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# Advances in non destructive methods of meat quality assessment and safety monitoring: A review

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**Abstract**
Due to the increasing consumer's concern about the composition, quality and safety of food products, legislation to employ mandatory inspection of all food products have been introduced. There are few parameters being considered by every consumers while purchasing a food item which include- appearance, price, taste, freshness and nutritional and safety status. Keeping in mind the consumer's safety, each nation has developed their own standards during import and export giving proper quality assurance. Traditional method of using various instruments and chemicals are a choice for quality evaluation. However, these methods have few disadvantages i.e. they are labour intensive, time-consuming, expensive, destructive, involves drudgery and also have environmental impact due to production of chemical waste. Also, these methods might unable to capture the entire sensory attributes of the inspected food. Viewing the importance of quality assurance, several food industries have been looking forward for improved process monitoring system. This has led to the development of several fast, non-destructive and reliable techniques-e-nose, computer vision technology, spectroscopy techniques and imaging techniques, which are presently gaining popularity in the meat industry. This paper reviews some of the advanced quality detection techniques along with their applications in various quality analysis in the production line of meat industry.

**Keywords:** Non-destructive, spectroscopy, e-nose, computer vision, meat quality, safety

## Introduction

Meat is an important component of a healthy, well-balanced diet since it contains vitamins, minerals, and essential amino acids than comparable foods, making it an ideal source of protein. The total meat production in India is estimated to be 10.25 million tonnes [11]. With the increasing pattern of urbanization, changing food habits and increasing exposure to variety of food cuisines, people are shifting towards non-vegetarian diet, especially making meat as a regular protein-based item in the food menu. Alongside the continuous improvement in the consumption level, change in consumption concept and with the development of economy, people are also searching for a good quality meat in a way to compensate with the harmful effects of a long-term stored, deteriorative and damaged meat items. Meat is one of the highly perishable food items and the quality of meat may be influenced by various factors like as its raising environment, slaughter timing, and storage temperature [50] Exposer to light, dust, and microbes can deteriorate the quality and appearance of meat at any point in the food supply chain, from storage to transportation to retail. When purchasing meat, consumers prioritise its quality and price. Some consumers are even prepared to pay an extra amount to ensure the quality of the meat. Some of the quality factors that are considered when assessing the quality of meat include sensory, nutritive, hygienic, toxicological, and technological properties. Producers and consumers both have to consider the quality of meat regarding its freshness. Traditionally, there are two ways to access the meat quality which includes subjective method and the objective method. Subjective sensory evaluation methods are included under the subjective method and chemical or the instrumentation tests falls under objective method. Sensory evaluation utilises human sensory perception to assess the characteristics of food products, conducted by trained panellists or semi-trained consumers who offer feedback on appearance, flavour, aroma, texture, and overall acceptability. Instrumental analysis employs scientific instruments and techniques to assess the chemical composition, physical characteristics, and structural attributes of meat. Laboratory tests that evaluate the physical and chemical characteristics of meat, as well as identify what microorganisms are present, have long served as objective methods of assessment [39]. However, instrumental analysis may not accurately interpret the sensory perception of food. Along with that the use of these conventional assessment methods might have some disadvantages i.e. they are labour intensive, time-consuming, expensive, destructive, involves drudgery and also have environmental impact due to production of chemical waste. Techniques for assessing the quality of meat have been developed and widely utilised in recent years. The application of modern analytical techniques could enhance the meat sector by facilitating non-destructive, non-invasive, simple and real-time processes.

Non-destructive testing (NDT) involves the detection and characterization of defects on the exterior or inside the objects without breaking the substance apart or physically modifying it. The non-destructive detection technique (NDDT) is a rapidly developing field that draws from a variety of disciplines, including computer science, physics, electronics, and artificial intelligence (AI). For meat quality inspection, NDDT is a promising technique because of its accuracy, speed, real-time performance, and non-destructive detection [71]. Currently, the demand for the non-destructive techniques that are applied for the real-time monitoring and detection of meat quality have been increasing and they include-electronic nose (e-nose), Computer Vision (CV) system, Spectroscopy techniques and imaging techniques.

**Electronic nose (E-nose)**

Electronic nose (E-nose) is an artificial and intelligent electronic device that mimics the functions of the human olfactory sensory system [9,76] with its array of sensors. This instrument is useful for evaluating the food aroma, identify volatile compounds, deterioration degree evaluation and is also capable of analysing simple or complex gases, vapors, or odors qualitatively and/or quantitatively [37]. A complex mixture of volatile organic compounds that originate from a variety of reactions gives meat its distinct odor. The characteristic aroma of meat originates either originates from thermal processes or during spoilage of meat. It works through detection, monitoring, and analysis of volatile organic compounds (VOCs) released from the product of interest due to microbial activities. This device has the ability to characterize and differentiate the aroma profiles of various food, including meat and meat products. E-nose has typically three major working systems: Sample delivery system, Detection system, and Computing system. The sample delivery system enables the generation of headspace of sample or volatile compounds which is a fraction to be analyzed. The system then sends this head space into the detection system of the electronic nose. The detection system includes a group of sensors to sense and react to the compounds, and the response is recorded by an electronic interface. The sensors record a specific response whenever they detect a smell, and that signal is converted into a digital value. To generate a result, the computing system combines the responses from every sensor. A database of qualified samples makes it possible to analyze these results. By comparing them to the samples in the database, new samples can be identified. E-nose has been used by many scholars to judge the meat freshness, its quality and its shelf life by detecting any change in meat odour which are mentioned in Table 1. Some commonly used sensors of e-nose are Metal oxide semiconductor (MOSFET), Metal Oxide sensors (MOS), Piezoelectric sensors, Quartz Crystal Microbalance, Conducting Polymers, etc. E-noses have been used extensively in food analysis in recent years and have proved themselves to be a fast, simple, affordable, and non-destructive way to evaluate and control the quality of food. Among all these, the most widely used one is the MOS with the following most common sensing materials-tin dioxides, zinc oxides, iron oxides, titanium di oxide, nickel oxide, cobalt oxide [64].

