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FOURIER TRANSFORM INFRARED (FTIR) SPECTROSCOPY, GAS CHROMATOGRAPHY AND CHEMOMETRIC ANALYSIS FOR *HALAL* AUTHENTICATION IN FOOD PRODUCTS

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Abstract

The increasing of worldwide demand for *halal*-certified food products warrants the robust analytical methods to ensure compliance with Islamic dietary laws. Conventional verification methods are insufficient to detect non-*halal* components in complex food matrices, especially the processed food products. This article explores the integration of Fourier transform infrared (FTIR) spectroscopy, gas chromatography (GC) and chemometric analysis as advanced and comprehensive tools for *halal* authentication. The FTIR spectroscopy offers rapid, non-destructive analysis of food samples while GC provides precise compositional profiling of fatty acids and volatile compounds, respectively. When the FTIR and GC data coupled with multivariate statistical approaches as such principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA), these techniques enable the identification of prohibited substances, including lard and porcine gelatine, even at trace levels. Case studies demonstrate high accuracy in classifying *halal* and non-*halal* food products using spectral and the chromatographic data. Furthermore, the development of portable instrumentation and cloud-based chemometric platforms has expanded the practical applicability of these methods for real-time quality control in industrial and regulatory settings. This article underscores current advancement, challenges and future directions in analytical *halal* authentication, emphasising the potential of these integrated techniques to ensure food integrity across the global supply chain.

Keywords: Chemometrics, FTIR spectroscopy, Gas chromatography, *Halal* authentication, *Halal* food products

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Introduction

The global *halal* food market has witnessed remarkable growth in recent decades, with current revenues exceeding USD1.9 trillion and projections indicating continued expansion at a compound annual growth rate of 6.3% through 2027 (Azam & Abdullah, 2020). This substantial market growth reflects the increasing Muslim population worldwide, which estimated at 1.9 billion people, alongside growing awareness among non-Muslim consumers regarding the quality, safety and ethical aspects of *halal*-certified products (Hafiz, 2020). *Halal* authentication, rooted in Islamic dietary laws, extends beyond religious observance to encompass comprehensive quality assurance that addresses food safety, hygiene and ethical production practices. These attributes have attracted significant interest from diverse consumer demographics seeking assurance of product integrity (Nazri et al., 2025; Usman et al., 2024).

The authentication of *halal* status in food products presents considerable analytical challenges due to the complexity of modern food supply chains, processing methods and ingredient sourcing. Traditional authentication methods primarily relied on documentation system and visual inspection, which have proven inadequate for detecting undeclared non-*halal* components, particularly in processed food with multiple ingredients (Ng et al., 2022). This limitation has necessitated the development and application of advanced analytical techniques capable of detecting prohibited substances such as porcine derivatives, alcohol and certain additives or preservatives that compromise the *halal* status (Hossain et al., 2021). Among the spectrum of analytical approaches, the Fourier transform infrared (FTIR) spectroscopy has emerged as a particularly valuable technique for *halal* authentication due to its non-destructive nature, minimal sample preparation requirements and capacity for rapid analysis. When coupled with gas chromatography (GC), these technologies provide complementary analytical capabilities that enable comprehensive characterization of food components at the molecular level (Lestari et al., 2022). The interpretation of complex spectral and chromatographic data generated by these techniques has been significantly enhanced through chemometric analysis, which employs multivariate statistical methods to extract meaningful patterns and identify characteristics markers of *halal* compliance or adulteration (Maritha et al., 2022).

This review article aims to critically evaluate recent advances in the application of FTIR spectroscopy, gas chromatography (GC) and chemometric analysis for *halal* authentication in diverse food products. Specifically, the article will examine the analytical principles underlying these techniques, assess their sensitivity and specificity in detecting non-*halal* components and evaluate the effectiveness of various chemometric approaches in data interpretation. Moreover, the review also will identify current limitations and challenges in analytical *halal* authentication and propose potential directions for future research to enhance the reliability and accessibility of these methods for regulatory authorities, industry stakeholders and certification bodies. By investigating recent scientific developments in this field, this review seeks to contribute to the establishment of more robust analytical frameworks for ensuring *halal* integrity across the global food supply chain.

Overview of Analytical Techniques

Fourier Transform Infrared (FTIR) Spectroscopy

The Fourier transform infrared (FTIR) spectroscopy operates the fundamental principle that molecules absorb infrared radiation at frequencies corresponding to their vibrational energies. When the infrared radiation interacts with a sample, chemical bonds within the molecule vibrate at characteristic frequencies, resulting in the absorption of specific wavelengths of the infrared spectrum as depicted in Figure 1 (Hashimoto et al., 2021). These vibrational modes are highly specific to specific functional groups and molecular structures, enabling the identification and quantification of various chemical constituents in complex food matrices (Nan et al., 2021). Furthermore, FTIR instruments employ an interferometer, typically a Michelson interferometer, which splits the infrared beam into two paths before recombining them to create an interference pattern. This interferogram contains intensity information across all wavelengths simultaneously, which is then mathematically converted into a frequency spectrum using the Fourier transform algorithm (Mukai et al., 2022). This technological viewpoint provides significant advantages over traditional dispersive infrared methods, including enhanced signal-to-noise ratio, improved spectral resolution and substantially faster acquisition times (Mukai et al., 2021).

The resultant infrared spectrum represents a molecular “fingerprint” of the sample, where absorption bands at specific wavenumber measured in cm^{-1} unit correspond to distinct molecular moieties. For *halal* authentication purposes, the FTIR spectroscopy can detect spectral patterns associated with prohibited substances such as porcine derivatives by identifying characteristics absorption bands related to their unique molecular structure (Rohman & Man, 2010). Meanwhile, FTIR spectroscopy also at the moment offers several significant advantages that have established it as a prominent analytical technique in food authentication, particularly for *halal* verification. The non-destructive nature of FTIR analysis represents a primary advantage, allowing samples to be analysed with minimal alteration to their composition, which is crucial for regulatory and confirmatory testing (Rahayu et al., 2018). Additionally, the technique requires minimal sample preparation, often limited to simple homogenization or solvent extraction, which reduces analytical time and minimizes the potential for contamination or analytical error (Irnawati et al., 2023).

