Non-Destructive Freshness Evaluation in Red Meat and Poultry: Advances in Intelligent Sensing Technologies

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Abstract

Freshness is a critical quality and safety attribute of red meat and poultry because deterioration is associated with microbial growth, biochemical reactions, lipid oxidation, protein degradation, colour changes, and the formation of volatile compounds. Conventional freshness evaluation methods generally require sample destruction, laboratory analysis, and considerable processing time. In recent years, non-destructive technologies have emerged as promising alternatives for rapid and real-time assessment of meat freshness. Hyperspectral imaging, visible–near-infrared spectroscopy, electronic nose systems, computer vision, electrical impedance spectroscopy, magnetic resonance techniques, and gas sensors can provide information about chemical, physical, and biological changes without destroying the product. Integrating these technologies with machine learning and artificial intelligence has further improved freshness classification and spoilage prediction. This review discusses recent advances in non-destructive freshness evaluation of red meat and poultry, their operating principles, applications, advantages, limitations, and potential for industrial implementation. Particular attention is given to the integration of sensing technologies with artificial intelligence, Internet of Things (IoT) systems, and real-time monitoring platforms.

Keywords: Red meat, poultry, freshness, non-destructive evaluation, hyperspectral imaging, NIR spectroscopy, electronic nose, gas sensors, machine learning, IoT.

1. Introduction

Red meat and poultry are highly perishable foods because of their high moisture content, nutrient availability, and susceptibility to microbial and biochemical deterioration. During storage, meat undergoes several changes involving microbial growth, protein degradation, lipid oxidation, pigment oxidation, moisture redistribution, and formation of volatile compounds. These processes can alter important quality attributes such as colour, odour, texture, pH, water-holding capacity, and freshness. Therefore, rapid and reliable freshness evaluation is essential for ensuring food safety, reducing food waste, and maintaining consumer confidence (Chen et al., 2024).

Traditional freshness evaluation includes microbiological testing, chemical analysis, and sensory assessment. Total viable count, pH, total volatile basic nitrogen (TVB-N), Thio barbituric acid reactive substances (TBARS), colour, texture, and sensory characteristics are frequently used as indicators of meat quality. However, these approaches commonly require sampling, laboratory analysis, trained personnel, and in many cases destruction of the tested product. These limitations make them difficult to apply for rapid, continuous, and real-time monitoring (Wu et al., 2022; Chen et al., 2024).

Non-destructive detection technologies have therefore emerged as promising alternatives. These technologies can obtain information about meat quality using optical, electromagnetic, electrical, or volatile-compound responses while preserving the product. Recent reviews identify spectroscopy, hyperspectral imaging, machine vision, electronic noses, and other sensor-based systems as important technologies for non-destructive meat-quality evaluation (Wu et al., 2022).

2. Freshness Changes in Red Meat and Poultry

During storage, microbial, chemical, and physical changes occur simultaneously.

Major freshness indicators include:

Indicator	Change during deterioration	Possible detection technology
Microbial load	Increase in microorganisms	HSI, spectroscopy, biosensors
pH	Changes due to biochemical reactions	HSI, NIR, EIS
TVB-N	Increase in volatile nitrogen compounds	HSI, NIR, gas sensors
TBARS	Increase due to lipid oxidation	HSI, spectroscopy
Colour	Browning/discoloration	Computer vision, HSI
Odour	Development of spoilage odours	Electronic nose
Texture	Softening/toughening	Imaging, spectroscopy
Moisture	Redistribution/loss	NIR, HSI
VOCs	Increase during microbial spoilage	E-nose, gas sensors

Chen et al. (2024) identified microbial growth and spoilage-related metabolites as important targets for emerging real-time and non-destructive meat monitoring technologies.

3. Conventional Methods and Their Limitations

Conventional meat freshness evaluation can be divided into three major categories:

3.1 Microbiological methods

Microbiological analysis determines the number and type of microorganisms present in meat. Total viable count is commonly used to assess microbial deterioration.