**Table 1:** Summary of Applications of Electronic Nose in meat industry

| Samples | Applications | References |
|---|---|---|
| Poultry meat | Poultry meat samples (fresh and after refrigeration) were analysed for the presence of volatile compounds | [14] |
| Poultry | Use of e-nose in modified atmosphere packaged poultry meat for the quality evaluation | [51] |
| Pork | Evaluation of meat freshness by using KAMINA e-nose | [46] |
| Pork, Mutton | Use of electronic nose of metal oxide sensors to determine the adulteration of pork in minced mutton | [65] |
| Beef | Monitoring the beef quality by a developed mobile electronic nose | [69] |
| Pork, beef and mutton | Detection and prediction of the freshness of three kinds of meat i.e. pork, beef and mutton | [18] |
| Pork | Employment of a metal-oxide based gas sensor array of commercially available chemoresistive sensors, functioning as an electronic nose, to differentiate between various categories of 100 pig meat samples collected at a slaughterhouse based on their odor characteristics, including a urine-like smell and post-mortem aging | [59] |

**Computer Vision (CV) System**

Computer vision system, also known as machine vision system, visual image system, or just image system is a branch of Artificial Intelligence (AI) which collects information from images by utilizing certain image sensors and thereby the images are analysed by converting the image information into digital information by application of computer technology. This technology works by recognizing the object, identifying it, tracking it's movements and detecting the object. The advantages of using this technology over human skills is it's speed, fairness, continuity, accuracy and scalability. The core components for proper functioning of a computer vision system include-cameras to capture high-resolution images or videos of the objects or scenes being inspected, proper lighting facilities, processors which runs the image processing algorithms that analyze the captured images and a software to translates the visual data into actionable information. The working steps involved in a computer vision system are-1) Image Acquisition which involves the use of high-resolution cameras and proper lighting to ensure that the images are clear and detailed; 2) Image Processing which means once the images are being captured, they are processed using sophisticated software algorithms which then analyzes the images to extract relevant information, such as shapes, colors, sizes, and defects that may damage the final product; 3) Decision making which helps to take a real-time decision by rejecting any kind of item from the production line if found to be defective; 4) Actions such as sorting items, rejecting defective products, or guiding robotic arms are used to carry out specific tasks. Applications for this technology include industrial automation and image processing, document analysis, robotics, radar imaging, medical image analysis, and the food industry [60]. Many researchers have conducted quality check test using this technology in the meat industry, few are being mentioned in Table 2.

**Table 2:** Summary of Applications of Machine Vision Technology in meat industry

| Samples | Applications | References |
|---|---|---|
| Pork | Pores and porosity in pork ham and their correlations with processing time, water content and texture were evaluated using automatic machines | [25] |
| Beef | Intramuscular fat in lean cattle was measured using machine vision technology with accuracy and precision | [1] |
| Pork | Prediction of percentage of intramuscular fat in pork (IMF%) | [44] |
| Pork | Application of online computer vision system and artificial intelligence model for predicting the pork loin quality | [63] |
| Pork | Different pork cuts were identified using machine vision technology | [33] |

## Spectroscopy Techniques

Spectroscopy is a method for determining the qualities of a substance utilizing light interaction and spectral acquisition employing reflectance, absorbance, and transmittance at relevant wavelengths [4]. Depending on the light's wavelength, spectrum can be divided successively from small to large as-Gamma rays, X-rays, ultraviolet light, visible light, infrared light, microwaves, and radio waves. Spectroscopy techniques are capable of analysing both the qualitative and quantitative parameters of meat and meat products. The basic principle of spectroscopy is that when electromagnetic radiation waves strike the meat samples or meat products, some of the energy from the waves is absorbed by the chemical molecules in the material and used to vibrate, while some is transmitted and some is reflected.

Near-Infrared Spectroscopy (NIR Spectroscopy), Fourier Transform Infrared (FTIR) Spectroscopy, Raman Spectroscopy and Terahertz (THz) Spectroscopy are some of the Spectroscopy techniques which are known to be applied in the meat industry.

