectroscopy. Journal of Near Infrared Spectroscopy, 13(2): 77–85. https://doi.org/10.1255/jnirs.460.
Prieto N, López-Campos Ó, Aalhus JL, Dugan MER, Juárez M, Uttaro B. 2014. Use of near infrared spectroscopy for estimating meat chemical composition, quality traits and fatty acid content from cattle fed sunflower or flaxseed. Meat Science, 98(2): 279–288. https://doi.org/10.1016/j.meatsci.2014.06.005.
Prieto N, Pawluczyk O, Dugan MER, Aalhus JL. 2017. A review of the principles and applications of near-infrared spectroscopy to characterize meat, fat, and meat products. Applied Spectroscopy, 71(7): 1403–1426. https://doi.org/10.1177/0003702817709299.
Qian J, Wang C, Zhuang H, Nasiru MM, Zhang J, Yan W. 2021. Evaluation of meat-quality and myofibrillar protein of chicken drumsticks treated with plasma-activated lactic acid as a novel sanitizer. LWT, 138, 110642. https://doi.org/10.1016/j.lwt.2020.110642.
Qu F, Ren D, He Y, Nie P, Lin L, Cai C, Dong T. 2018. Predicting pork freshness using multi-index statistical information fusion method based on near infrared spectroscopy. Meat Science, 146: 59–67. https://doi.org/10.1016/j.meatsci.2018.07.023.
Rady A, Adedeji A. 2018. Assessing different processed meats for adulterants using visible-near-infrared spectroscopy. Meat Science, 136: 59–67. https://doi.org/10.1016/j.meatsci.2017.10.014.
Rahman U ur, Sahar A, Pasha I, Rahman S ur, Ishaq A. 2018. Assessing the capability of Fourier transform infrared spectroscopy in tandem with chemometric analysis for predicting poultry meat spoilage. PeerJ, 6, e5376. https://doi.org/10.7717/peerj.5376.
Rodriguez-Saona LE, Allendorf ME. 2011. Use of FTIR for rapid authentication and detection of adulteration of food. Annual Review of Food Science and Technology, 2(1): 467–483. https://doi.org/10.1146/annurev-food-022510-133750.
Rohman A, Ghazali MAB, Windarsih A, Irnawati I, Riyanto S, Yusof FM, Mustafa S. 2020. Comprehensive review on application of FTIR spectroscopy coupled with chemometrics for authentication analysis of fats and oils in the food products. Molecules, 25(22), 5485. https://doi.org/10.3390/molecules25225485.
Rong Y, Zareef M, Liu L, Din ZU, Chen Q, Ouyang Q. 2023. Application of portable Vis-NIR spectroscopy for rapid detection of myoglobin in frozen pork. Meat Science, 201, 109170. https://doi.org/10.1016/j.meatsci.2023.109170.
Sadakuzzaman M, Rahman MM, Hashem MA, Ali MS, Alam AMMN. 2024. Synergistic effects of gamma irradiation and butylated hydroxyanisole on the sensory, physicochemical, and microbiological quality of beef. Applied Food Research, 4 (2): 100547.
Sahar A, Allen P, Sweeney T, Cafferky J, Downey G, Cromie A, Hamill R. 2019. Online prediction of physico-chemical quality attributes of beef using visible-near-infrared spectroscopy and chemometrics. Foods, 8(11), 525. https://doi.org/10.3390/foods8110525.
Saleem A, Imtiaz A, Yaqoob S, Awais M, Awan KA, Naveed H, Khalifa I, Ercisli S, Mugabi R, Alotaibi SS, Nayik GA, Qian J-Y, Shen Q. 2025. Integration of non-invasive and conventional systems for quality assessment and authentication of meat stuffs: A review with bibliometric analysis. Food Chemistry: X, 29, 102778. https://doi.org/10.1016/j.fochx.2025.102778.
Sanden KW, Kohler A, Afseth NK, Böcker U, Rønning SB, Liland KH, Pedersen ME. 2019. The use of Fourier-transform infrared spectroscopy to characterize connective tissue components in skeletal muscle of Atlantic cod (Gadusmorhua L.). Journal of Biophotonics, 12(9). https://doi.org/10.1002/jbio.201800436.
Sarker T, Jahan R, Deen RA, Ghosh D, Hashem MA. 2024a. Tenderness, histomorphology of muscle fiber and gene expression in primal cuts of cattle-A review. Meat Research, 4(5). https://doi.org/10.55002/mr.4.5.101.