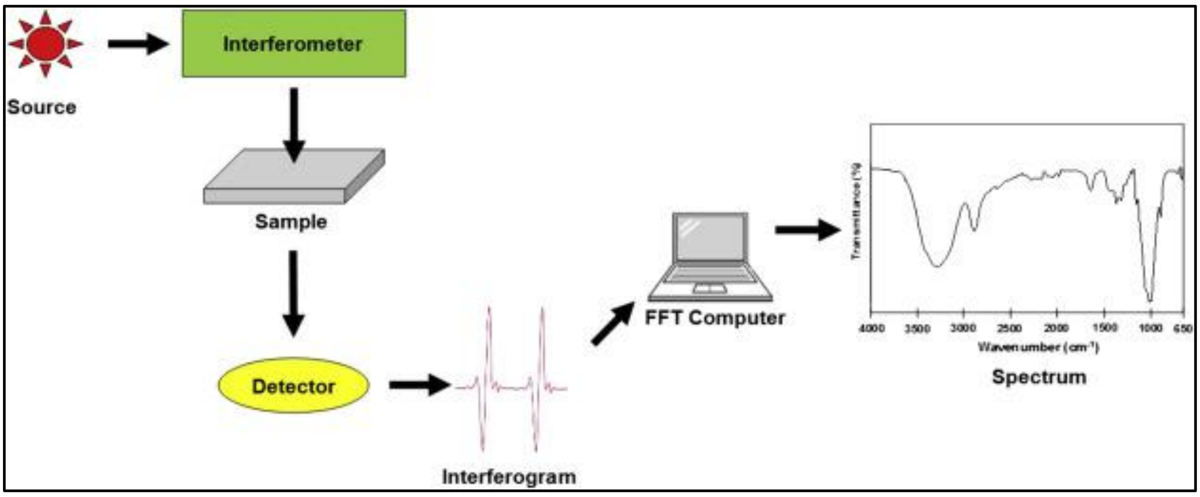

Figure 1. The basic component of Fourier transforms infrared spectroscopy [Adapted from Mohamed et al. (2017)].

The capability for rapid analysis constitutes another substantial benefit, with typical scan times ranging from seconds to minutes, enabling high-throughput screening essential for industrial and regulatory applications (Witjaksono et al., 2017). This rapidity combined with the technique's inherent sensitivity to subtle molecular differences, facilitates the detection of adulterants even at relatively low concentrations, often below 5% in complex food matrices (Nurrulhidayah et al., 2013). Modern FTIR instrumentation offers exceptional versatility through various sampling accessories including attenuated total reflectance (ATR), diffuse reflectance and transmission modes, which can be adapted to different sample types ranging from liquids and solutions to solids and powders (Durak & Depciuch, 2020). In addition, the technique demonstrates excellent reproducibility with relative standard deviations typically below 2% ensuring consistent results across multiple analyses (Dashti et al., 2022). From an economic perspective, FTIR analysis presents a cost-effective alternative to more resource-intensive chromatographic or mass spectrometric methods, with lower per-sample costs and reduced solvent consumption aligning with sustainable analytical practices (Rahmania & Rohman, 2015). When coupled with chemometric analysis techniques, FTIR data can yield comprehensive information about sample composition, enabling simultaneous verification of multiple quality and authenticity parameters beyond *halal* status, including geographical origin, processing methods and overall quality indicators.

The infrared spectrum contains several regions that provide critical information for *halal* authentication, particularly in the analysis of fats and oils where the detection of porcine-derived materials represents a primary concern. The fingerprint region between 1500 – 900 cm^{-1} contains highly specific vibrational modes that can distinguish between different lipid sources based on their unique molecular composition (Ahda & Guntarti, 2023). Within this region, the C–O stretching vibrations at 1175 – 1140 cm^{-1} and C–O–C stretching at 1150 – 1085 cm^{-1} have been identified at particularly valuable for differentiating between animal fats of different origins (Nazri et al., 2024). The carbonyl (C=O) stretching region at approximately 1750 – 1735 cm^{-1} represents another significant spectral area that reflects the ester linkages in triacylglycerols, with subtle shifts in peak position and shape correlating with fatty acid composition and distribution (Lucarini et al., 2019). Animal fats from different species exhibit characteristic differences in this region, with porcine fats typically showing a slightly lower wavenumber absorption maximum compared to bovine or ovine sources. Next, the C–H stretching vibrations in the wavenumber region of 3000 – 2800 cm^{-1} provide valuable information regarding the relative proportions of saturated and unsaturated fatty acids, with peaks at approximately 3006 cm^{-1} (=C–H stretching), 2922 cm^{-1} (asymmetric CH_2 stretching) and 2853 cm^{-1} (symmetric CH_2 stretching) serving as important markers for the degree of unsaturation and chain length distribution in lipids. The characteristic absorption band at 3006 cm^{-1}, associated with *cis*-olefinic double bonds is particularly informative for distinguishing between fats from different animal sources based on their unsaturation profiles. Additional diagnostic spectral features include the scissoring and rocking vibrations of CH_2 groups at 1465 cm^{-1} and 720 cm^{-1}, respectively, which provide information on the crystalline structure and chain packing lipids. The band at approximately 966 cm^{-1}, attributed to the out-of-plane deformation of *trans* double bonds, serves as an indicator of processing history and can help identify thermally or chemically modified fats that may be present in processed food products (Fajriati et al., 2021). The summary of advantages and limitation of FTIR spectroscopy are shown in Table 1 especially for the *halal* authentication research purpose.

Table 1. Summary of advantages and limitations of FTIR spectroscopy in *halal* authentication based on Basri (2025) and Usman et al. (2024).

Analytical Technique	Advantages	Limitations
FTIR spectroscopy	Non-destructive analysis, preserves sample integrity.	Requires extensive spectral libraries for reliable interpretation.
	Rapid analysis (scans completed in seconds to minutes), enabling high-throughput screening.	Less effective for highly complex or multi-ingredient samples due to overlapping absorption bands.
	Minimal sample preparation required (such as FTIR-ATR).	Sensitivity may decrease in presence of moisture or emulsions without proper preprocessing.
	Excellent for identifying functional groups and fingerprint regions specific to porcine lipids.	Lower specificity compared to GC-MS for identifying individual compounds.
	Cost-effective with low solvent use; environmentally friendly.	
	When combined with chemometrics (PCA, PLS-DA), enhances discriminatory power for fat origin classification.	

Gas Chromatography

Gas chromatography (GC) represent one of the cornerstones of analytical techniques in modern chemistry, biochemistry and food science. This powerful separation method based on component as shown in Figure 2 has revolutionized the analysis of complex mixtures by enabling the identification and quantification of individual compounds with remarkable precision. The techniques versatility and sensitivity have made it particularly valuable for characterizing fatty acids and volatile organic compounds across numerous scientific disciplines. Meanwhile, GC operates on the fundamental principle of differential partitioning of analytes between a mobile gaseous phase and a stationary phase coating the interior of a column. When a sample is injected into the heated inlet port, it vaporizes and is moving through the column by an inert carrier gas such as helium, hydrogen or nitrogen. Components separate based on their relative affinities for the stationary phase and their vapor pressure, with those having greater affinity for the stationary phase moving more slowly through the column. This differential migration leads to sequential elution of components, which are then detected and recorded as peaks on a chromatogram (Prebihalo et al., 2018).