## Near-Infrared Spectroscopy (NIR Spectroscopy)

Near-infrared spectroscopy is one of the non-destructive methods developed to support product testing more quickly and efficiently which is able to measure the absorption of electromagnetic radiation including wavelengths from 750 to 2500nm. A light source, beam splitter system (wavelength selector), sample detector, optical detector, and data processing system are the main constituents of an NIR spectrometer. To light the sample and acquire a spectrum, the light source can emit in the near-infrared spectrum, which is generally between 700 and 2500 nm. Many light sources are available, among which Quartz-Tungsten-Halogen (QTH) lamps are the most commonly used [42]. QTH lamps stands for its high intensity radiation and cost-effectiveness. However, the QTH lamps can create various problems in industrial application due to their low energy efficiency, heat generation, temperature sensitivity, vibration sensitivity, and long start-up times. In contrast, light emitting diodes (LED) have recently emerged in the NIR field as they address several of the problems with QTH light sources. However, due to the costliness of LED, they have not been widely adopted in NIR spectrometers [17]. The sample interacts with NIR radiation during spectra collection, and the energy may be absorbed, transmitted, or reflected. Within the NIR spectrometer, sample detectors vary in terms of their spectral response, response speed, and minimum threshold for detectable radiant power. NIR spectrometers typically use single and multi-channel photon detectors. Lead sulfide (PbS, 1100-2500 nm), indium gallium arsenide (InGaAs, 800-1700 nm or extended range up to 2500 nm), and silicon detectors (400-1100 nm) are examples of lead salt semi-conductors used in single-channel detectors. Diode arrays or charge-coupled devices (CCDs) are used in multi-channel detectors [13]. Applying this technology during analysis of meat has been on focus recently. This technology was used in the determination of meat quality attributes such as-pH, Color L*, a*, b* and Warner-Bratzler shear force [8]. Similarly, [49] determined the carcass fat quality attributes: Iodine value, SFA(%), MUFA(%), PUFA(%), Omega-3(%) and Omega-6(%) and [48] applied a handheld NIR combined with machine learning to assess the chicken meat quality.

## Fourier Transform Infrared (FTIR) Spectroscopy

Fourier-transform infrared (FTIR) spectroscopy has emerged as a useful analytical method for studying the structural and functional change as it is quick, non-destructive, economical, and sensitive in terms of physicochemical fingerprinting. FTIR is unlike the conventional IR spectroscopy in that this particular technique is based on the use of interferometry making use of the complete source spectrum. A beamsplitter is used in an interferometer to split the radiation from the source into two parts, which are then reflected to a moving mirror and a fixed mirror, respectively. They recombine at the beamsplitter after both the beams undergo constructive and destructive interference. A detector is utilized to measure the intensity fluctuations produced by the interference effect and hence the spectral information related to the sample is produced in the form of an interferogram. A fourier transformation is used in order to interpret the information by converting the digital interferogram to a conventional IR emittance spectrum [67]. Advantages of using this technique is : improvement in the signal-to-noise ratio, higher energy throughput, superior wavelength resolution (0.003-0.006 $cm^{-1}$) and superior wavelength accuracy [67]. FTIR has been successfully applied in the quality analysis of different meat samples since it can analyse the proximate composition, adulteration with various contaminants or other meat samples in meat as well as minced meat products, summary of it's utilization has been mentioned in Table 3.

**Table 3:** Summary of Applications of Fourier Transform Infrared Spectroscopy in meat industry

| Samples | Applications | References |
|---|---|---|
| Beef | Rapid monitoring of beef spoilage by determining the biochemical changes using Fourier Transform Infrared Spectroscopy | [5] |
| Pork, Beef | Use of Fourier transform infrared (FTIR) spectroscopy and partial least square (PLS) calibration to detect and quantify pork in beef meatball | [54] |
| Lard | Detecting the presence of pork fat (lard) in meatball broth | [41] |
| Chicken | Determination of the spoilage microorganism on the surface of chicken breast fillets that were kept aerobically at 5 °C for 0, 1, 2, 3, 5 and 8 days, and at 15 °C for 0, 0.5, 1, 2, 3 and 5 days | [55] |
| Chicken | Demonstration of the competence of Fourier transform infrared spectroscopy (FTIR) to detect spoilage in chicken fillets stored under aerobic refrigerated conditions | [66] |
| Beef, Chicken | Determination of meat quality | [2] |

## Raman Spectroscopy

The technique, Raman spectroscopy was given by an Indian Physicist Sir C.V Raman, which is based on inelastic scattering of monochromatic light with the sample. The scattering of Raman Spectroscopy depends on the "Raman effect" [15]. The term "Raman effect" means the inelastic process of light scattering between the incident light and a substance under irradiation, which then results in shifted energy frequencies [15]. Every molecule has a distinct Raman spectrum signal which is created using the results of frequency shift, which provides the information about the vibrational modes involved. Therefore, once the unique molecular information in the samples has been extracted, it is possible to effectively carry out the qualitative evaluation of the material structure. Light and molecules from a sample collide and scatter inelastically to produce unique Raman spectrum signals. A monochromatic laser beam helps attain the illumination of the sample [15]. A unique structural fingerprint has been provided by this technique whereby the structural, qualitative, and quantitative analyses of the molecules and compounds may be analysed in the samples . Qualitative and quantitative analysis of the samples can be done by measuring the frequency of the scattered radiation and intensity of the scattered radiation respectively [61, 70]. Raman spectroscopy is an effective and non-invasive method which have received much attention recently in the meat industry in terms of obtaining the in situ information about the composition and structure of meat proteins and lipid or any kind of changes in meat proteins and lipids occurring during storage [31]. Raman spectroscopy do not need any sample preparation, providing detailed spectral information about the chemical composition of the sample with causing any sample destruction. Chemometrics have often been used along with Raman Spectroscopy to analyze any kind of meat sample. Raman Spectroscopy applied in meat industry has been mentioned in Table 4.