Advantages:

- Reliable reference method
- Direct information about microbial population
- Important for food-safety evaluation

Limitations:

- Destructive sampling
- Laboratory-dependent
- Time-consuming
- Requires trained personnel

3.2 Chemical methods

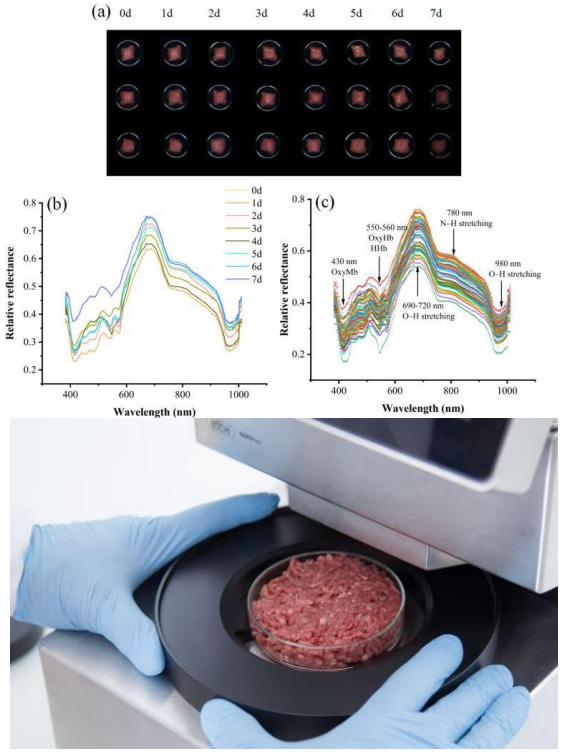
Chemical methods include pH, TVB-N, TBARS, and other biochemical measurements.

These methods provide valuable information about the biochemical condition of meat but generally require sample preparation and laboratory analysis.

3.3 Sensory evaluation

Colour, odour, appearance, and texture are evaluated by trained panelists. Although sensory evaluation is important, it can be subjective and cannot provide continuous quantitative monitoring. Wu et al. (2022) concluded that non-destructive detection can provide faster and non-invasive alternatives while still requiring conventional methods as important reference measurements.

4. Non-Destructive Technologies for Meat Freshness Evaluation



4.1 Hyperspectral Imaging

Hyperspectral imaging (HSI) combines conventional imaging with spectroscopy. Instead of recording only RGB information, HSI records spectral information at multiple wavelengths for individual pixels. A typical HSI system consists of:

Light source → Meat sample → Hyperspectral camera → Spectral data → Image processing → Machine learning → Freshness prediction

HSI can provide both spatial and spectral information and has been investigated for monitoring microbial growth, TVB-N, TBARS, pH, colour, texture, and other meat-quality indicators.

A recent 2026 review specifically focused on HSI for spoilage detection in meat and poultry and reported its potential for non-destructive and real-time freshness evaluation. The review also highlighted the use of PCA, PLS-DA, CNN, LSTM and other machine-learning approaches.

Advantages

- Non-destructive
- Provides spatial + chemical information
- Can evaluate several quality parameters
- Suitable for automated inspection **Limitations**
- High equipment cost
- Large datasets
- Complex data processing
- Lighting and temperature effects
- Need for industrial-scale validation

5. Visible–Near-Infrared Spectroscopy

Visible–near-infrared spectroscopy measures the interaction of electromagnetic radiation with meat. Changes in absorption characteristics can be related to chemical composition and physical properties.

Vis-NIR/NIR spectroscopy has been investigated for evaluating:

- Moisture
- Fat
- Protein
- pH
- Colour
- Freshness
- Meat classification

A 2025 review by León-Ecay et al. reported that Vis-NIR and HSI have demonstrated high classification performance in laboratory studies, with many studies reporting overall accuracies above 90%. However, the authors also identified the need for further development before widespread real-time industrial implementation.

