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Review Article

Laboratory Instrumentations for *Halalan Toyyiban* Food Authentication: A Critical Review

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Abstract: The *halalan toyyiban* (HT) concept is based on the Islamic concept to ensuring that the food products comply with *halal* (permissible) and *toyyiban* (wholesome) standards, encompassing ethical, safety and quality dimensions in the global food industry. Despite advancements, limitations such as the complexity of food matrices and the prevalence of adulterants necessitate the adoption of revolutionary analytical approaches. This comprehensive review examines current detection laboratory instrumentations, emphasizing spectroscopic techniques such as Fourier transform infrared spectroscopy (FTIR) for rapid, non-destructive analysis, chromatographic methods such as high-performance liquid chromatography (HPLC) for precise quantification, molecular tools including polymerase chain reaction (PCR) for high-sensitivity contaminant detection, and microbiological approaches for safety and hygiene assessments. In addition, the multivariate data analysis (MVDA) mainly principal component (PCA), discriminant (DA) and partial least squares discriminant (PLS-DA) analyses are highlighted as a transformative tool for processing complex datasets, enabling enhanced pattern recognition, predictive modelling and decision-making, respectively. The findings underscore the synergistic potential of integrating these methodologies to enhance HT detection, though disadvantages of high costs, limited standardization and technical expertise must also be addressed. The comprehensive review concludes with a call for research into cost-effective, automated and

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standardized detection systems to advance the reliability and accessibility of HT assurance in the evolving food landscape.

1. Introduction

The increasing global Muslim population and the growing awareness of *halal* integrity among non-Muslim consumers have driven a substantial rise in demand for *halal*-certified food products. Ensuring *halal* authenticity is not only a matter of religious observance but also a critical element of food safety and quality assurance. In Malaysia and other Muslim-majority nations, compliance with *halalan toyyiban* (HT) principles which emphasising lawful (*halal*) and wholesome (*toyyiban*) attributes forms the foundation towards the halal certification (Ahmad *et al.*, 2021). While *halal* ensures adherence to Islamic dietary law, *toyyiban* emphasise safety, cleanliness and ethical production which then aligning closely with international food safety standards. Consumer trust and compliance with religious dietary regulations depend on *halal* food products having authentic and safe. The HT highlights the need for food to be healthful and acceptable, emphasizing the requirement for safety and purity in eating. The complexity of contemporary food processing and the possibility of adulteration make traditional *halal* authentication techniques insufficient. Therefore, authenticating *halal* food is crucial for maintaining consumer confidence, especially with Muslim customers who follow stringent dietary regulations (Bonne & Verbeke, 2008).

Verifying *halal* certification has become more difficult due to rapid development of food processing technology especially when involving complex food matrices, since traditional *halal* authentication techniques like visual inspection and documentation review are frequently insufficient (Nakyinsige *et al.*, 2012). The basic components of conventional *halal* verification techniques include visual examination, ingredient tracking and documentation. These methods however are inadequate for identifying food adulteration, particularly when non-*halal* materials such as lard or pork derivatives are chemically altered to mimic *halal* ingredients. Traditional procedures are unreliable due to problems including adulteration, substitution and cross contamination; therefore, the scientific methodologies are required for authentication (Rohman *et al.*, 2014). More reliable scientific methods must be used because the authentication procedure is made more difficult by dishonest business strategies, accidental cross-contamination and the complicated process of food processing. Therefore, to uphold consumer trust and regulatory credibility, *halal* authentication now necessitates validated analytical procedures consistent with MS1500:2019 (Halal Food – General Requirement) and ISO/IEC 17025 (Testing and Calibration Laboratory Competence) standard.

This aim of this review is to critically highlights gap in current *halal* research despite increasing use of analytical instrumentation, there remains limited integration and

standardisation of multi-technique approaches for HT verification especially in complex food matrices such fermented or processed food products. Thus, this paper aims to (i) critically evaluate recent analytical techniques used in *halal* authentication including FTIR spectroscopy, HPLC, PCR and microbiological profiling; (ii) explore the role of multivariate data analysis (MVDA) in enhancing method reliability and interpretation; and (iii) propose a harmonised analytical framework aligned with *halal* certification and laboratory accreditation requirement, respectively. Regarding the terminology, the literature inconsistently employs both *toyyib* and *toyyiban* by which in this manuscript, *toyyiban* is the plural form used in the Quranic phrase of HT is standardised to maintain linguistic and contextual accuracy, encompassing dimensions of purity, safety and wholesomeness. Moreover, structurally, this review first outlines the conceptual basis of HT in relation to food safety regulations, followed by a critical analysis of contemporary analytical techniques and their MVDA applications. It concludes with a proposed framework for integrated *halal* authentication and recommendations for future research to enhance the scientific robustness and traceability of *halal* verification systems.