**Table 4:** Summary of Applications of Raman Spectroscopy in meat industry

| Samples | Applications | References |
|---|---|---|
| Beef | Utilization of Raman spectroscopy for evaluating the beef tenderness | [12] |
| Pork | pH prediction using Raman spectroscopy and metaheuristics as a measure of the quality of pork | [47] |
| Pork | Prediction of fresh pork tenderness and slice shear force (SSF) by using Raman Spectroscopy. | [56] |
| Chicken | Use of Surface-enhanced Raman spectroscopy (SERS) technology and the two-dimensional correlation spectroscopy (2D-COS) to optimize the characteristic variables of the Enrofloxacin in chicken meat. | [38] |
| Beef | Determining Warner-Bratzler shear force, intramuscular fat, drip-loss and cook-loss with the help of Raman Spectroscopy | [16] |
| Beef, Venision and lamb | Rapid discrimination of intact beef, venison and lamb meat. | [52] |
| Pork, Beef | Detection and quantification of pork adulteration in beef meatballs with Raman spectroscopy and near infrared spectroscopy | [35] |

## Terahertz (THz) Spectroscopy

Terahertz Spectroscopy is a type of non-destructive analytical method belonging to the far-infrared band which able to provide both the qualitative and quantitative properties of a food sample. The terahertz region, which spans frequencies between about 0.1 and 10 THz, is where the areas of electronics and photonics in the electromagnetic spectrum converge [28]. A typical terahertz system is composed of a detector, components, and a source. A broad spectrum of terahertz radiation is produced by a terahertz source. The components of a terahertz system includes lenses, mirrors, and polarizers that manipulate the radiation. The radiation reaching it is being measured by a detector [29]. The characteristics of both microwave and infrared are present in THz Spectroscopy, which are also able to penetrate and interact with many commonly used materials. able to provide both the qualitative and quantitative properties of a food sample. Previous studies suggests application of this technique in food industries such as the detection of moisture, foreign bodies or any harmful compounds, antibiotics, microorganisms, inspection, quality control and it has been a great tool for characterization of carbohydrates, amino acids, fatty acids, and vitamins [3]. It is also able to provide valuable information about the interior and intermolecular structure of a product [36] and hence been used in analysis of quality of meat and its products. With the help of this technique, the freshness of pork meat and the process of deterioration and differentiate between preserved and bad pork meat was monitored [34, 43, 68] determined the effectiveness of THz spectroscopic imaging for foreign material detection among sausages. [73] analyzed the spectrum of different kinds of samples, including fresh tissues (fat, skin and lean meat) and freeze-dried meats (different varieties: fish, chicken, beef; different brands: Pin-de-xian pig, Mao-feng pig, Yi-hao-tu pig).

### Imaging Techniques
Imaging techniques are image-based systems that have the advantage of being non-invasive and can monitor products and processes quickly and affordably. Image analysis-based approaches have drawn special attention in the context of quick, non-destructive, and reliable methods. These techniques have the ability to spatially characterise heterogeneous samples. Imaging techniques such as the Hyperspectral Imaging (HIS) technique, Thermal imaging, X-Ray Imaging are frequently being used in the food industry particularly the meat industry due to their ability to determine both the internal and external parameters of the sample, hence providing a proper overview of the quality of the sample analysed.

### Hyperspectral Imaging Technique (HSI Technique)
Hyperspectral imaging technique, which has been developed basically by combination of two techniques i.e. spectroscopy and imaging techniques has emerged as a powerful non-destructive technique for various quantitative applications in the food industry. It is the simultaneous acquisition of spatial images in many spectrally contiguous wavebands measured for every spatial position of a specific sample [57]. A corresponding spectrum exists for every pixel represented in an image. A camera, a spectrograph, a detector, an illuminator, and a translation stage are typically connected to a computer to form an HSI system. Three imaging configurations—whiskbroom imaging (point scan), push-broom imaging (line scan), and staredown imaging (wavelength scan)—are available for producing a hyperspectral image from a sample [30]. The basic working principle of this technique is that when light interacts with a food sample, several phenomena occur simultaneously. The light energy can be reflected, absorbed, scattered, or emitted, depending on the sample's physical and chemical properties in distinctive patterns at specific wavelengths. Hyperspectral imaging technique measures these interactions, particularly the reflected light, which contains spectral signature or spectral fingerprint or simply the spectrum which is unique to specific biochemical components [26]. A significant amount of information can be provided by this technique in three-dimensional hypercubes [40]. Hyperspectral imaging technique has gained a lot of recognition in ensuring the quality and safety in the meat industry. This technique can be efficiently applied in predicting both the internal attributes (tenderness and chemical composition) and external attributes (e.g. size, intramuscular fat, color); determining microbial spoilage; detecting faeces and parasites [26]. A more thorough description of the distribution and concentration of ingredients in any type of heterogeneous sample is made possible by hyperspectral imaging [30]. Spectral measurements at the entire surface area of the product can be provided by HIS technique while conventional spectrometers only give point measurements [27]. In meat industry, this technique has been used in various applications which is summarized in Table 5.