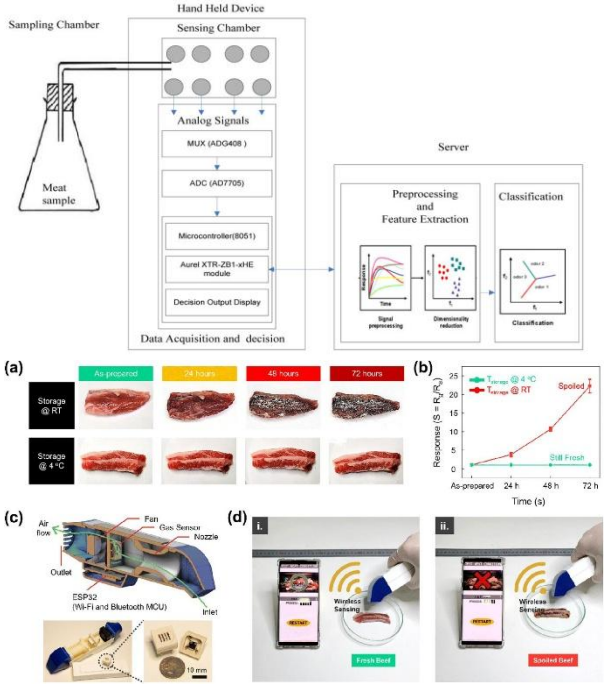
Advantages

- Rapid
- Non-destructive
- Minimal sample preparation
- Potential for portable instruments

Limitations

- Requires calibration
- Sensitive to temperature and sample composition
- Large spectral datasets
- Industrial validation remains limited

6. Electronic Nose Technology



The electronic nose (E-nose) is an array of gas sensors designed to detect patterns of volatile organic compounds (VOCs). During meat spoilage, microorganisms and biochemical reactions produce compounds such as:

Ammonia + amines + sulfur compounds + aldehydes + ketones → characteristic spoilage odour

The E-nose measures the overall volatile profile rather than relying on a single compound. Chen et al. (2024) identified electronic noses and other portable sensing systems as promising approaches for rapid and real-time meat-spoilage monitoring.

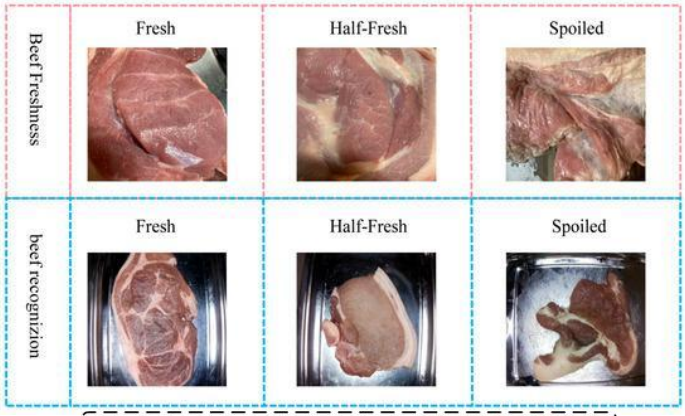
Advantages

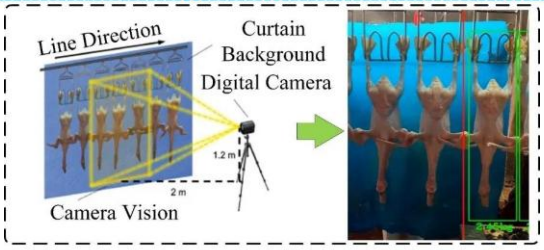
- Rapid
- Non-destructive
- Can be portable
- Suitable for continuous monitoring

Limitations

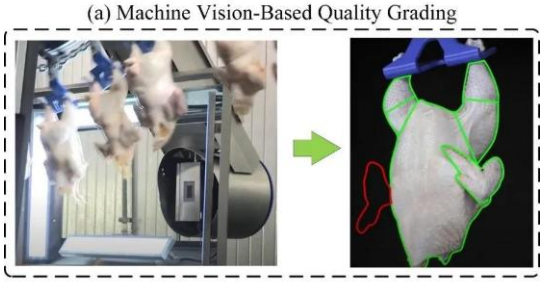
- Sensor drift
- Cross-sensitivity
- Temperature and humidity effects
- Requires pattern-recognition algorithms

7. Computer Vision and Machine Vision

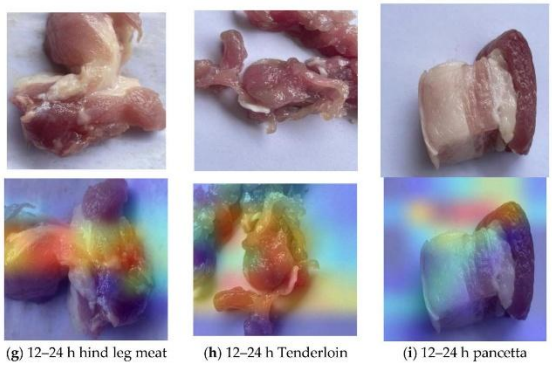




(a) Machine Vision-Based Quality Grading



(b) Machine Vision-Based Quality Inspection



(g) 12–24 h hind leg meat (h) 12–24 h Tenderloin (i) 12–24 h pancetta

Computer vision uses digital cameras to evaluate visible characteristics of meat.