2. Fourier Transform Infrared (FTIR) Spectroscopy for HT Authentication

The Fourier Transform Infrared (FTIR) spectroscopy has emerged as a rapid, non-destructive and cost-effective analytical tool in food authentication, quality control, pharmaceutical analysis and *halal* verification. This technique measures the absorption of infrared light by molecular bonds, producing characteristic vibration patterns that act as a unique spectral fingerprint for each sample analyse (Gong *et al.*, 2024). Within the context of HT authentication, FTIR spectroscopy supports the assurance of *halal* (lawful) and *toyyiban* (wholesome, safe and pure) attributes by detecting impurities, adulteration or contamination that may compromise the integrity, safety or lawful status of food products.

Typically, attenuated total reflectance (ATR) is used for food analysis because it requires minimal sample preparation and enables direct measurement of solids, liquids or semi-solid matrices, respectively. The spectral range of 4000 – 400 cm^{-1} (mid-IR region) is commonly analysed, with the fingerprint region (1500 – 600 cm^{-1}) providing the highest discriminatory power for complex lipid and protein structures. In *halal* verification, FTIR-ATR can rapidly profile fats, oils and processed food ingredients to screen for potential non-*halal* constituents. Moreover, conventional *halal* verifications methods such as DNA-based technique (PCR) and chromatography (GC-MS, HPLC), while accurate, can be time-consuming, costly and require tedious and laborious sample extraction preparation (Suparman, 2015). In contrast, the FTIR provides a faster, more practical and affordable alternative for large-scale *halal* authentication and quality assurance programs.

Raw FTIR spectra often contain background noise, baseline shifts and overlapping peaks which made data interpretation difficult. To address the aforementioned problems, it has been noted that chemometric techniques such as principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) are routinely applied to extract meaningful

information from the spectral data (Rahayu *et al.*, 2021). Data pre-processing steps such as smoothing, baseline correction, first or second derivative transformation and standard normal variate (SNV) normalisation are typically performed to enhance spectral clarity and reduce noise before multivariate analysis. Chemometric analysis enables pattern recognition, classification and quantitative prediction of *halal* status, transforming FTIR into a powerful tool for food authentication. For example, the PCA helps in visualizing clustering patterns in differentiate FTIR spectral pattern of proteins, fat and other macromolecules from *halal* and non-*halal* sources while PLS-DA build predictive classification models by correlating FTIR features with verified reference data (Sani *et al.*, 2023). A comparative review by Ahda & Guntarti (2023) showed that FTIR-multivariate data analysis yields comparable accuracy to GC-MS, e-nose and PCR-RT techniques in detecting non-*halal* components while being simpler, faster and more cost-efficient.

Empirical validation studies further support FTIR's reliability as reported by Xu *et al.* (2012) where successfully discriminated between *halal* and non-*halal* Chinese sausages using transmission FTIR (4000 – 400 cm^{-1}) and PLS-DA, achieving >90% classification sensitivity. Witjaksono *et al.* (2017) identified distinct lard-specific absorption peaks of FTIR wavenumber at 1159.6, 1743.4, 2853.1 and 2922.5 cm^{-1} by which were absent in *halal* animal fats such as beef and lamb. Complementary the GC-TOF-MS analysis confirmed higher concentrations of 1,2,3-trimethylbenzene, indane and undecane in lard, validating the FTIR's discriminatory capacity. More recently, Alsaqri *et al.* (2023) used FTIR-ATR coupled with PLS-DA to detect lard-adulterated gelatine in ice cream, which achieving a prediction error of 0.098 while studies on pork oil adulteration in tuna oil reported $R^2 > 0.99$ and root mean square error (RMSE) < 3%, which capable of identifying contamination as low as 1 – 2% (*w/w*). These results highlight FTIR's potential in monitoring HT integrity, where even trace levels of contamination are unacceptable. Despite its proven utility, FTIR is fundamentally a profiling (non-targeted) approach that relies on multivariate modelling and high-quality reference datasets. Its accuracy depends on robust calibration, controlled measurement conditions and representative sample diversity. Variability due to matrix effects or overlapping peaks can affect reproducibility, thus, the FTIR should ideally be integrated with complementary other targeted techniques such as GC-FID, LC-MS or DNA-based assays for confirmatory verification (Nazri *et al.*, 2025). Standardisation of FTIR acquisition parameters, spectral libraries and multivariate data analysis workflows across laboratories is also essential for enhancing regulatory acceptance and ensuring analytical consistency.