**Table 5:** Summary of Applications of Hyperspectral Imaging Technique in meat industry

| Samples | Applications | References |
|---|---|---|
| Pork | Use of near-infrared hyperspectral imaging to determine the chemical composition in intact and minced pork | [10] |
| Beef | Visualization and determination of the intramuscular fat in beef samples using hyperspectral imaging technique | [45] |
| Pork | Degree of protein oxidation of frozen-thawed pork were detected and visualised using fluorescence hyperspectral imaging | [20] |
| Pork | Evaluation of lipid oxidation in pork through hyperspectral imaging combined with three-dimensional convolutional neural network | [21] |
| Mutton | Investigating the feasibility of using hyperspectral imaging (HSI) for evaluating lamb meat freshness | [74] |

### Thermal Imaging (TI)
TI or infrared (IR) thermography is a two-dimensional, non-contact emerging approach for measuring the outside temperature of materials and thereby providing real-time visualisations of temperature variations which can be usefully employed in non-destructive quality evaluation of food items including meat and its products within a short period of time. It enables identification of those objects whose exterior temperature is distinguishable from that of background objects and can analyze patterns of temperature change. This technique produces images by recognizing and capturing different levels of infrared light which is being emitted by the objects and can be felt as heat. With the help of this technique, the unnoticeable radiation pattern of an object can be detected which then is converted into visible images for attribute extraction and analysis. The basic principle behind this imaging technique is that there is production of heat by the incoming infrared radiation which then raises the temperature and that temperature variation is being measured by any temperature-dependent mechanism, such as thermoelectric voltage, resistance or pyroelectric voltage [53]. Major components for functioning of thermal imaging includes: camera, an optical system (e.g. focusing lens, collimating lenses, filters), detector array (e.g. microbolometers), signal processing, image processing system. [23] were able to evaluate whether the surface temperature differences were related to meat and ham quality. The effectiveness of ohmic thawing (OT) on temperature distribution (TD) was evaluated in minced beef by using this technique [24]. By using this technique, the classification and quantification of minced mutton and its adulteration with pork was done by detected the adulteration in minced beef by the help of this technique.

### X-Ray Imaging
Computed tomography (CT) is a type of electromagnetic radiation with wavelengths ranging from 0.01 to 10 nm. It is currently one of the most widely used X-ray imaging methods. Conveying belt, stepping motor, image-acquisition card, computer, computer-controlled X-ray generator (also known as an X-ray source tube), and line-scanning sensor for X-ray detection (also known as an X-ray CCD camera that can produce an enlarged radiograph (projection)) are the key components of an X-ray imaging system [19This

technique's basic idea is that when an X-ray passes through a sample, it flows through it in a variety of directions and via various pathways, producing a series of 2D radiographs or projection images that show variations in density at various points in a 2D slice [7]. It is frequently used to evaluate the safety and quality of food, and it offers a lot of opportunities to do research on the composition and structure of meat. has applied this technique in detecting the meat and fat quality of pork and beef. The quality of mutton was measured by the application of small angle X-ray scattering synchrotron technology, by using X-ray imaging has successfully inactivated the foodborne pathogens in ready-to-eat sliced ham.

## Conclusion

Non-destructive methods have proven to be highly promising alternative to the conventional methods in the meat industry. These non-destructive techniques enables evaluation of meat quality by determining its freshness, tenderness, by analysing the sensory properties of meat such as appearance, flavour, aroma, texture, and overall acceptance and determining the microbial load in meat without altering the meat sample. The non-destructive methods when combined with chemometrics and computer based alogrithms can provide rapid and precise results suitable for application in the meat industry. However, challenging part of using these methods are the use of highly sophisticated equipments. Future advancements in non-destructive techniques must focus on minimizing the cost and enhancement of portable devices to enable on-site and in-line applications.