The separation efficiency in GC depends on several critical parameters, including column temperature, carrier gas flow rate, stationary phase polarity and column dimensions. Modern instruments typically employ temperature programming – a controlled increase in column temperature over time – to enhance separation of compounds with wide-ranging volatilities. This approach allows volatile components to elute rapidly at lower temperatures while providing sufficient time for less volatile compounds to elute as the temperature increases (Aspromonte et al., 2024). Consequently, the flame ionization detector (FID) represents one of the most widely used detection systems coupled with GC. In the GC-FID, compounds eluting from the column enter a hydrogen-air flame, where they undergo combustion to produce ions and electrons. These charged particles are collected by electrodes, generating an electrical current proportional to the amount of carbon atoms in the flame. This signal is then amplified and recorded as a function of time (Mubiru et al., 2013). The FID system offers several advantages that have contributed to its widespread adoption. It provides excellent sensitivity for carbon-containing compounds, with detection limits normally in the picogram range. The detector exhibits a wide linear response range, spanning approximately seven orders of magnitude, which enables accurate quantification across varying concentration levels. Additionally, FID demonstrates remarkable stability and responds to virtually all organic compounds, making it particularly valuable for analysing hydrocarbons, fatty acids and their derivatives.

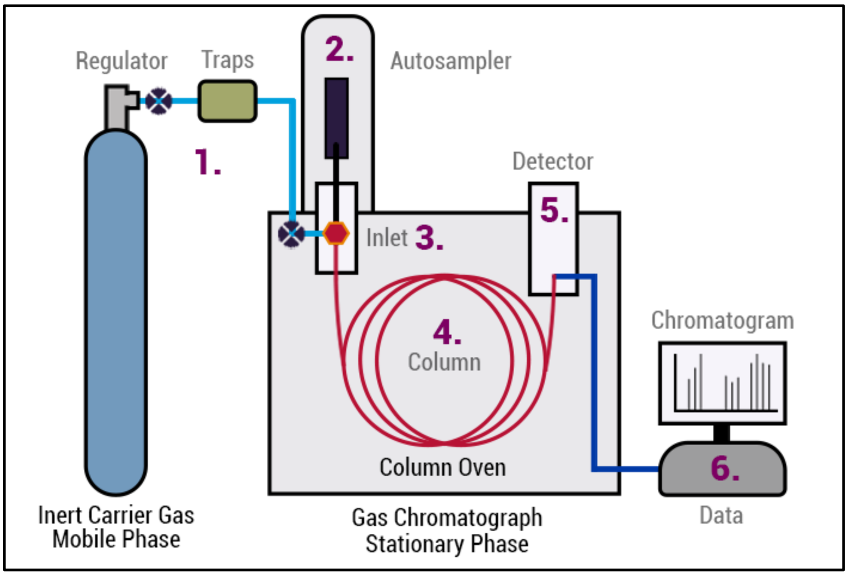

Figure 2. The basic component of gas chromatography [Adapted from Laajimi et al. (2022)].

Next, GC coupled with mass spectrometry (GC-MS) represents a powerful hyphenated technique that combines the separation capabilities of GC with the identification power of mass spectrometry. After compounds are separated chromatographically, they enter the mass spectrometer where they undergo ionization. The most common ionization method is electron impact (EI), in which high-energy electron bombard molecules, causing fragmentation into characteristic ion patterns. These ions are subsequently separated according to their mass-to-charge (*m/z*) ratios and detected, generating mass spectra that serve as molecular fingerprints for identification. The true power of GC-MS lies in its capability to provide both retention time data and mass spectral information for each component in a mixture. This dual approach enables confident identification of compounds even in complex matrices. Modern GC-MS systems typically incorporate extensive spectral libraries containing thousands of reference compounds, facilitating automated identification through spectral matching algorithms. Additionally, the technique offers superior sensitivity, with detection limits often reaching the nanogram to picogram range and excellent specificity due to the unique fragmentation patterns of different molecules (Maritha et al., 2022).

GC has emerged as the gold standard for fatty acid analysis across diverse biological matrices. The procedure typically involves a preliminary sample preparation step in which fatty acids are converted to more volatile methyl ester derivatives (FAMEs) through a process called derivatization. These FAMEs are then separated by GC, typically using polar stationary phases such as polyethylene glycol or cyanopropyl polysiloxane, which provide excellent resolution of geometric and positional isomers. The GC-FID has traditionally been the detection method of choice for fatty acid analysis due to its reliability, wide linear range and the predictable response factors that facilitate accurate quantification. The detector's response is proportional to the carbon content of FAME, allowing for relatively straightforward quantitative analysis (Kalogiouri et al., 2022). When combined with appropriate internal standards, the GC-FID enables precise determination of fatty acid compositions in complex lipid extraction from foods, biological tissues and microorganisms.

In one notable study, Ahda et al. (2021) demonstrated the use of GC-MS to analyze FAME profiles to authenticate beef meatballs. The research focused on detecting the adulteration of beef with pork or wild boar. The authors successfully identified key differences in the fatty acid composition and, more critically, the saturated fatty acid to monounsaturated fatty acid (SFA:MUFA) ratio. They found a distinct ratio for pork (~1.0) and wild boar (~1.2) that was significantly different from beef (~3.6). The study's strength lies in its use of a specific, quantifiable marker (the SFA:MUFA ratio) which provides a clear analytical signature for *halal* authentication, moving beyond a simple presence or absence test. A complementary study by Ahamed et al. (2024) focused on "volatilomics" the analysis of volatile organic compounds (VOCs), for authenticating cooked meat products. Using headspace solid-phase microextraction (HS-SPME) coupled with GC-MS, the researchers successfully differentiated beef, pork, and their admixtures. They identified lipid degradation products, such as various aldehydes, as the primary discriminating markers. The study highlighted that the cooking process produces a unique set of VOCs that can serve as a "fingerprint" for a specific meat species. By analyzing these volatile compounds, the authors could detect pork adulteration in beef at different concentrations, demonstrating the method's potential for both qualitative and quantitative analysis of processed foods. This approach is particularly valuable for complex food products where DNA or protein markers may be degraded by thermal processing

The summary of advantages and limitations of GC according to Haider et al. (2024) and Aziz et al. (2022) has shown in Table 2, respectively. The analysis of volatile organic compounds represents another domain where the GC excels. These compounds, characterized by their tendency to vaporize at ambient temperatures, play crucial roles in areas ranging from food flavour chemistry to environmental monitoring. The GC offers the sensitivity and resolution necessary to separate and identify these often trace-level components from complex mixtures. Meanwhile, sample preparation for volatile analysis frequently involves concentration techniques such as solid-phase microextraction (SPME), headspace sampling or purge-and-trap methods. These approaches help to isolate the volatile compounds from complex matrices before introduction to the GC system. Once separated, compounds can be detected using FID for quantification purposes, but GC-MS has become increasingly prevalent due to its superior identification capabilities. The application of GC-MS to volatile analysis has transformed our understanding of aroma chemistry in foods and beverages. By identifying key odorants and their concentrations, researchers can establish relationships between chemical composition and sensory properties. This approach has been extensively applied to characterize the volatile profiles of products ranging from wines and coffees to fruits and fermented foods, providing insights into flavour development during processing and storage.