The FTIR has been proven to be a useful screening tool in *halal* authentication in many consumer products particularly food. However, its effectiveness relies on optimized spectral analysis and advanced chemometric methods like PCA and PLS-DA to enhance it classification accuracy. Furthermore, knowingly FTIR is fast but often requires multivariate modelling and high-quality reference datasets; it is generally profiling (not targeted) and therefore needs robust validation. Its sensitivity to sample preparation, matrix complexity and spectral overlaps can also limit its accuracy. The integration with DNA-based or

chromatography techniques can offer a more definitive approach. Standardization of FTIR protocols across different food matrices is also essential to enhance its reliability and regulatory acceptance and its potential lies with combination with machine learning and complementary analytical methods to strengthen food integrity and consumer trust.

3. Chromatography Aspects of HT in Food Products

Chromatographic techniques, such as high-performance liquid chromatography (HPLC) is one of the essential analytical techniques in HT authentication, offering a reliable foundation for the precise separation, identification, and quantification of chemical substances that could compromise the integrity of *halal*-certified products (Hossain *et al.*, 2021). This segment of the review provides a comprehensive and analytical examination of chromatographic method function in complying not only with *halal* principles but in terms of safety (*toyyiban*), highlighting its efficacy in detecting prohibited substances, verifying the authenticity of *halal* ingredients, and assessing aspects related to product safety and quality. The operational principles of HPLC, which rely on the differential partitioning of analytes between a stationary and mobile phase, facilitate the high-resolution separation of intricate mixtures (Nurani *et al.*, 2022). It explores the selection and optimisation of various combinations of stationary and mobile phases, as well as the use of several detection techniques, including UV-Vis, a diode array, and mass spectrometry.

The identification of porcine-derived materials, a major concern in *halal* certification, is investigated through the study of certain amino acid in *halal* and non-*halal* gelatines (Rohman *et al.*, 2025). Ismail *et al.* (2021) used ultra-high-performance liquid chromatography diode-array detector (UHPLC–DAD) with the incorporation of principal component analysis (PCA) to investigate the distribution of 17 amino acids (AAs) in 50 fish, 50 bovine and 54 porcine gelatines. The PCA showed that the L-Serine (Ser), Arginine (Arg), Glycine (Gly), L-Threonine (Thr), L-Methionine (Met), L-Histidine (His) and L-Hydroxyproline (Hyp) were significant in fish gelatine; Hyp, Met, Thr, Ser, His, Gly, and Arg in bovine gelatine; and L-Proline (Pro), L-Tyrosine (Tyr), L-Valine (Val), L-Leucine (Leu), and L-Phenylalanine (Phe) in porcine gelatine. The 100% fish, bovine and porcine gelatines accommodated grouping 1, 2 and 3, respectively, which proved that AAs with strong factor loading (Hyp, His, Ser, Arg, Gly, Thr, Pro, Tyr, Met, Val, Leu and Phe) were the significant AAs and becomes the biomarkers to identify the gelatine source.

In the meanwhile, liquid chromatography-mass spectrometry (LC-MS) is a powerful tool for HT authentication due to its high sensitivity and low detection limit. It can simultaneously detect multiple species markers and identify different tissue origins with a single species. Windarsih *et al.* (2022) developed an untargeted metabolomics approach to detect the presence of pork in beef meatballs for *halal* authentication. This method involved the analysis of various metabolite classes, including amino acids, organic acids, fatty acids, nucleotides, peptides and lipids, using liquid chromatography-high resolution mass spectrometry of LC-HRMS combined with chemometrics. The study also identified several key metabolites that