## References

1. Aass L, Fristedt CG, Gresham JD. Ultrasound prediction of intramuscular fat content in lean cattle. Livest Sci. 2009 Nov;125(2-3):177-186.
2. Abd Rashid AN, Kormin F, Asman S. Quality analysis of meats using FTIR Spectroscopy, Colour Spectrophotometer, Texture Analyser and physical image analysis. J Sustain Sci Manag. 2020 Jan 31;16(1):103-119.
3. Afsah-Hejri L, Hajeb P, Ara P, Ehsani RJ. A comprehensive review on food applications of terahertz spectroscopy and imaging. Compr Rev Food Sci Food Saf. 2019 Sep;18(5):1563-1621.
4. Alander JT, Bochko V, Martinkauppi B, Saranwong S, Mantere T. A Review of Optical Nondestructive Visual and Near-Infrared Methods for Food Quality and Safety. Int J Spectrosc. 2013 Mar 24;2013:1-36.
5. Ammor MS, Argyri A, Nychas GJE. 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 Sci. 2009 Mar;81(3):507-514.
6. Bahmani L, Minaei S, Banakar A, Mahdavian A, Soltani Firouz M. Thermography and deep learning for detection of ground beef adulteration. Microchem J. 2024 Oct;205:111174.
7. Baker DR, Mancini L, Polacci M, Higgins MD, Gualda GAR, Hill RJ, *et al.* An introduction to the application of X-ray microtomography to the three-dimensional study of igneous rocks. Lithos. 2012 Sep;148:262-276.
8. Balage JM, da Luz e Silva S, Gomide CA, Bonin M de N, Figueira AC. Predicting pork quality using Vis/NIR spectroscopy. Meat Sci. 2015 Oct;108:37-43.
9. Balasubramanian S, Amamcharla J, Shin JE. Possible Application of Electronic Nose Systems for Meat Safety: An Overview. In: Electronic Noses and Tongues in Food Science [Internet]. Elsevier; 2016 [cited 2025 Oct 23]. p. 59-71. Available from: https://doi.org/10.1016/b978-0-12-800243-8.00007-x
10. Barbin DF, ElMasry G, Sun DW, Allen P. Non-destructive determination of chemical composition in intact and minced pork using near-infrared hyperspectral imaging. Food Chem. 2013 Jun;138(2-3):1162-1171.
11. Basic Animal Husbandry Statistics (BAHS)-2024.
12. Bauer A, Scheier R, Eberle T, Schmidt H. Assessment of tenderness of aged bovine gluteus medius muscles using Raman spectroscopy. Meat Sci. 2016 May;115:27-33.
13. Berzaghi P, Riovanto R. Near infrared spectroscopy in animal science production: principles and applications. Ital J Anim Sci. 2009 Jan 1;8(sup3):39-62.
14. Boothe DDH, Arnold JW. Electronic nose analysis of volatile compounds from poultry meat samples, fresh and after refrigerated storage. J Sci Food Agric. 2002 Jan 15;82(3):315-322.
15. Bumbrah GS, Sharma RM. Raman spectroscopy-Basic principle, instrumentation and selected applications for the characterization of drugs of abuse. Egypt J Forensic Sci. 2016 Sep;6(3):209-215.
16. Cama-Moncunill R, Cafferky J, Augier C, Sweeney T, Allen P, Ferragina A, *et al.* Prediction of Warner-Bratzler shear force, intramuscular fat, drip-loss and cook-loss in beef via Raman spectroscopy and chemometrics. Meat Sci. 2020 Sep;167:108157.
17. Cen H, He Y. Theory and application of near infrared reflectance spectroscopy in determination of food quality. Trends Food Sci Technol. 2007 Feb;18(2):72-83.
18. Chen J, Gu J, Zhang R, Mao Y, Tian S. Freshness Evaluation of Three Kinds of Meats Based on the Electronic Nose. Sensors (Basel). 2019 Jan 31;19(3):605.
19. Chen Q, Zhang C, Zhao J, Ouyang Q. Recent advances in emerging imaging techniques for non-destructive detection of food quality and safety. TrAC Trends Anal Chem. 2013 Dec;52:261-274.
20. Cheng J, Sun J, Xu M, Zhou X. Non-destructive detection of lipid oxidation in frozen pork using hyperspectral imaging technology. J Food Compos Anal. 2023 Oct;123:105497.
21. Cheng J, Sun J, Yao K, Dai C. Generalized and hetero two-dimensional correlation analysis of hyperspectral imaging combined with three-dimensional convolutional neural network for evaluating lipid oxidation in pork. Food Control. 2023 Nov;153:109940.
22. Cho GL, Ha JW. Application of X-ray for inactivation of foodborne pathogens in ready-to-eat sliced ham and mechanism of the bactericidal action. Food Control. 2019 Feb;96:343-350.
23. Costa N, Stelletta C, Cannizzo C, Gianesella M, Lo Fiego P, Morgante M. The use of thermography on the slaughter-line for the assessment of pork and raw ham quality. Ital J Anim Sci. 2007 Jan;6(sup1):704-706.