Table 2. Summary of advantages and limitations of gas chromatography in *halal* authentication based on Haider et al. (2024) and Aziz et al. (2022).

Analytical technique	Advantages	Limitations
Gas chromatography	High separation efficiency for fatty acids and volatile compounds.	Requires derivatization (e.g., FAME preparation) for fatty acid profiling.
	GC-FID offers excellent linearity and sensitivity for quantitative analysis of fats.	Longer analysis time compared to FTIR, especially with complex samples.
	GC-MS allows for structural identification through mass spectral fingerprinting.	Equipment cost and operational complexity are higher, requiring skilled analysts.
	Superior in identifying specific fatty acids (such as C16:0, C18:1) and adulteration markers.	Sample preparation can be labor-intensive, with potential for analytical errors during derivatization.
	Robust detection of volatile organic compounds relevant to flavor and fat source authentication.	Difficult to adapt for on-site or portable applications without miniaturized systems.

Chemometric Analysis

Chemometric analysis represents a powerful approach to transforming complex analytical data into meaningful, interpretable information for food authentication studies. In the realm of food science, multivariate data analysis serves as an essential bridge between raw analytical measurements and actionable insights. This statistical framework allows scientists to simultaneously examine multiple variables and their interrelationships, uncovering hidden patterns that would remain invisible to conventional univariate methods. By reducing dimensionality while preserving critical information, multivariate techniques can extract signal from noise in complex food matrices, making them invaluable for detecting adulterations or verifying product authenticity (Windarsih et al., 2023).

The chemometric toolbox includes several cornerstone techniques that have revolutionized food authentication. The principal component analysis (PCA) functions as an unsupervised exploratory method that transforms correlated variables into linearly uncorrelated principal components, providing visualization of natural clustering and outlier detection. The first principal component (PC1) represents the direction that explains the largest amount of variance in the dataset. The second principal component (PC2) captures the second largest amount of variance and is orthogonal (perpendicular) to the PC1. Each subsequent component explains progressively less variance while remaining orthogonal to all previous components. In a comprehensively study by Suparman (2015) used PCA to address the challenge of detecting lard in chocolate products. The researchers collected FTIR spectra from chocolates containing different proportions of cocoa butter (*halal*) and lard (non-*halal*). Each FTIR spectrum consisted of absorbance values at 1650 different wavenumber, creating a dataset far too complex for direct visual interpretation. Thus, when applied PCA towards this dataset, the PC1 explained 86.2% of the total variance while PC2 explained an additional 11.4%. Together, these two components captured 97.6% of the total information in the original dataset. When plotting the chocolate samples on a PC1 against PC2 scatter plot, it is observed clear clustering patterns. Pure cocoa butter chocolates formed a tight cluster in the negative PC1 region, while lard-containing chocolates progressively shifted toward the positive PC1 region as lard concentration increased.

This visual separation enabled even non-statistical person to identify potential non-*halal* chocolate products at glance. Moreover, a study by Zilhadia et al. (2022) used PCA to address the challenging problem of identifying gelatine sources in pharmaceutical capsules which was a significant concern for Muslim consumers since gelatine can be derived from either bovine (*halal*) or porcine (*haram*) sources. The researchers analysed various commercial capsules using FTIR spectroscopy and subjected the data to PCA. The results were particularly interesting as PC1 and PC2 explained 61.4% and 22.8% of the variances regardless PC3 explained an additional 9.7% of the variance. While a two-dimensional plot (PC1 against PC2) showed some separation between bovine and porcine gelatine capsules, there was still some overlap between the clusters. However, when they plotted PC1 against PC3 instead, they achieved much clearer separation. This demonstrates an important advantage of PCA which the flexibility to examine different principal component combinations to find the most discriminative view of the data. Moreover, the loading analysis revealed that the amide I (1660 – 1650 cm^{-1}) and amide II (1550 – 1530 cm^{-1}) regions were most crucial for this discrimination, reflecting subtle differences in protein structure between gelatines from different animal sources. These differences remain detectable even after the extensive processing involved in pharmaceutical capsule manufacturing.

Partial least squares-discriminant analysis (PLS-DA) represents a powerful advancement in chemometric techniques that has significantly enhanced *halal* food authentication capabilities. Unlike PCA, the PLS-DA is a supervised technique specifically designed for classification tasks as it combines the dimensionality reduction strengths of partial least squares regression with the classification capabilities of discriminant analysis. Although PCA finds components that maximize variance in the data, PLS-DA finds components that maximize the covariance between predictor variables and the response variables. This makes PLS-DA particularly powerful when trying to differentiate between predefined groups. Moreover, the technique works by simultaneously decomposing both the X-matrix (analytical measurements) and Y-matrix (class information) to find the latent variables that best explain the covariance between the X- and Y-matrices. This focused approach often leads to better classification results than using PCA followed by a separate classification method. A comprehensive study by Windarsih et al. (2024) provides an excellent example of PLS-DA effectiveness in *halal* authentication. The researchers tackled the challenging problem of detecting dog meat in beef meatballs which was a processed product where visual identification is impossible. The researchers analysed 120 meatball samples containing varying percentage of 0 – 100% pork using FTIR spectroscopy. When they applied PLS-DA to this data is were found that the model identified optimal latent variables that specifically emphasized the spectral differences between *halal* (100% beef) and non-*halal* (dog meat-containing) meatball. Furthermore, cross-validation showed that using 8 latent variables provided the optimal balance between model complexity and prediction accuracy as the resulting model achieved 97.5% accuracy in classifying independent test samples. The researchers also tested commercially prepared meatballs with different spice mixtures and processing methods. The PLS-DA model maintained high classification accuracy of 95% even with these variations, demonstrating its robustness for practical *halal* verification. The most discriminative spectral regions identified by the PLS-DA analysis were associated with differences in fatty acid profiles between beef and dog meat.

A study by Nurani et al. (2022) provides a comprehensive review of chemometric applications in *halal* authentication, highlighting their critical role in handling multivariate data. The review outlines the use of both unsupervised and supervised pattern recognition techniques. For instance, unsupervised methods like PCA are used for exploratory data analysis to visualize natural groupings and differences among samples. A key finding from the reviewed literature is that PCA score plots consistently show distinct clustering for *halal* and non-*halal* samples, even when their individual spectra or chromatograms appear similar. Supervised methods, such as PLS-DA, take this a step further by building predictive models that can accurately classify unknown samples. The authors emphasize that the synergy between a reliable analytical instrument and a robust chemometric model is essential for achieving high accuracy and sensitivity in *halal* authentication. Similarly, Supandi et al. (2024) demonstrated the power of combining FTIR spectroscopy with multivariate calibration for the analysis of porcine gelatin in gummy candies. The study used PCA to successfully differentiate between pork and bovine gelatin based on subtle variations in their FTIR spectra, which are difficult to discern by visual inspection alone. They also employed Partial Least Squares Regression (PLSR) to develop a quantitative model that could accurately predict the concentration of pork gelatin in adulterated samples. The success of this approach lay in its ability to detect and quantify adulteration in a processed food matrix, a scenario where other methods might fail due to the degradation of molecular markers. This work underscores the importance of chemometrics in not only classifying samples but also providing quantitative data, which is crucial for regulatory and quality control purposes. Moreover, the summary of studies of chemometric techniques with respective instruments used are shown in Table 3 for *halal* authentication and verification research through notable researchers.