play a crucial role in distinguishing pork contamination, including 1-(1Z-hexadecenyl)-sn-glycero-3-phosphocholine, N-acetyl-L-carnitine, DL-carnitine, anserine, hypoxanthine, linoleic acid, and prolylleucine. These biomarkers provide a reliable basis for detecting the presence of pork in processed meat products. The findings suggest that LC-HRMS-based untargeted metabolomics, when integrated with advanced chemometric techniques, offers a rapid, effective, and efficient analytical method for *halal* verification in meat products. Furthermore, the LC-MS/MS enables highly selective species identification with excellent sensitivity, supporting trace-level detection and quantitative estimation of adulteration in complex matrices. The technique also allows multiplex analysis, where many markers for different species can be monitored simultaneously in a single run, making it suitable for routine screening of highly processed commercial products. Recent proteomics studies have highlighted structured workflows for peptide marker discovery and validation that typically begin with untargeted LC-MS/MS or in-silico digestion to identify candidate peptides, followed by synthesis of standards, targeted method development and rigorous evaluation of marker robustness across processing conditions (Güngör *et al.*, 2025). These investigations show that peptide markers should be evaluated for processing stability, matrix effects and species specificity, supported by analytical validation parameters such as limit of detection, accuracy, precision, and reproducibility. Contemporary proteomics research underscores that the success of peptide-based authentication lies not only in marker discovery, but also in systematic validation to ensure that selected peptides are stable, unique and quantifiable under realistic processing conditions paving the way for transferable, standardized methods suitable for regulatory or industrial applications especially in HT food authentication, respectively.

Ethanol is commonly used in the food industry as a solvent, preservative, and flavour enhancer. However, its presence raises concerns in *halal* compliance, as alcohol is generally prohibited in Islam. The acceptability of ethanol in food depends on its source, concentration, and purpose (Pauzi *et al.*, 2019). Naturally occurring ethanol, such as in fermented foods or flavouring extracts, may be tolerated in minimal amounts, while ethanol added as an intoxicant is strictly prohibited. To ensure HT compliance, food products must be carefully analyzed to distinguish between permissible and non-permissible ethanol levels, ensuring they meet Islamic dietary laws. The study by Albaseer & Dören (2023) presents a simple and sensitive HPLC method for the simultaneous determination of ethanol and methanol in non-alcoholic beverages. Using pre-column derivatization with 9-fluorenylmethyl chloroformate (Fmoc-Cl) and fluorescence detection, the method demonstrated high sensitivity (LOD: 0.004 g/L for methanol, 0.015 g/L for ethanol) and high accuracy (98 – 109% recovery). Analysis of market samples revealed ethanol levels ranging from 0.11 – 0.71 g/L, with apple juice containing the highest amount, while no methanol was detected. The study concludes that this rapid and reliable HPLC method serves as an alternative to GC techniques and is valuable for monitoring ethanol content in food products, ensuring *halal* certification and consumer trust.

A different HPLC-UV approach was proposed by Nadeem *et al.* (2019) using a simple and efficient RP-HPLC-UV method for histamine detection in fish without derivatization. The method utilized a 2,5-dihydroxybenzoic acid (2,5-DHBA) UV probe, detecting histamine as a negative peak at 205 nm. Optimized with a mobile phase of acetonitrile and 2,5-DHBA (50:50, pH 2.65), the method achieved histamine detection within 5 minutes. Validation confirmed high accuracy, precision, and specificity, with a LOD of 1 mg/kg, LOQ of 3 mg/kg, and recovery above 82%, making it a cost-effective and rapid alternative for histamine analysis in fish. However, many studies have explored strategies to reduce biogenic amines (BAs) levels in food products, such as using selected starter cultures during the production and ripening of fermented sausages (Xie *et al.*, 2015). Similarly, incorporating probiotic bacteria in douchi fermentation and applying rose polyphenols (RPs) help prevent pH increase, lipid oxidation, and BAs formation in naturally dry-fermented sausages (Fong *et al.*, 2020; Capitani *et al.*, 2013). The reduction of BAs in each sample was quantified using high-performance liquid chromatography (HPLC) techniques with a gradient elution procedure and UV detection. The ability of HPLC to separate, identify, and quantify species-specific markers, contaminants, and bioactive compounds reinforces its role in *halal* authentication. Advancements in chemometric techniques, untargeted metabolomics, and novel derivatization methods have further improved detection accuracy and efficiency. As food safety regulations become more stringent, integrating HPLC with mass spectrometry and fluorescence detection techniques will enhance *halal* verification processes, ensuring compliance with Islamic dietary laws and global food safety standards. Additionally, Yuswan *et al.* (2020) emphasize that *halal* laboratories must comply with ISO 17025, GLP, and GMP standards to ensure accurate and reliable analytical results.