Sarker T, Deen RA, Ghosh D, Mia N, Rahman MM, Hashem MA. 2024b. AI driven approach and NIRS: A review on meat quality and safety. Meat Research, 4(6), Article 105. https://doi.org/10.55002/mr.4.6.105.

Savoia S, Albera A, Brugiapaglia A, Di Stasio L, Cecchinato A, Bittante G. 2021. Prediction of meat quality traits in the abattoir using portable near-infrared spectrometers: Heritability of predicted traits and genetic correlations with laboratory-measured traits. Journal of Animal Science and Biotechnology, 12(1), 29. https://doi.org/10.1186/s40104-021-00555-5.

Schwaighofer A, Montemurro M, Freitag S, Kristament C, Culzoni MJ, Lendl B. 2018. Beyond Fourier transform infrared spectroscopy: External cavity quantum cascade laser-based mid-infrared transmission spectroscopy of proteins in the amide I and amide II region. Analytical Chemistry, 90(11): 7072–7079. https://doi.org/10.1021/acs.analchem.8b01632.

Severcan F, Akkas SB, Turker S, Yucel R (Eds). 2012. Methodological approaches from experimental to computational analysis in vibrational spectroscopy and microspectroscopy. IOS Press. https://doi.org/10.3233/978-1-61499-059-8-12.

Shohiduzjaman M, Biplob MAKA, Hashem MA, Rahman MM. 2024. Effects of natural and synthetic antioxidant on the quality of beef in short-term preservation. Meat Research, 4: 6. Article No. 107. https://doi.org/10.55002/mr.4.6.107

Siddiqui MA, Khir MHM, Witjaksono G, Ghumman ASM, Junaid M, Magsi SA, Saboor A. 2021. Multivariate analysis coupled with M-SVM classification for lard adulteration detection in meat mixtures of beef, lamb, and chicken using FTIR spectroscopy. Foods, 10(10), 2405. https://doi.org/10.3390/foods10102405.

Sinelli N, Limbo S, Torri L, Di Egidio V, Casiraghi E. 2010. Evaluation of freshness decay of minced beef stored in high-oxygen modified atmosphere packaged at different temperatures using NIR and MIR spectroscopy. Meat Science, 86(3): 748–752. https://doi.org/10.1016/j.meatsci.2010.06.016.

Soji Z. 2021. Effect of the muscle nanostructure changes during post-mortem aging on tenderness of different beef breeds. Animal Bioscience, 34(11): 1849–1858. https://doi.org/10.5713/ajas.20.0488.

Spyrelli ED, Ozcan O, Mohareb F, Panagou EZ, Nychas G-JE. 2021. Spoilage assessment of chicken breast fillets by means of Fourier transform infrared spectroscopy and multispectral image analysis. Current Research in Food Science, 4: 121–131. https://doi.org/10.1016/j.crfs.2021.02.007.

Sristi PR, Das NR, Akhter A, Kaniya NM, Hashem MA. 2025. Relation among meat pH, color and tenderness-A review. Meat Research, 5(3), Article 117. https://doi.org/10.55002/mr.5.3.117.

St John AL, Bulhões AAV de C, Kubota JPYPC, Dorneles SVF, Da Silva VC, Sampaio DWM, De Carvalho GA, Marinho ERL, Sá ED, Mota DCM, Da Silva EAT, Gomes MM, Nardi AP de M, Waterloo M de ML. 2025. Application of spectroscopic techniques (NIR and Raman) in the non-destructive inspection of meat and milk: Advances for the safety and quality of products of animal origin. International Seven Journal of Multidisciplinary, 4(3): 645–651. https://doi.org/10.56238/isevmjv4n3-019.

Stani C, Vaccari L, Mitri E, Birarda G. 2020. FTIR investigation of the secondary structure of type I collagen: new insight into the amide III band. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 229, 118006. https://doi.org/10.1016/j.saa.2019.118006.

Suman SP, Wang Y, Gagaoua M, Kiyimba F, Ramanathan R. 2023. Proteomic approaches to characterize biochemistry of fresh beef color. Journal of Proteomics, 281, 104893. https://doi.org/10.1016/j.jprot.2023.104893.

Taheri-Garavand A, Fatahi S, Omid M, Makino Y. 2019. Meat quality evaluation based on computer vision technique: A review. Meat Science, 156: 183–195. https://doi.org/10.1016/j.meatsci.2019.06.002.