Table 3. Summary of studies employing chemometric techniques for *halal* authentication by different researchers.

Author(s)	Dataset/ Sample Type	Instrument Used	Chemometric Method	Key Outcome/ Benefits
Suparman (2015)	Chocolate with lard adulteration	FTIR	PCA	PC1 and PC2 explained 97.6% variance: allowed easy cluster separation of *halal* vs non-*halal* chocolates.
Zilhadia et al. (2022)	Pharmaceutical gelatine capsules (bovine/porcine)	FTIR	PCA	PC1–PC3 captured >90% variance; effective clustering; key wavenumbers identified.
Windarsih et al. (2024)	Beef meatballs adulterated with dog meat	FTIR	PLS-DA	Achieved 97.5% accuracy; robust across different seasoning/matrices.
Pavlidis et al. (2019)	Minced meat mixtures (beef/pork)	GC-MS	PCA	Differentiation based on volatile profiles; good separation of mixtures.
Dahimi et al. (2014)	Various fats including lard	GC-FID	PCA	Accurate classification using fatty acid profiles; good for edible fat screening.
Nazri et al. (2024)	Animal fats (lard, chicken, fish) and palm oil	FTIR-ATR	PCA + PLS-DA	Distinction of fats based on C=O and C–O–C absorbance; good for fat-type differentiation.
Rahmania & Rohman (2015)	Meatballs adulterated with rat meat	FTIR	PCA + LDA	Detected rat meat down to 10%; useful for rapid meat authentication.
Rahayu et al. (2018)	Beef meatballs with dog meat	FTIR	PCA + SIMCA	Rapid screening; high sensitivity to adulteration using mid-IR bands.
Salleh et al. (2022)	Lard from different regions/body parts	FTIR (portable)	PLS-DA	Achieved 98% sensitivity in field testing; supports portable *halal* screening.
Nazri et al. (2026)	Imported fish pellets adulterated with lard	FTIR-ATR	PCA	PC1 and PC2 explained 93.80% and 98.20% variance: allowed easy cluster separation of imported fish pellets with lard
Ahda et al. (2020)	Beef meatball adulterated with pork and wild boar	GC-MS	PCA	The PCA distinguished by the SFA:MUFA ratios of fat which grouped to match the fats and meatballs
Ahamed et al. (2024)	Cooked meat products	HS-SPME with GC-MS	PCA + PLS-DA	The PCA and PLS-DA yield significant sample separation with PC1 and PC2 capturing 80% and 72.1% of total variance for reliable detection meat adulteration in cooked meat
Supandi et al. (2024)	Porcine gelatine in gummy candies	FTIR	PCA + PLS	The multivariate regression curved showed pattern of linear absorbance changes according to gelatine concentration of pork and cows.

Applications in *Halal* Authentication

Detection of Lard and Other Non-*Halal* Fats

The authentication of *halal* food products has become increasingly notable with FTIR spectroscopy and GC emerging as powerful analytical tools for detecting the non-*halal* components. Studies employing FTIR have demonstrated remarkable success in identifying lard adulteration through distinctive spectral patterns, particularly in the fingerprint region of 1500 – 900 cm^{-1}, where C-O and C-C stretching vibrations exhibit characteristic absorbance profiles unique to porcine lipids. Multiple studies have validated the FTIR's capability to detect lard adulterations at concentrations as low as 1% in various food matrices, with attenuated total reflectance (FTIR-ATR) proving especially valuable for rapid screening without extensive sample preparation (Man et al., 2005). Moreover, complementing spectroscopic approaches, the GC techniques have provided deeper insights into the molecular composition of lipids, particularly FAME analysis, revealing that lard possesses distinctive markers including elevated proportions of palmitic acid (C16:0) at the sn-2 position of triacylglycerols and characteristic ratios of stearic (C18:0) to oleic (C18:1) acids that serve as reliable indicators of porcine origin (Dahimi et al., 2014). The application of these analytical methodologies has been successfully demonstrated across various food categories, with notable case studies including the detection of lard in bakery shortening through multivariate analysis of FTIR spectra combined with fatty acid profiling that achieved 100% classification accuracy and the identification of undeclared pork fat in processed meat products using a combination of GC-MS and chemometric pattern recognition that successfully differentiated beef-pork mixtures at adulteration levels of 5%. Similarly, a comprehensive investigation of *halal* chocolate products employing both FTIR and GC-FID coupled with PCA demonstrated that distinct clustering patterns emerge based on fatty acid composition, enabling regulatory authorities to verify compliance with *halal* standards even in complex confectionary formulations (Pavlidis et al., 2019). These analytical approaches collectively provide robust methodologies for *halal* authentication, offering essential tools for both industry quality assurance and regulatory compliance verification in global food markets where the *halal* integrity is increasingly prioritised.

Rapid Screening and Routine Quality Control

The complementary integration of FTIR spectroscopy with GC techniques, enhanced through sophisticated chemometric analysis, has revolutionised on-site *halal* authentication capabilities by providing multi-level verification systems adaptable to diverse food matrices and processing conditions. Portable FTIR devices equipped with ATR accessories now deliver preliminary screening results within minutes directly at production facilities, generating spectral fingerprints across the mid-infrared region of 4000 – 400 cm^{-1} that when processed through pre-trained chemometric models employing PLS-DA, can rapidly flag potentially non-compliant samples with sensitivity levels approaching 98% for lard detection in complex food system (Salleh et al., 2022). For samples flagging positive in initial screening, field-portable gas chromatography systems with simplified column configurations optimised specifically for targeted FAME analysis provide confirmatory testing capabilities without requiring sample transport to centralised laboratories, utilising pre-calibrated retention time libraries and characteristic fatty acid ratios such as C16:0/C18:0 and C18:1/C18:0 that's serve as reliable markers for differentiating permitted animal fats from prohibited porcine derivatives. These complementary analytical approaches are seamlessly integrated through unified chemometric platforms employing hierarchical cluster analysis (HCA) and artificial neural network (ANN) that synthesise multidimensional data from both techniques, transforming complex spectroscopic and chromatographic patterns into accessible binary compliance determinations interpretable by non-specialist quality control personnel (Miraboutalebi et al., 2016).