4. Molecular Study of HT in Food Products

The exploration of molecular studies, particularly the application of Polymerase Chain Reaction (PCR) in HT detection laboratories has gained substantial significance in the context of food products in Malaysia. As the HT entails both the permissibility and the quality of food, necessitating rigorous methodologies to ensure that products meet both Islamic law and health standards (Azmi *et al.*, 2024; Azahar *et al.*, 2023). As Malaysia prides itself on being a global leader in *halal* food production, the integration of modern scientific methods such as PCR into the HT detection protocol is both a necessity and a commitment to quality and safety in food products. PCR has revolutionized the detection and analysis of biological materials. Its ability to amplify specific DNA sequences allows for detailed genetic fingerprints of microorganisms present in food products (Man *et al.*, 2007). For example, local fermented food products where the fermentation process can often produce complex microbial communities, PCR provides a robust mechanism for identifying potential contaminants and ensuring that products remain within the standards prescribed by *halal* certification bodies and health regulations (Salipante *et al.*, 2013). Furthermore, the application of real-time PCR (qPCR) in food safety underlines its applicability not just for

pathogen quantification but also for the rapid testing necessary for the vast array of food products in the market (Cohen *et al.*, 2020).

The necessity of rigorous testing methodologies aligns with the HT principles which require not only the *halal* nature of ingredients but also the health benefits associated with the final product (Dahlal, 2021). Research indicates that ensuring the safety and quality of HT products encompasses a multi-faceted approach involving quality management systems, operational efficiency and adherence to stringent hygiene standards throughout the production and supply chain (Abdul Rahman & Sahari, 2022). Statistical analysis such as Exploratory Factor Analysis (EFA) have shown that total quality management practices directly influence the HT attributes of *halal* food items which reinforcing the importance of scientific validation in maintaining *halal* integrity. Moreover, local fermented food products rich in probiotics and other beneficial microorganisms which complicate the microbial landscape, making effective monitoring crucial. Conventional microbiological methods, while useful, fall short when it comes to the specificity and sensitivity that PCR-based methods offer. For instance, the ability of PCR to detect rare bacterial sequences within complex mixtures is essential in ensuring the reliability of fermented food products and thus, bolstering consumer trust (Singpanomchai *et al.*, 2019). Additionally, the advancements in PCR technology such as combining it with other molecular techniques such as Recombinase Polymerase Amplification (RPA) demonstrate the ongoing evolution of these methodologies toward achieving more complex and rapid diagnostic capabilities (Daher *et al.*, 2016).

In terms of instrumentation, the integration of automated systems into HT detection laboratories revolutionizes the efficiency of PCR testing, streamlining workflows and reducing the possibility of human error (Lin & Wu, 2024). Novel designs of low-cost, multichannel automatic pipetting systems highlight an essential step toward making molecular diagnostics more accessible within local contexts especially in Malaysian laboratories serving diverse populations and product ranges (Walczak, 2011). These advancements are particularly crucial in geographically dispersed rural areas where access to sophisticated laboratory infrastructure is limited and thus, portable and decentralized testing can play a significant role in ensuring compliance with *halal* standards nationwide. The interpretation of PCR results also involves evaluating the amplification bias that may arise during the testing of heterogeneous food matrices. This can lead to inaccurate results or misinterpretation of the actual microbial populations present in foods (Gorris & Soukka, 2022). Continuous studies and innovations are required to mitigate such challenges particularly through meticulous optimization of primer selection and amplification processes aligned with the unique microbial ecosystems associated with various food products (Kua *et al.*, 2022; Kralik & Ricchi, 2017). The sensitivity of the assay also underscores the need for rapid pathogen detection which emphasizing the critical role of PCR in safeguarding public health by enabling swift identification of potential hazards in food (Chessler & Lee, 2018).