Important image features include:

- Colour
- Texture
- Shape
- Surface defects

- Discoloration
- Marbling

Image-processing algorithms can extract these features, after which machine-learning models classify samples according to freshness level.

Example workflow

Camera → Image acquisition → pre-processing → Feature extraction → ML model → Freshness classification

Computer vision is relatively inexpensive compared with hyperspectral imaging and can potentially be integrated into processing lines. However, it mainly provides surface information and may not detect internal spoilage at an early stage.

8. Electrical Impedance Spectroscopy

Electrical impedance spectroscopy (EIS) measures changes in the electrical properties of meat over a range of frequencies.

Microbial growth, cell damage, changes in ionic concentration, moisture redistribution, and structural changes can alter electrical impedance. Therefore:

Storage deterioration → Cellular/chemical changes → Electrical-property changes → Impedance response →Freshness prediction

EIS has potential as a compact and relatively low-cost non-destructive sensing technique, although electrode configuration, temperature, moisture and sample geometry can affect the measurements.

9. Gas Sensors and Biosensors

Gas sensors can detect volatile compounds generated during meat deterioration.

Important target compounds may include:

- NH_3
- Amines
- H_2S
- VOCs
- Aldehydes
- Ketones

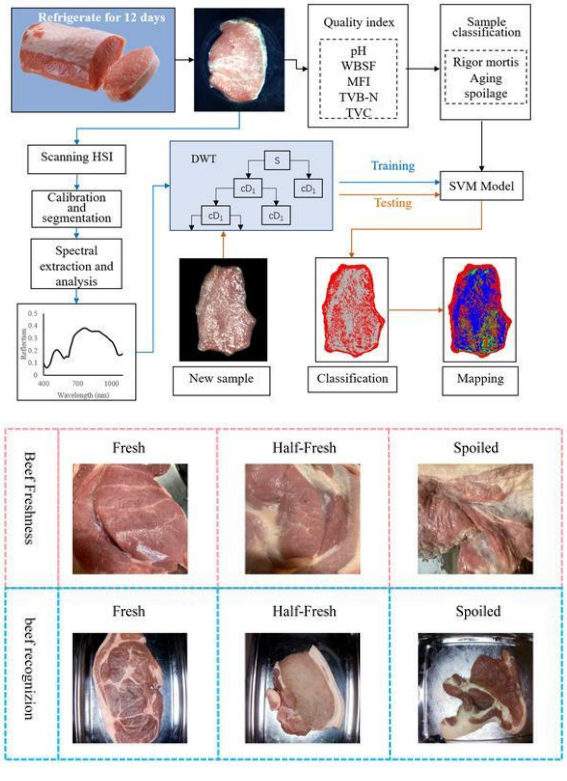
A multi-sensor array can produce a characteristic gas fingerprint corresponding to different freshness levels. Recent research is increasingly focused on combining sensor materials, biosensing systems, wireless communication and intelligent data analysis for meat-spoilage monitoring. Chen et al. (2024) highlighted the movement toward portable, low-cost and real-time sensing systems.

10. Comparison of Non-Destructive Technologies

Technology	Main information	Destructive?	Real-time potential	Main limitation
HSI	Spectral + spatial	No	High	Cost/data processing
NIR	Chemical composition	No	High	Calibration
E-nose	VOC pattern	No	High	Sensor drift
Computer vision	Colour/appearance	No	High	Mainly surface information
EIS	Electrical properties	No	High	Electrode effects
Gas sensors	Spoilage gases	No	Very high	Cross-sensitivity
Thermal imaging	Temperature distribution	No	High	Environmental effects
NMR/MRI	Internal structure/water	No	Moderate	Very high cost

A broad review by Wu et al. (2022) categorized non-destructive meat evaluation into spectroscopy, imaging, machine vision, and electronic-nose technologies and emphasized the potential of integrating multiple technologies for comprehensive assessment.