Small and medium enterprises (SMEs), previously disadvantaged by limited access to advanced analytical infrastructure, have particularly benefited from these technological developments, as the significantly reduced capital investment required for portable instrumentation coupled with subscription-based chemometric processing services enable implementation of science-based verification protocols without prohibitive laboratory establishment costs or specialised analytical staff requirements. Certification bodies have likewise embraced these technological advances, transitioning from periodic laboratory-based verification to continuous monitoring programs where inspectors equipped with portable analytical systems can conduct unannounced compliance checks throughout production chains, substantially increasing both the frequency and comprehensiveness of verification procedures while simultaneously reducing the administrative burden associated with sample collection, transportation and centralized testing. Moreover, since the development of cloud-based data repositories housing standardised spectral and chromatographic reference libraries has facilitated unprecedented harmonisation of analytical standards across certification bodies operating in different geographical regions, addressing previous concerns regarding equivalence of certification outcomes and enhancing international trade opportunities for *halal*-certified products through mutual recognition agreements founded on objective analytical methodologies rather than subjective interpretation of documentation requirements (Ellahi et al., 2025). The continued evolution of these integrated analytical approaches through miniaturisation of instrumentation, automation of data interpretation and expansion of reference databases promises to further democratise access to scientific authentication methods across the *halal* supply chain, ultimately strengthening consumer confidence while simultaneously reducing compliance costs and verification timelines for producers operating within this rapidly expanding market segment.

Perspective, Challenges and Future Trends

Despite significant advances in *halal* authentication methodologies employing FTIR spectroscopy and GC, several fundamental challenges persist that impact the reliability and universal applicability of these techniques across diverse food system. The establishment of comprehensive spectral and chromatographic reference libraries remain particularly problematic, as current databases frequently lack sufficient representation of global ingredient variations, regional processing techniques and the full spectrum of permitted animal fats from different *halal*-compliant species, thus limiting the robustness of chemometric models when applied to novel food matrices or ingredients sourced from geographically diverse supply chains. Sample matrix variability introduces additional complications, with high-moisture foods, complex emulsions and multi-ingredient formulations often requiring extensive sample preparation that undermines the rapidity of analysis, while certain food additives, processing aids and thermal treatments can significantly alter lipid profiles, potentially masking adulteration markers or generating confounding spectral interferences that reduce analytical specificity.

These limitations are progressively being addressed through emerging technologies, with next-generation portable FTIR system incorporating advanced optical configurations and microfluidic sample handling capabilities that maintain analytical performance while reducing instrument footprint and complexity, enabling truly field-deployable authentication directly within production environments or at border inspection points without compromising detection capabilities. Artificial intelligence-enhanced chemometric approaches represent another promising frontier, with deep learning algorithms demonstrating superior classification performance compared to traditional statistical methods, particularly for complex sample matrices where non-linear relationships between spectral features and compositional variables predominate, with recent neural network implementations achieving detection limits below 0.5% for lard in processed foods even in the presence of significant matrix interferences (Sharma et al., 2025; Bhagya Raj & Dash, 2022). Environmentally conscientious “green” sample preparation methodologies utilising natural deep eutectic solvents derived from renewable sources have emerged as sustainable alternatives to traditional organic solvent-based extraction procedures, not only reducing environmental impact but also enhancing selectivity for targeted lipid fractions while simultaneously streamlining sample processing workflows. Perhaps most transformative is the nascent integration of these analytical technologies with blockchain-based traceability systems, where analytical results from critical control points throughout supply chains are cryptographically secured and immutably recorded, creating verifiable authentication records accessible to all stakeholders including certification bodies, regulatory authorities, manufacturers, retailers and ultimately consumers, who can scan product QR codes to access comprehensive verification histories including analytical test results, raw spectral data and certifier approvals. This convergence of advanced analytical science with digital traceability technologies promises to establish new paradigms for *halal* authentication, transitioning from isolated point-in-time testing to continuous, transparent verification systems that maintain unbroken chains of analytical evidence from farm to fork, thereupon addressing fundamental consumer concerns regarding the authenticity and integrity of *halal*-certified products in increasingly complex global supply network.

Conclusion

The analytical authentication of *halal*-certified food products has advanced significantly through the integration of FTIR spectroscopy and GC, enhanced by sophisticated chemometric analysis technique of PCA and PLS-DA, respectively. These complementary methodologies have transformed *halal* verification from subjective documentation-based approaches to objective, science-driven analytical frameworks capable of detecting prohibited substances like porcine derivatives at concentration as low as 1% in complex food matrices. The FTIR spectroscopy serves as an excellent first-line screening tool due to its non-destructive nature and rapid analysis capabilities, while GC techniques provide deeper insights into molecular composition through fatty acid profiling that reliably differentiates between *halal*-compliant and non-compliant animal fats. Despite significant progress, challenges remain in developing comprehensive reference databases, addressing matrix interference effects and establishing standardised protocols applicable across diverse supply chains. Future advancement will likely focus on integrating these analytical techniques with emerging technologies like artificial intelligence and blockchain-based traceability systems, creating transparent verification platforms that strengthen consumer confidence while supporting industry compliance in the rapidly expanding global *halal* marketplace where certification represents not only religious observance but also comprehensive quality assurance valued by diverse consumer demographics worldwide.

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Author Contribution

M. Z. Nazri – conceptualization, formal analysis, funding acquisition, writing – original draft; **S. N. A. A. Rashid** – validation, writing – original draft; **D. N. A. Zaidel** – validation, writing – review & editing

Conflict of Interest

All authors declare there is no conflict of interest regarding the publication of the manuscript.

Declaration on the Use of Generative AI

The authors used ChatGPT during the preparation of this work for generating ideas for this manuscript writing. After utilising the ChatGPT, the authors thoroughly reviewed and edited the content as necessary and assumed full responsibility for the publication's content.

References

Ahamed, Z., Seo, J. K., Eom, J. U., & Yang, H. S. (2024). Volatile compounds for discrimination between beef, pork, and their admixture using solid-phase-microextraction-gas chromatography-mass spectrometry (SPME-GC-MS) and chemometrics analysis. *Food Science of Animal Resources*, *44*(4), 934. https://doi.org/10.5851/kosfa.2024.e32

Ahda, M., & Guntarti, A. (2023). *Halal* food analysis using FTIR spectroscopy combined with chemometrics: A review. *Current Nutrition & Food Science*, *19*(2), 125-135. https://doi.org/10.2174/1573401318666220328095542

Ahda, M., Guntarti, A., Kusbandari, A., & Melianto, Y. (2020). Authenticity analysis of beef meatball adulteration with wild boar using FTIR spectroscopy combined with chemometrics. *Journal of Microbiology, Biotechnology and Food Sciences*, *9*(5), 937-940. https://doi.org/10.15414/jmbfs.2020.9.5.937-940

Ahda, M., Guntarti, A., Kusbandari, A., & Melianto, Y. (2021). *Halal* food analysis using GC-MS combined with principal component analysis (PCA) based on saturated and unsaturated fatty acid composition. *Songklanakarin Journal of Science and Technology*, *43*(2), 352-355. https://doi.org/10.14456/sjst-psu.2021.46