The need for an evidence-based approach toward HT food products is not solely grounded in compliance but also in narrative-building around the health benefits and quality assurance

associated with the *halal* status. Integrating scientific methods reinforces the credibility of *halal* certifications and enhances consumer confidence in locally produced items (Al-Saari *et al.*, 2024). The intersection of faith and scientific inquiry creates a compelling narrative that positions *halal* food products as not merely compliant with religious standards but also as scientifically validated options that promote consumer health and well-being (Sultana *et al.*, 2024). It is also important to address the implications of digital immunoassays and the emergence of lab-on-a-chip technologies that may complement traditional PCR methodologies. Such innovations promise to further enhance the sensitivity and efficiency of detecting foodborne pathogens and thus, contributing to the overarching goals of HT through rapid and reliable diagnostics in food safety (Herdiana *et al.*, 2024). These advances align with the holistic view required for modern food safety which bridging traditional practices with contemporary scientific advancements.

The contemporary landscape of *halal* food production in Malaysia is marked by a symbiotic relationship between traditional values and modern scientific inquiry. This confluence is demonstrated in HT products which leverage molecular techniques such as PCR to uphold food integrity. By rigorously applying these techniques, laboratories can assure stakeholders from producers to consumers that the products adhere to the twin pillars of halal compliance and health-promoting attributes. In conclusion, the integration of PCR in HT detection laboratories of food products underscores a transition toward more sophisticated, science-based practices. The emphasis on aligning these practices with rigorous quality control measures contributes significantly to the growth and sustainability of Malaysia's *halal* food sector. As we continue to explore and refine these methodologies, it is crucial to maintain an adaptive framework that incorporates emerging technologies, stakeholder engagement and ongoing research to which ensuring that Malaysia remains at the forefront of the global *halal* food arena.

Table 1. The summary of comparison PCR-based molecular detection considerations for HT food products.

Parameter	Performance in PCR-based detection	Matrix dependency (Hydrolysed vs Intact)	Common inhibitors in Food Matrices	False negative risks	Required controls	Recommended confirmatory strategies
Analytical sensitivity	High sensitivity; capable of detecting low copy number targets due to exponential amplification and primer specificity	Hydrolysed samples: increased accessibility of DNA, improving detection; Intact samples: cell wall integrity can reduce DNA release	Polysaccharides, phenolic compounds, lipids, proteins, humic substances; fermentation metabolites	Incomplete lysis, primer mismatch, low template, poor extraction efficiency, inhibitor interference	Positive amplification control (PAC), internal amplification control (IAC), extraction control	Repeat assay with optimized extraction, sequence verification (Sanger), increased cycle number only if validated
Matrix Dependency	High susceptibility to complex food matrices; performance influenced by extraction quality, DNA fragmentation, and sample heterogeneity	Hydrolysed: degraded DNA may reduce amplicon size suitability; Intact: higher structural complexity affects extraction yield	Salt, fats, pH extremes, fermentation by-products	Underestimation of microbial load, absence of amplification despite target presence	Matrix spike recovery controls; negative matrix blank	Orthogonal method (culture, microscopy), spiking experiments
Specificity	High when primers/probes are well designed; prevents cross-reactivity with non-target microorganisms	Minimal differences between matrix states; design more influential than matrix	Non-specific binding due to degraded DNA	Amplification of off-target sequences interpreted as positive	No-template control (NTC), melt-curve analysis	Sequencing of amplicons; species-specific confirmatory assay

Parameter	Performance in PCR-based detection	Matrix dependency (Hydrolysed vs Intact)	Common inhibitors in Food Matrices	False negative risks	Required controls	Recommended confirmatory strategies
Robustness Against Inhibitors	Moderately robust; qPCR more tolerant than conventional PCR	Hydrolysed: potential accumulation of soluble inhibitors; Intact: inhibitor entrapment in tissue	Polysaccharides, organic acids, peptides, crude fats	Delayed Ct values, incomplete amplification, false negatives	IAC to detect inhibition; dilution control; inhibitor removal steps	Alternative extraction method; droplet digital PCR for inhibitor tolerance
Turnaround Time	Rapid detection capability pivotal for high-throughput *halal* testing	Faster with hydrolysed matrices due to improved extraction kinetics	Time-consuming purification steps when inhibitors present	Premature assay termination due to inhibition	Workflow controls, reagent blanks	Rapid isothermal methods (RPA), lab-on-chip verification
Quantitative Interpretation	qPCR enables quantification of microbial load with high precision	Hydrolysed matrices may produce fragmented DNA affecting quantification accuracy	Variation in extraction efficiency	Under or over-estimation of contaminant populations	Standard curve validation, extraction efficiency controls	Digital PCR for absolute quantification; culture confirmation