Talari ACS, Martinez MAG, Movasaghi Z, Rehman S, Rehman IU. 2017. Advances in Fourier transform infrared (FTIR) spectroscopy of biological tissues. Applied Spectroscopy Reviews, 52(5): 456–506. https://doi.org/10.1080/05704928.2016.1230863.

Tarapoulouzi M, Jia W, Koidis A. 2026. New developments and future challenges of non-destructive near-infrared spectroscopy sensors in the cheese industry. Sensors, 26(2), 556. https://doi.org/10.3390/s26020556.

Torun MMR, Khan MMH, Rahman MM, Sadakuzzaman M, Hashem MA. 2023. Influence of degree of doneness on the sensory, physiochemical, nutritional, and microbial properties of beef. Meat Research, Vol 3, Issue 5: 1-9, Article 69. https://doi.org/10.55002/mr.3.5.69

Troy DJ, Ojha KS, Kerry JP, Tiwari BK. 2016. Sustainable and consumer-friendly emerging technologies for application within the meat industry: An overview. Meat Science, 120: 2–9. https://doi.org/10.1016/j.meatsci.2016.04.002.

Tushar ZH, Rahman MM, Hashem MA. 2023. Metmyoglobin reducing activity and meat color: A review. Meat Research, 3:5. Article No. 67.

Uhlig E, Bucher M, Strenger M, Kloß S, Schmid M. 2024. Towards reducing food wastage: Analysis of degradation products formed during meat spoilage under different conditions. Foods, 13(17), 2751. https://doi.org/10.3390/foods13172751.

Valand R, Tanna S, Lawson G, Bengtström L. 2020. A review of Fourier transforms infrared (FTIR) spectroscopy used in food adulteration and authenticity investigations. Food Additives & Contaminants: Part A, 37(1): 19–38. https://doi.org/10.1080/19440049.2019.1675909.

Wang B, Stephen JJ, Vashishth D. 2026. Identification of water compartment in bone using ATR-FTIR spectroscopy. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 349, 127360. https://doi.org/10.1016/j.saa.2025.127360.

Weyer LG. 1985. Near-infrared spectroscopy of organic substances. Applied Spectroscopy Reviews, 21(1–2): 1–43. https://doi.org/10.1080/05704928508060427.

Wojnowski W, Majchrzak T, Dymerski T, Gębicki J, Namieśnik J. 2017. Electronic noses: Powerful tools in meat quality assessment. Meat Science, 131: 119–131. https://doi.org/10.1016/j.meatsci.2017.04.240.

Xiong Z, Sun D-W, Pu H, Gao W, Dai Q. 2017. Applications of emerging imaging techniques for meat quality and safety detection and evaluation: A review. Critical Reviews in Food Science and Nutrition, 57(4): 755–768. https://doi.org/10.1080/10408398.2014.954282.

Yamada W, Cherney J, Cherney D, Runge T, Digman M. 2024. Handheld near-infrared spectroscopy for undried forage quality estimation. Sensors, 24(16), 5136. https://doi.org/10.3390/s24165136.

Yang S, Zhang Q, Yang H, Shi H, Dong A, Wang L, Yu S. 2022. Progress in infrared spectroscopy as an efficient tool for predicting protein secondary structure. International Journal of Biological Macromolecules, 206: 175–187. https://doi.org/10.1016/j.ijbiomac.2022.02.104.

Yin T, Yang T, Dong X, Liu B, Qiao Z. 2025. Mid-infrared spectroscopy and its applications in biomedical analysis and imaging. Biochemical and Biophysical Research Communications, 790, 152890. https://doi.org/10.1016/j.bbrc.2025.152890.

Zhang Z, Wang S, Zhang Y. 2023. Non-destructive detection of water content in pork based on NIR spatially resolved spectroscopy. Agriculture, 13(11), 2114. https://doi.org/10.3390/agriculture13112114.

Zheng X, Chen L, Li X, Zhang D. 2023. Non-destructive detection of meat quality based on multiple spectral dimension reduction methods by near-infrared spectroscopy. Foods, 12(2), 300. https://doi.org/10.3390/foods12020300.

Zuo X, Li Y, Chen X, Chen L, Liu C. 2024. Rapid detection of adulteration in minced lamb meat using Vis-NIR reflectance spectroscopy. Processes, 12(10), 2307. https://doi.org/10.3390/pr12102307.