Aspromonte, J., Mascrez, S., Eggermont, D., & Purcaro, G. (2024). Solid-phase microextraction coupled to comprehensive multidimensional gas chromatography for food analysis. *Analytical and Bioanalytical*

Chemistry, *416*(9), 2221-2246. https://doi.org/10.1007/s00216-023-05048-0

Azam, M. S. E., & Abdullah, M. A. (2020). Global *halal* industry: realities and opportunities. *IJIBE (International Journal of Islamic Business Ethics)*, *5*(1), 47-59. http://dx.doi.org/10.30659/ijibe.5.1.47-59

Aziz, A. A., Nordin, F. N. M., Zakaria, Z., & Abu Bakar, N. K. (2022). A systematic literature review on the current detection tools for authentication analysis of cosmetic ingredients. *Journal of Cosmetic Dermatology*, *21*(1), 71-84. https://doi.org/10.1111/jocd.14402

Basri, K. N. (2025). Integration of spectroscopy and chemometric analysis for food authentication: A review. *Halalsphere*, *5*(2), 69-79. https://doi.org/10.31436/hs.v5i2.127

Bhagya Raj, G. V. S., & Dash, K. K. (2022). Comprehensive study on applications of artificial neural network in food process modeling. *Critical Reviews in Food Science and Nutrition*, *62*(10), 2756-2783. https://doi.org/10.1080/10408398.2020.1858398

Dahimi, O., Hassan, M. S., Rahim, A. A., & Abdulkarim, S. M. (2014). Differentiation of lard from other edible fats by gas chromatography-flame ionisation detector (GC-FID) and chemometrics. *Journal of Food and Pharmaceutical Sciences*, *2*(1), 27-31. https://doi.org/10.14499/jfps

Durak, T., & Depciuch, J. (2020). Effect of plant sample preparation and measuring methods on ATR-FTIR spectra results. *Environmental and Experimental Botany*, *169*, 103915. https://doi.org/10.1016/j.envexpbot.2019.103915

Ellahi, R. M., Wood, L. C., Khan, M., & Bekhit, A. E. D. A. (2025). Integrity challenges in *halal* meat supply chain: Potential industry 4.0 technologies as catalysts for resolution. *Foods*, *14*(7), 1135. https://doi.org/10.3390/foods14071135

Fajriati, I., Rosadi, Y., Rosadi, N. N., & Khamidinal, K. (2021). Detection of animal fat mixtures in meatballs using fourier transform infrared spectroscopy (FTIR Spectroscopy). *Indonesian Journal of Halal Research*, *3*(1), 8-12. https://doi.org/10.15575/ijhar.v3i1.11166

Hafiz, W. A. (2020). Assessment of global *halal* market: challenges and opportunities. *African Journal of Business and Economic Research*, *15*(4), 5. https://hdl.handle.net/10520/ejc-aa_ajber_v15_n4_a1

Haider, A., Iqbal, S. Z., Bhatti, I. A., Alim, M. B., Waseem, M., Iqbal, M., & Mousavi Khaneghah, A. (2024). Food authentication, current issues, analytical techniques, and future challenges: A comprehensive review. *Comprehensive reviews in food science and food safety*, *23*(3), e13360. https://doi.org/10.1111/1541-4337.13360

Hashimoto, K., Badarla, V. R., & Ideguchi, T. (2021). High-speed Fourier-transform infrared spectroscopy with phase-controlled delay line. *Laser & Photonics Reviews*, *15*(1), 2000374. https://doi.org/10.1002/lpor.202000374

Hossain, M. M., Uddin, S. M. K., Sultana, S., Wahab, Y. A., Sagadevan, S., Johan, M. R., & Ali, M. E. (2021). Authentication of *halal* and kosher meat and meat products: Analytical approaches, current progresses and future prospects. *Critical Reviews in Food Science and Nutrition*, *62*(2), 285-310. https://doi.org/10.1080/10408398.2020.1814691

Kalogiouri, N. P., Manousi, N., Mourtzinos, I., Rosenberg, E., & Zachariadis, G. A. (2022). A rapid GC-FID method for the determination of fatty acids in walnut oils and their use as markers in authenticity studies. *Food Analytical Methods*, 1-11. https://doi.org/10.1007/s12161-021-02157-3

Laajimi, H., Galli, F., Patience, G. S., & Schieppati, D. (2022). Experimental methods in chemical engineering: Gas chromatography—GC. *The Canadian Journal of Chemical Engineering*, *100*(11), 3123-3144. https://doi.org/10.1002/cjce.24395

Lestari, D., Rohman, A., Syofyan, S., Yuliana, N. D., Abu Bakar, N. K. B., & Hamidi, D. (2022). Analysis of beef meatballs with rat meat adulteration using Fourier Transform Infrared (FTIR) spectroscopy in combination with chemometrics. *International Journal of Food Properties*, *25*(1), 1446-1457. https://doi.org/10.1080/10942912.2022.2083637

Man, Y. C., Gan, H. L., NorAini, I., Nazimah, S. A. H., & Tan, C. P. (2005). Detection of lard adulteration in RBD palm olein using an electronic nose. *Food chemistry*, *90*(4), 829-835. https://doi.org/10.1016/j.foodchem.2004.05.062

Maritha, V., Harlina, P. W., Musfiroh, I., Gazzali, A. M., & Muchtaridi, M. (2022). The application of chemometrics in metabolomic and lipidomic analysis data presentation for *halal* authentication of meat products. *Molecules*, *27*(21), 7571. https://doi.org/10.3390/molecules27217571

Miraboutalebi, S. M., Kazemi, P., & Bahrami, P. (2016). Fatty acid methyl ester (FAME) composition used for estimation of biodiesel cetane number employing random forest and artificial neural networks: A new approach. *Fuel*, *166*, 143-151. https://doi.org/10.1016/j.fuel.2015.10.118

Mohamed, M. A., Jaafar, J., Ismail, A. F., Othman, M. H. D., & Rahman, M. A. (2017). Fourier transform infrared (FTIR) spectroscopy. In *Membrane Characterization* (pp. 3-29). Elsevier. https://doi.org/10.1016/B978-0-444-63776-5.00001-2

Mubiru, E., Shrestha, K., Papastergiadis, A., & De Meulenaer, B. (2013). Improved gas chromatography-flame ionization detector analytical method for the analysis of epoxy fatty acids. *Journal of Chromatography A*, *1318*, 217-225. https://doi.org/10.1016/j.chroma.2013.10.025

Mukai, Y., Arahata, M., Tashima, T., Okamoto, R., & Takeuchi, S. (2021). Quantum Fourier-transform infrared spectroscopy for complex transmittance measurements. *Physical Review Applied*, *15*(3), 034019. https://doi.org/10.1103/PhysRevApplied.15.034019

Mukai, Y., Okamoto, R., & Takeuchi, S. (2022). Quantum Fourier-transform infrared spectroscopy in the far-infrared region. In *2022 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)* (pp. 1-2). IEEE. https://10.1109/CLEO-PR62338.2022.10431982