5. Microbiology-Based Intervention for HT Concept Validation

Globalization of food supply has further increased the emergence and spread of food-borne pathogens, requiring a more comprehensive safety framework in determining *halal* food status. Interestingly, as the word *halal* always coupled with *toyyiban* with combined expression as HT. Concerning the concept of *toyyiban*, all wholesomeness considerations which relates to hygiene, ingredient additives, contaminants status and pesticide residues need to be clarified as part of *halal* certificate issuance. On regulatory guideline aspect, implementing Halal Control Point (HCP), which resembles Hazard Analysis Critical Control Point (HACCP) approach, has ensured the highest possible levels of food safety with emphasis on eliminating cross-contamination of non-*halal* items into *halal* product (Demirci *et al.*, 2016). This guideline embodies the spirit of standardization of food cleanliness that should be read together HACCP MS 1480, Food Safety Principal MS 1514 and Good Hygienic Practice (GHP) regulations. In addition to that, any foods certified as *halal* should be safe for consumption, non-poisonous and non-hazardous to human health. Achieving this requires universally accepted framework, One Health (OH) approach brings adoption of HT paradigm with pre-defined components with a particular emphasis on sustainability of food safety interventions (Abdul Mokti *et al.*, 2024).

While FTIR, HPLC, and PCR target compositional authenticity, microbiological analysis complements them by verifying cleanliness and wholesomeness integral to HT assurance. Unluckily, the aspect of *toyyiban* is given a less consideration and voluntarily practiced especially on perishable items that potentially led to foodborne illnesses because of improper food handling and poor hygiene status (Fayyaz *et al*., 2022). Some examples of pathogenic microorganisms found such as *Salmonella*, *Campylobacter*, *Clostridium perfringens*, *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella sp.* and *Listeria monocytogenes* are of greatest global concern while producing lethal toxin (Biswas *et al.*, 2011). Taking an example of *Escherichia coli*, this bacteria group could possibly cause haemorrhagic diarrhoea and kidney failure. Failure to immediate product recall if enumeration testing showed up to minimum 20 colonies may result in mortality. High favourable conditions with high moisture of undercooked foods may accelerate the psychotropic growth of *Clostridium botulinum*, in which produces toxin botulin, the most poisonous substances ever. Besides, the impact of foodborne disease outbreaks can be tremendous, causing economic loss with approximately 513,000 reported death cases (WHO, 2019). In response to this deadly hazard, microbiological assessment of food safety has put a top priority to detect pathogenic and spoilage microorganisms present based on microbial load in the food products. A measurable hygiene indicator that commonly used by the laboratories is the total viable count of *Escherichia coli* and *Staphylococcus aureus*, which expressed as number of colonies appeared onto the selective media per grams of tested foods. This analysis method is culture-based method, which culturable propagules of microorganisms were then allowed to grow for minimum 1 up to 5 days (Bujang & Abdullah, 2018). Furthermore, Carrasco *et al.* (2022) spotlighted the standout observations of *halal* meat consumption in non-Muslim consumer.

It is noteworthy that *halal* meat consumption not only had a positive impact on participant's physiological appearance but gave a presence of crucial important gut microbiota with low antibiotic resistance. From their point of view, detection of bacterial genera of *Bacteroides* and *Alistipes* is instrumental in prevention of foodborne pathogens.