24. Döner D, Çokgezme ÖF, Çevik M, Engin M, İçier F. Thermal Image Processing Technique for Determination of Temperature Distributions of Minced Beef Thawed by Ohmic and Conventional Methods. Food Bioprocess Technol. 2020 Sep 23;13(11):1878-1892.
25. Du CJ, Sun DW. Automatic measurement of pores and porosity in pork ham and their correlations with processing time, water content and texture. Meat Sci. 2006 Feb;72(2):294-302.
26. Elmasry G, Barbin DF, Sun DW, Allen P. Meat Quality Evaluation by Hyperspectral Imaging Technique: An Overview. Crit Rev Food Sci Nutr. 2012 Aug;52(8):689-711.
27. ElMasry G, Sun DW. Principles of Hyperspectral Imaging Technology. In: Hyperspectral Imaging for Food Quality Analysis and Control [Internet]. Elsevier; 2010 [cited 2025 Oct 23]. p. 3-43. Available from: https://doi.org/10.1016/b978-0-12-374753-2.10001-2
28. Garbacz P. Terahertz imaging-principles, techniques, benefits, and limitations. Probl Eksploatacji. 2016(1):81-92.
29. Ghann W, Uddin J. Terahertz (THz) Spectroscopy: A Cutting-Edge Technology. In: Terahertz Spectroscopy-A Cutting Edge Technology [Internet]. InTech; 2017 [cited 2025 Oct 23]. Available from: https://doi.org/10.5772/67031
30. Gowen AA, O'Donnell CP, Taghizadeh M, Gaston E, O'Gorman A, Cullen PJ, *et al.* Hyperspectral imaging for the investigation of quality deterioration in sliced mushrooms (*Agaricus bisporus*) during storage. Sensing Instrum Food Qual Saf. 2008 Mar 14;2(3):133-143.
31. Herrero AM. Raman spectroscopy a promising technique for quality assessment of meat and fish: A review. Food Chem. 2008 Apr;107(4):1642-1651.
32. Hoban JM, Hopkins DL, Kirby N, Collins D, Dunshea FR, Kerr MG, *et al.* Application of small angle X-ray scattering synchrotron technology for measuring ovine meat quality. Meat Sci. 2016 Jul;117:122-129.
33. Huang H, Zhan W, Du Z, Hong S, Dong T, She J, *et al.* Pork primal cuts recognition method via computer vision. Meat Sci. 2022 Oct;192:108898.
34. Huang XB, Hou DB, Huang PJ, Ma YH, Li X, Zhang GX. The meat freshness detection based on terahertz wave. In: SPIE Proceedings [Internet]. SPIE; 2015 [cited 2025 Oct 23]. p. 97953D. Available from: https://doi.org/10.1117/12.2211973
35. Iqbal Z, Afseth NK, Postelmans A, Wold JP, Andersen PV, Kusnadi J, *et al.* Detection and quantification of pork adulteration in beef meatballs with Raman spectroscopy and near infrared spectroscopy. Spectrochim Acta Part A Mol Biomol Spectrosc. 2025 Sep;337:126069.
36. Jepsen PU, Cooke DG, Koch M. Terahertz spectroscopy and imaging-Modern techniques and applications [Laser Photon. Rev. 5, No. 124-166 (2011)]. Laser Photonics Rev. 2012 May 2;6(3):418-418.
37. Jia W, Liang G, Wang Y, Wang J. Electronic Noses as a Powerful Tool for Assessing Meat Quality: a Mini Review. Food Anal Methods. 2018 May 5;11(10):2916-2924.
38. Jing-jing BA, Gui-shan LI, Jian-guo HE, Li-juan CH, Nai-yun FA, Rui-rui YU. Detection of Enrofloxacin residues in chicken based on surface enhanced Raman spectroscopy and two-dimensional correlation spectroscopy. Food Mach. 2020;36(7):55-58.
39. Kamruzzaman M, Makino Y, Oshita S. Non-invasive analytical technology for the detection of contamination, adulteration, and authenticity of meat, poultry, and fish: A review. Anal Chim Acta. 2015 Jan;853:19-29.
40. Khaled AY, Parrish CA, Adedeji A. Emerging nondestructive approaches for meat quality and safety evaluation—A review. Compr Rev Food Sci Food Saf. 2021 Jun 20;20(4):3438-3463.
41. Kurniawati E, Rohman A, Triyana K. Analysis of lard in meatball broth using Fourier transform infrared spectroscopy and chemometrics. Meat Sci. 2014 Jan;96(1):94-98.
42. Lee H, Cho S, Lim J, Lee A, Kim G, Song D-J, *et al.* Performance comparison of tungsten-halogen light and phosphor-converted nir led in soluble solid content estimation of apple. Sensors (Basel). 2023;23(4):1961.
43. Liang Q, Maocheng Z, Jie Z, Yuweiyi T. Preliminary investigation of Terahertz spectroscopy to predict pork freshness non-destructively. Food Sci Technol. 2019 Dec;39(suppl 2):563-570.
44. Liu JH, Sun X, Young JM, Bachmeier LA, Newman DJ. Predicting pork loin intramuscular fat using computer vision system. Meat Sci. 2018 Sep;143:18-23.
45. Lohumi S, Lee S, Lee H, Kim MS, Lee WH, Cho BK. Application of hyperspectral imaging for characterization of intramuscular fat distribution in beef. Infrared Phys Technol. 2016 Jan;74:1-10.
46. Musatov VYu, Sysoev VV, Sommer M, Kiselev I. Assessment of meat freshness with metal oxide sensor microarray electronic nose: A practical approach. Sens Actuators B Chem. 2010 Jan 29;144(1):99-103.
47. Nache M, Hinrichs J, Scheier R, Schmidt H, Hitzmann B. Prediction of the pH as indicator of porcine meat quality using Raman spectroscopy and metaheuristics. Chemom Intell Lab Syst. 2016 May;154:45-51.
48. Parastar H, van Kollenburg G, Weesepoel Y, van den Doel A, Buydens L, Jansen J. Integration of handheld NIR and machine learning to "Measure & Monitor" chicken meat authenticity. Food Control. 2020 Jun 1;112:107149.
49. Prieto N, Dugan ME, Juárez M, López-Campos Ó, Zijlstra RT, Aalhus JL. Using portable near-infrared spectroscopy to predict pig subcutaneous fat composition and iodine value. Can J Anim Sci. 2017 Oct 5;98(2):221-229.
50. Prieto N, Roehe R, Lavín P, Batten G, Andrés S. Application of near infrared reflectance spectroscopy to predict meat and meat products quality: A review. Meat Sci. 2009 Oct;83(2):175-186.
51. Rajamäki T, Alakomi HL, Ritvanen T, Skyttä E, Smolander M, Ahvenainen R. Application of an electronic nose for quality assessment of modified atmosphere packaged poultry meat. Food Control. 2006 Jan;17(1):5-13.
52. Robert C, Fraser-Miller SJ, Jessep WT, Bain WE, Hicks TM, Ward JF, *et al.* Rapid discrimination of intact beef, venison and lamb meat using Raman spectroscopy. Food Chem. 2021 May;343:128441.

