Emerging Technologies for Halal Meat Authentication: From Molecular Markers to On-site Detection

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Abstract

Meat adulteration is an important food-authenticity problem involving the substitution or mixing of undeclared animal species or ingredients. The challenge becomes greater when meat is minced, cooked or processed into products such as sausages, meatballs and nuggets. For halal foods, authentication is particularly important because the identity of the animal and compliance with halal requirements are central to product acceptability. Modern analytical technologies are transforming meat authentication from conventional inspection to molecular, chemical, spectroscopic and data-driven approaches. Polymerase chain reaction (PCR), Fourier-transform infrared spectrometry (FTIR), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-high-resolution mass spectrometry (LC-HRMS), nuclear magnetic resonance (NMR), hyperspectral imaging (HSI), omics approaches, biosensors, lateral flow assays (LFAs), chemometrics and artificial intelligence (AI) can provide information from DNA, proteins, peptides, metabolites, lipids, volatile compounds and spectral fingerprints. The integration of these technologies with portable devices and AI-based analysis could make halal meat authentication faster, more sensitive and increasingly feasible at processing and retail points.

Keywords: Meat adulteration, Halal authentication, meat species identification, PCR, spectroscopy, omics, biosensors, artificial intelligence

1. Introduction

Meat adulteration refers to the addition, substitution or mixing of undeclared animal material with a meat product, often to reduce production costs or misrepresent product identity. Beef may be mixed with pork or another cheaper species, while animal fat or other undeclared ingredients may also enter processed meat products. Such practices affect food quality, economic interests, consumer confidence and, in halal foods, religious requirements (Mortas et al., 2022).

The problem becomes more difficult after mincing, cooking, curing and processing, because the visible characteristics of the original meat may disappear. This has increased the need for analytical methods capable of identifying meat species even when adulteration is difficult to recognize by conventional inspection.

2. Halal and Halal Authentication

Halal refers to what is permissible according to Islamic requirements. For meat, halal status involves the animal species, slaughtering procedure, handling and prevention of contamination with non-halal materials.

Halal authentication is the scientific verification of food identity and composition to determine whether it is consistent with its declared halal status. Analytical methods are particularly useful for detecting undeclared pork and other non-halal animal materials in meat and processed foods, although laboratory testing cannot independently verify every aspect of halal slaughter compliance (Musfiroh et al., 2026).

3. Why is Halal Meat Authentication Needed?

Halal authentication is increasingly important because modern meat products may contain several ingredients and undergo extensive processing before reaching consumers.

The main concerns include:

- Species substitution: beef, mutton or chicken may be mixed with cheaper undeclared meat.
- Pork contamination: pork meat, fat, gelatin or other derivatives may enter products claimed to be halal.
- Processed meat complexity: cooking, curing, mincing and blending can make visual species identification difficult.
- Cross contamination: non-halal materials may enter products during processing or handling.
- Consumer confidence: reliable analytical verification supports halal certification and protects consumers.

A particularly important point is that species identification and halal slaughter authentication are not identical. Analytical methods can provide strong evidence about the animal material present in a product, but laboratory testing alone cannot independently confirm every aspect of slaughter compliance.

4. Why are Advanced Techniques Required?

Traditional visual inspection and labelling are inadequate for highly processed or mixed meat products. A piece of fresh beef may be visually distinguishable from pork, but these differences become difficult to recognise after mincing, heating, curing or incorporation into sausages and other formulated foods.

Modern authentication therefore investigates different types of biological and chemical information, including:

- DNA and species-specific genetic markers
- Proteins and peptides
- Metabolites
- Lipid and fatty acids
- Volatile compounds
- Spectral fingerprints

The selection of a technique depends on the meat matrix, processing conditions, adulterant level and required sensitivity (Yang et al., 2026).

5. Modern Techniques for Meat Authentication

5.1 Polymerase Chain Reaction (PCR)

PCR is one of the most established approaches for species identification because it targets species-specific DNA sequences. Real-time PCR and multiplex PCR can improve quantitative analysis and simultaneous identification of multiple species. PCR-RFLP combines PCR amplification with restriction enzyme digestion to generate species-specific DNA fragment patterns. The resulting fragments are separated by electrophoresis, allowing differentiation of closely related meat species.