11. Machine Learning and Artificial Intelligence



Non-destructive sensors generate complex datasets that require advanced data-processing techniques.

A typical AI-based system can be represented as:

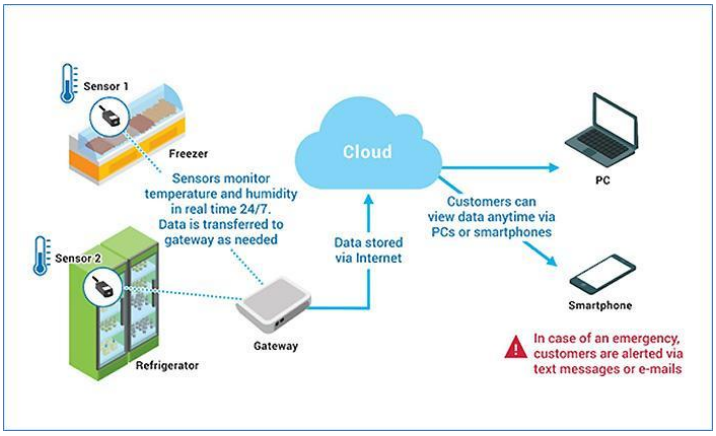
Sensor/Image acquisition
↓
Data preprocessing
↓
Feature extraction
↓
Machine-learning model
↓
Freshness prediction
↓
Fresh / Acceptable / Spoiled

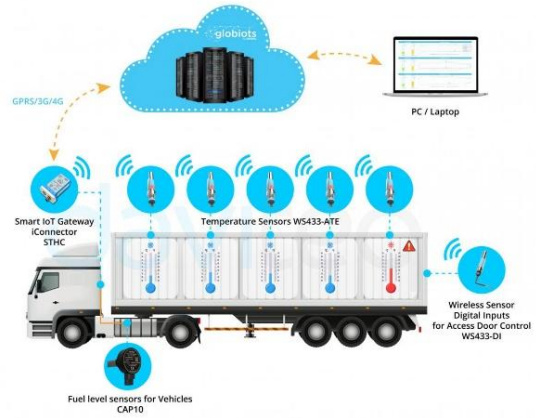
Common algorithms include:

- PCA
- PLSR
- PLS-DA
- SVM
- Random Forest
- Artificial Neural Networks
- CNN
- LSTM

The 2026 HSI review specifically highlights PCA, PLS-DA, CNN, LSTM and other advanced models for meat and poultry spoilage prediction.

12. IoT-Based Real-Time Freshness Monitoring





The combination of non-destructive sensors and IoT can provide continuous monitoring throughout the cold chain.

Proposed system

Meat/Poultry
↓
Non-destructive sensors

- Temperature
- RH
- Gas/VOCs
- HSI/NIR
- E-nose

↓
ESP32 / Microcontroller
↓
Wireless communication
↓
Cloud database
↓
Machine-learning model
↓
Mobile/Web dashboard
↓
Freshness status + early spoilage warning

This approach can potentially provide continuous information during processing, storage, transportation and retail. Chen et al. (2024) emphasized the importance of portable, online/in-line and real-time systems for future meat-spoilage monitoring.

13. Conclusion

Non-destructive freshness evaluation has considerable potential to transform the monitoring of red meat and poultry. Technologies including hyperspectral imaging, Vis-NIR spectroscopy, electronic noses, computer vision, electrical impedance spectroscopy and gas sensors can provide rapid information without destroying the product. Among these technologies, HSI and spectroscopy offer rich spectral information, while E-nose and gas sensors provide information related to volatile spoilage compounds. Computer vision provides a relatively economical method for evaluating visible quality changes.

The integration of these technologies with machine learning, deep learning and IoT can enable automated and real-time freshness monitoring. However, challenges associated with cost, calibration, sensor drift, data standardization, model robustness and industrial validation must be addressed before widespread commercial implementation. Future research should therefore focus on low-cost multimodal sensors, portable devices, explainable AI,

IoT connectivity, standardized datasets and real-world validation.

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