53. Rogalski A. Infrared detectors: status and trends. Prog Quantum Electron. 2003 Jan;27(2-3):59-210.
54. Rohman A, Sismindari, Erwanto Y, Che Man YB. Analysis of pork adulteration in beef meatball using Fourier transform infrared (FTIR) spectroscopy. Meat Sci. 2011 May;88(1):91-95.
55. Sahar A, Dufour É. Use of Fourier transform-infrared spectroscopy to predict spoilage bacteria on aerobically stored chicken breast fillets. LWT Food Sci Technol. 2014 May;56(2):315-320.
56. Santos CC, Zhao J, Dong X, Lonergan SM, Huff-Lonergan E, Outhouse A, *et al.* Predicting aged pork quality using a portable Raman device. Meat Sci. 2018 Nov;145:79-85.
57. Schaepman ME. Spectrodirectional remote sensing: From pixels to processes. Int J Appl Earth Obs Geoinf. 2007 May;9(2):204-223.
58. Schubert M. Detection of meat and fat quality in pork and beef using X-ray [dissertation]. Copenhagen: Faculty of Life Sciences, University of Copenhagen; 2009.
59. Shtepliuk I, Domènech-Gil G, Almqvist V, Kautto AH, Vågsholm I, Boqvist S, *et al.* Electronic nose and machine learning for modern meat inspection. J Big Data. 2025 Apr 18;12(1).
60. Singh M, Kaur G, Kaur S. Machine vision: An upcoming realm. In: WHERE IS "HE, WHO CAN" TEACH?; 2004. p. 186.
61. Skoog DA, West DM, Holler FJ, Crouch SR. Principles of Instrumental Analysis. 6th ed. Thomson, Brooks/Cole; 2007.
62. Sowoidnich K, Kronfeldt HD. Shifted excitation Raman difference spectroscopy at multiple wavelengths for in-situ meat species differentiation. Appl Phys B. 2012 Sep;108(4):975-982.
63. Sun X, Young J, Liu JH, Newman D. Prediction of pork loin quality using online computer vision system and artificial intelligence model. Meat Sci. 2018 Jun;140:72-77.
64. Tan J, Xu J. Applications of electronic nose (e-nose) and electronic tongue (e-tongue) in food quality-related properties determination: A review. Artif Intell Agric. 2020;4:104-115.
65. Tian X, Wang J, Cui S. Analysis of pork adulteration in minced mutton using electronic nose of metal oxide sensors. J Food Eng. 2013 Dec;119(4):744-749.
66. ur Rahman U, Sahar A, Pasha I, ur Rahman S, Ishaq A. Assessing the capability of Fourier transform infrared spectroscopy in tandem with chemometric analysis for predicting poultry meat spoilage. PeerJ. 2018 Aug 6;6:e5376.
67. van de Voort FR. Fourier transform infrared spectroscopy applied to food analysis. Food Res Int. 1992 Jan;25(5):397-403.
68. Wang C, Zhou R, Huang Y, Xie L, Ying Y. Terahertz spectroscopic imaging with discriminant analysis for detecting foreign materials among sausages. Food Control. 2019 Mar;97:100-104.
69. Wijaya DR, Sarno R, Zulaika E, Sabila SI. Development of mobile electronic nose for beef quality monitoring. Procedia Comput Sci. 2017;124:728-735.
70. Willard HH, Merritt Jr LL, Dean JA, Settle Jr FA. Instrumental methods of analysis. 1988.
71. Wu X, Liang X, Wang Y, Wu B, Sun J. Non-Destructive Techniques for the Analysis and Evaluation of Meat Quality and Safety: A Review. Foods. 2022 Nov 18;11(22):3713.
72. Yang D, Ying Y. Applications of Raman Spectroscopy in Agricultural Products and Food Analysis: A Review. Appl Spectrosc Rev. 2011 Oct;46(7):539-560.
73. Yang SZ, Li C, Li C, Wang ZQ, Huang LL. Study of meat identification based on terahertz spectroscopy. 2021.
74. Zhang J, Tian H, Gong M, Zhang L, Zhao K, Yu Y. Machine learning-optimized techniques for enhancing freshness assessment in lamb meat using hyperspectral imaging. J Food Compos Anal. 2025 Aug;144:107752.
75. Zheng M, Zhang Y, Gu J, Bai Z, Zhu R. Classification and quantification of minced mutton adulteration with pork using thermal imaging and convolutional neural network. Food Control. 2021 Aug;126:108044.
76. Zhong Y. Electronic nose for food sensory evaluation. In: Evaluation technologies for food quality. Woodhead Publishing; 2019 Jan 1. p. 7-22.