PCR has been applied to pork, beef, chicken, sheep and fish-derived materials, including processed meat products. It is particularly valuable when a small amount of undeclared meat must be detected.

Important considerations include:

- DNA extraction and purification
- Species-specific primer selection
- PCR amplification
- Electrophoresis or real-time fluorescence analysis

- Validation using known reference samples

However, severe processing may degrade DNA and reduce detection efficiency (Mortas et al., 2022; Musfiroh et al., 2026).

5.2 FTIR and Molecular Spectroscopy

Fourier-transform infrared spectroscopy (FTIR) provides a chemical fingerprint based on molecular vibrations. It can analyse meat with limited sample preparation and is suitable for rapid screening.

FTIR combined with chemometrics has been used for pork and beef discrimination and for authentication of halal and non-halal meat products.

Common approaches include:

- FTIR-chemometrics
- FTIR-PLS
- Spectral fingerprinting
- Multivariate classification

The method is attractive for routine screening because it is rapid and requires relatively little sample preparation (Mortas et al., 2022; Yang et al., 2026).

5.3 GC-MS and Volatile Profiling

Gas chromatography–mass spectrometry (GC-MS) examines volatile and semi-volatile chemical compounds that can act as characteristic fingerprints of different meats.

GC-MS-based approaches have been applied to mutton, chicken and beef, while GC-MS methods have also been investigated for processed pork-containing foods.

Headspace GC-MS (HS-GC-MS) is particularly useful because volatile compounds can be analysed from the headspace above a sample, reducing direct handling of the meat matrix (Mortas et al., 2022).

These methods generally require:

- Sample pretreatment
- Extraction or headspace preparation
- Chromatographic separation
- Mass spectral identification
- Statistical or chemometric analysis

5.4 HPLC and LC-MS

High-performance liquid chromatography (HPLC) and liquid chromatography–mass spectrometry (LC-MS/MS) provide information on proteins, peptides and other molecular components.

HPLC-based methods have been applied to distinguish horse, pork and beef, while chromatographic approaches can also be combined with multivariate analysis for gelatin and meat authentication.

LC-MS offers greater molecular selectivity and can support the detection of species-specific molecular signatures in complex meat products. However, these methods generally require more extensive sample preparation and specialised instrumentation (Mortas et al., 2022; Musfiroh et al., 2026).

5.5 Omics Approaches

The development of proteomics, metabolomics and lipidomics is expanding meat authentication from single markers to complete molecular profiles.

- **Proteomics**: examines species-specific proteins and peptides.
- **Metabolomics**: detects differences in small-molecule metabolites.
- **Lipidomics**: examines species-related lipid and fatty-acid profiles
- **Integrated omics**: combines several molecular layers for more comprehensive authentication.

These approaches are especially promising for complex and highly processed meat products, where a single marker may not provide sufficient information. Omics technologies can also provide new biomarkers for species identification and authentication, although large reference datasets and rigorous validation are required (Martinez et al., 2025).

5.6 NMR-Based Authentication

Nuclear magnetic resonance (NMR) spectroscopy provides information about the molecular composition of meat without requiring extensive chemical separation.

NMR can investigate:

- Metabolite profiles
- Lipids
- Fatty acids
- Amino acids
- Other small molecules

Differences in molecular composition can be used to discriminate meat species and identify characteristic profiles. NMR is therefore particularly relevant to metabolomic and lipidomic authentication, although instrument cost and data interpretation remain important limitations (Musfiroh et al., 2026; Martínez et al., 2025).

5.7 Hyperspectral Imaging

Hyperspectral imaging (HSI) combines imaging and spectroscopy to obtain both spatial and spectral information from meat samples.

Recent approaches combine HSI with methods such as:

- Independent Component Analysis (ICA)
- Principal Component Analysis (PCA)
- Machine Learning
- Spectral classification

Its non-destructive nature makes HSI promising for screening large numbers of meat samples (Gao et al., 2026).

5.8 Electronic Nose

An electronic nose (E-nose) analyses volatile compounds and generates an aroma pattern that can be used to differentiate food samples.