Nan, C., Yue, W., Tao, L., & Yang, X. (2021). Fourier transform infrared nano-spectroscopy: Mechanism and applications. *Applied Spectroscopy Reviews*, *56*(7), 531-552. https://doi.org/10.1080/05704928.2020.1830789

Nazri, M. Z., Abd Rashid, S. N. A., Mustafa, R. R., & Zaidel, D. N. A. (2025). *Halal* assurance beyond science: A perspective on socioeconomic factors and consumer trust in food authentication. *Halalsphere*, *5*(2), 92-100. https://doi.org/10.31436/hs.v5i2.129

Nazri, M. Z., Rashid, S. N. A. A., Latiff, N. A., Malik, S. A., Muthu, D. T., Karim, H. A. A., Basar, N., Rohman, A., & Zaidel, D. N. A. (2026). *Halal* verification of imported fish pellets by FTIR-ATR spectroscopy approach and multivariate data analysis. *Journal of Advanced Research Design*, *139*(1), 158–174. https://doi.org/10.37934/ard.139.1.158174

Nazri, M. Z., Rashid, S. N. A. A., Malik, S. A., Karim, H. A. A., Sani, M. S. A., & Zaidel, D. N. A. (2024). The FTIR-ATR spectroscopy and multivariate data analysis (MVDA) for *halal* authentication of animal fatty acids. *Malaysian Journal of Chemistry*, 26(6), 184-193. https://doi.org/10.55373/mjchem.v26i6.184

Ng, P. C., Ahmad Ruslan, N. A. S., Chin, L. X., Ahmad, M., Abu Hanifah, S., Abdullah, Z., & Khor, S. M. (2022). Recent advances in *halal* food authentication: Challenges and strategies. *Journal of Food Science*, *87*(1), 8-35. https://doi.org/10.1111/1750-3841.15998

Nurani, L. H., Riswanto, F. D. O., Windarsih, A., Edityaningrum, C. A., Guntarti, A., & Rohman, A. (2022). Use of chromatographic-based techniques and chemometrics for *halal* authentication of food products: A review. *International Journal of Food Properties*, *25*(1), 1399-1416. https://doi.org/10.1080/10942912.2022.2082468

Nurrulhidayah, A. F., Man, C. Y., Rohman, A., Amin, I., Shuhaimi, M., & Khatib, A. (2013). Authentication analysis of butter from beef fat using Fourier Transform Infrared (FTIR) spectroscopy coupled with chemometrics. *International Food Research Journal*, *20*(3), 1383.

Pavlidis, D. E., Mallouchos, A., Ercolini, D., Panagou, E. Z., & Nychas, G. J. E. (2019). A volatilomics approach for off-line discrimination of minced beef and pork meat and their admixture using HS-SPME GC/MS in tandem with multivariate data analysis. *Meat science*, *151*, 43-53. https://doi.org/10.1016/j.meatsci.2019.01.003
Prebihalo, S. E., Berrier, K. L., Freye, C. E., Bahaghighat, H. D., Moore, N. R., Pinkerton, D. K., & Synovec, R.

E. (2018). Multidimensional gas chromatography: advances in instrumentation, chemometrics, and applications. *Analytical Chemistry*, *90*(1), 505-532. https://doi.org/10.1021/acs.analchem.7b04226

Rahayu, W. S., Rohman, A., Martono, S., & Sudjadi, S. (2018). Application of FTIR spectroscopy and chemometrics for *halal* authentication of beef meatball adulterated with dog meat. *Indonesian Journal of Chemistry*, *18*(2), 376-381. https://doi.org/10.22146/ijc.27159

Rahmania, H., & Rohman, A. (2015). The employment of FTIR spectroscopy in combination with chemometrics for analysis of rat meat in meatball formulation. *Meat science*, *100*, 301-305. https://doi.org/10.1016/j.meatsci.2014.10.028

Rohman, A., & Man, Y. C. (2010). Fourier transform infrared (FTIR) spectroscopy for analysis of extra virgin olive oil adulterated with palm oil. *Food research international*, *43*(3), 886-892. https://doi.org/10.1016/j.foodres.2009.12.006

Salleh, N. A. M., Yahaya, N., Rosli, D., Azizan, M. F., Yamin, B. M., & Hassan, M. S. (2022). Characterization of lard profile from different geographical regions of husbandries and body parts of pig using FTIR technique combined with chemometrics. *International Journal on Advanced Science, Engineering and Information Technology*, *12*(4), 1565-1573. https://doi.org/10.18517/ijaseit.12.4.17167

Sharma, R., Agarwal, M., & Singh, B. (2025). Enhancing Food Quality Analysis: The Transformative Role of Artificial Neural Networks in Modern Analytical Techniques. *Critical Reviews in Analytical Chemistry*, 1-18. https://doi.org/10.1080/10408347.2025.2505081

Supandi, S., Septiana, A. D., Kusumadewi, N., & Fatmawati, S. (2024). *Halal* authentication: Fourier transform infrared spectroscopy and multivariate calibration application for pork gelatin analysis in gummy candy. *Food Research*, *8*(5), 44-48. https://doi.org/10.26656/fr.2017.8(5).573

Suparman, S. (2015). The use of Fourier transform infrared spectroscopy (FTIR) and gas chromatography mass spectroscopy (GCMS) for halal authentication in imported chocolate with various variants. *Journal of Food and Pharmaceutical Sciences*, *3*(1), 6-11. https://doi.org/10.14499/jfps

Usman, I., Sana, S., Afzaal, M., Imran, A., Saeed, F., Ahmed, A., Shah, Y. A., Munir, M., Ateeq, H., Afzal, A., Azam, I., Ejaz, A., Nayik, G. A., & Khan, M. R. (2024). Advances and challenges in conventional and modern techniques for *halal* food authentication: A review. *Food Science & Nutrition*, *12*(3), 1430-1443. https://doi.org/10.1002/fsn3.3870

Windarsih, A., Bakar, N. K. A., Dachriyanus, Yuliana, N. D., Riswanto, F. D. O., & Rohman, A. (2023). Analysis of pork in beef sausages using LC-orbitrap HRMS untargeted metabolomics combined with chemometrics for *halal* authentication study. *Molecules*, *28*(16), 5964. https://doi.org/10.3390/molecules28165964

Windarsih, A., Bakar, N. K. A., Rohman, A., Yuliana, N. D., & Dachriyanus, D. (2024). Untargeted metabolomics using liquid chromatography-high resolution mass spectrometry and chemometrics for analysis of non-*halal* meats adulteration in beef meat. *Animal Bioscience*, *37*(5), 918. https://doi.org/10.5713/ab.23.0238

Zilhadia, Z., Harahap, Y., Jaswir, I., & Anwar, E. (2022). Evaluation and characterization of hard-shell capsules formulated by using goatskin gelatin. *Polymers*, *14*(20), 4416. https://doi.org/10.3390/polym14204416