In meat authentication, E-nose systems can be combined with:

- Principal component analysis (PCA)
- Machine learning
- Pattern recognition

The approach is useful because different meat species can produce characteristic volatile profiles. However, environmental conditions, sample storage and changes in aroma during processing must be carefully controlled (Mortas et al., 2022).

5.9 Biosensors and Lateral Flow Assays

Biosensors offer an important pathway towards simpler and more portable authentication. Depending on their design, they can recognise DNA, proteins, antibodies, antigens or other species-specific markers.

Emerging formats include:

- Antibody-based biosensors
- Aptamer-based sensors
- Electrochemical biosensors
- Colorimetric sensors
- Surface-enhanced Raman spectroscopy (SERS)
- CRISPR-based detection
- Lateral flow assays (LFAs)

LFAs are particularly attractive for halal meat screening because they can provide simple visual results without large laboratory equipment. Such systems may be useful for detecting pork or other undeclared animal materials in meat products (Liu et al., 2025; Han et al., 2025).

5.10 Meat-Related Analytical Approaches Reported in Earlier Studies

Several analytical approaches have already been applied to different meat matrices. The following examples summarise meat-related techniques and their important validation requirements reported in the literature.

Meat/sample analysed	Technique	Important requirements
Chicken, cow, sheep and pig meat	PCR-RFLP	DNA isolation, primer selection and

		electrophoresis
Mutton, chicken and beef	GC-MS-HS	Sample pretreatment, controlled storage and statistical analysis
Horse, pork and beef	HPLC-MS/MS	Mincing/heating, extraction and chromatographic analysis
Ham sausages	FTIR-chemometrics	Sample preparation, FTIR analysis and statistical analysis
Pork and beef	FTIR-PLS	Sample preparation, extraction, FTIR and PLS analysis
Meat products	E-nose-PCA	Controlled sample pretreatment, aroma analysis and statistical analysis

(Usman et al., 2023)

These examples demonstrate that no single analytical method is universally suitable for all meat matrices. Sample preparation, marker selection, analytical performance and statistical validation must be considered according to the product and adulteration problem.

5.11 Chemometrics and Artificial Intelligence

Advanced instruments generate complex datasets that require appropriate statistical interpretation. Chemometrics and artificial intelligence (AI) can convert spectral, chromatographic and molecular information into useful classification models.

Common approaches include:

- Principal component analysis (PCA)
- Partial least squares-discriminant analysis (PLS-DA)
- Support Vector Machines (SVM)
- Machine Learning
- Pattern recognition

These tools can differentiate authentic and adulterated samples, estimate adulteration levels and classify unknown meat samples. The combination of spectroscopy, chemometrics and AI is particularly promising for rapid meat authentication (Polu et al., 2026).

5.12 On-site Authentication

The direction of meat authentication is gradually shifting from centralised laboratory testing towards portable and on-site analysis.

Emerging possibilities include:

- Portable spectroscopy
- Handheld Raman spectroscopy
- Portable biosensors
- Lateral flow assays
- Smartphone-assisted detection
- Miniaturized analytical devices
- AI-assisted interpretation

Such systems could allow preliminary screening at slaughterhouses, processing plants, certification centres, markets and retail outlets. Suspicious samples could then be transferred to laboratories for confirmatory testing (Han et al., 2025).

6. Challenges and Future Prospects

Despite technological advances, complex processing, low-level adulteration and matrix effects can affect analytical accuracy. Standardised methods, validated reference materials and reliable datasets are needed, particularly for AI and omics-based approaches. High costs and specialised expertise remain limitations for techniques such as LC-MS and NMR. Regulatory validation is also essential, while species identification alone cannot confirm all aspects of halal slaughter and handling (El-tahlawy & Alahmad, 2025).

7. Conclusion

Modern technologies are transforming halal meat authentication from conventional inspection to molecular, spectroscopic, omics and data-driven approaches. Combining rapid screening with advanced laboratory confirmation can improve the detection of meat adulteration and support more reliable halal verification. Portable biosensors, on-site devices and AI-assisted analysis may further enable faster authentication at processing and retail levels. Continued validation and standardization will be essential for their wider application.

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