Here are the fieldwork ground assessments of various food products based on multiple detection approaches with reference to spoilage microorganisms in the context of *halal* production. Berthold-Pluta *et al.* (2019) concentrated their attention on the prevalence of enterotoxin-producing *Bacillus cereus* from 600 cereal food products. About 38% of samples were found positive with *B. cereus* with further characterization of 1022 spoilage isolates. The relatively high percentage (78%) among isolated strains is alarming with 803 were able to produce non-hemolytic enterotoxin (Nhe) toxin as detected by Tecra BDA VIATM Kit. Bacteria profiling from food samples based on their biochemical characterization can be performed by automated identification machine VITEK 2 system. Employing the dataset cluster analysis result generated by VITEK system, Al-Mazrouei *et al.* (2024) assessed the microbiological quality of Oman local raw beef meat, monitoring potential of spoilage pathogens risk based on the standard set by the Gulf countries. Coliform occurrence with 93% was found in thirty-three beef samples, while psychrotrophic spoilage bacteria known as *Pseudomonas fluorescens, Shewanella putrefaciens* and *Acinetobacter baumannii* were detected. The need of collaboration between meat industry and food safety authorities is essential to establish robust microbial monitoring system for public consumer health. Alijagić *et al.* (2023) proposed an investigation on the presence of *Listeria monocytogenes* focusing on fish products. The study showed that 3.12% was not compliant with *halal* quality criteria as *L. monocytogenes* were found positive in the selective *Listeria* agar. The authors reiterated that the persistence of *L. monocytogenes* recontamination along with production line was high likely possible to happen if prescribed sanitary measures was not taken in place. Hygienic-sanitary fish processing is required to avoid proliferation of listeriosis-inducing bacteria. Cheah *et al.* (2021) delved into the performance of the Food Safety Management System Diagnostic Tools (FSMS-DI) and Microbial Assessment Scheme (MAS) among powdered beverage manufacturers. Compliance into stringent food safety regulations with higher scores obtained has contributed to acceptable microbiological limit detection in the food operators' industries. No presence of *Escherichia coli* appeared in all critical sampling points.

Speaking the microbiological risk in food samples, Taha-Abdelaziz *et al.* (2023) outlined the strategies to control the *Campylobacter* outbreak in the chicken processing industries. One of the measures that have been received considerable attention is probiotic administration in the chicken feeding system. Dietary supplementation of probiotic strains (*Lactobacillus acidophilus*, *Lacticaseibacillus casei* and *Bifidobacterium thermophilum*) to chicken challenged by *Campylobacter jejuni* has resulted in 12% pathogen reduction. Safer alternatives including essential oils, short-chain fatty acids, eggshell sanitation and post-harvest stringent measures are suggested to reduce as much possible *Campylobacter* load

count. Noteworthy studies by Djenane *et al.* (2018) explored the biocontrol potential of olive leaves extract from *Olea europaea var. sylvestris* in raw *halal* minced beef. They treated minced beef with an extract concentration of 5% (*v/w*) and achieved a reduction of psychrotrophic counts as well as the level of *Salmonella enterica* and *Shiga* toxin-producing *E. coli* O157:H7, without jeopardizing the meat palatability quality. The chemistry of the oleuropein in terms of polyphenols has been identified with higher antimicrobial activity, hinting the preference of natural products over artificial preservatives. Another area of interest in food pathogen suppression is the application of bacteriocins derived from lactic acid bacteria (LAB) known as antimicrobial peptides (AMPs) for food preservation. Incorporation these antimicrobials into food products was believed to disrupt the intracellular components of targeted microbes that lead to cell dysfunction. Taking an example, Pimentel-Filho *et al.* (2014) observed reduction of *L. monocytogenes* after treating fresh cheese with bacteriocin nisin. Importantly, this approach requires additional scrutiny to ensure *halal* integrity, aligning the HT principles. To the best of our knowledge, the convergence of microbiological-based intervention into *halal* products holds a promising avenue to promote both consumer safety and unified standardisation systems.

6. Multivariate Data Analysis Approach

The multivariate data analysis (MVDA) or chemometric can defined as the discipline of knowledge that uses mathematical and statistical methodology to extract information from large and complex datasets with chemical and biological information. The concept of pulling out the information from chemical systems by usage of multivariate statistics was already investigated in the 1960s (Brereton, 2014). Moreover, it is known that the use of multivariate methods is by far the most popular in the area of applied or analytical chemistry (Wang *et al.*, 2022), which then later the MVDA has been introduced step-by-step in various research areas as such food sciences, postharvest technology and in recent years in the *halal* science, respectively (Nurani *et al.*, 2022). Thereupon, for some reasons, the application of MVDA for *halal* research has not yet fully utilized especially for the HT laboratory instrumentation detections due to several challenges and limitations. Firstly, as the adoption of MVDA requires advanced analytical skills and specialized software, which may not be readily available in all laboratories. Due to this reason, many existing HT laboratories rely on conventional single-variable analysis methods that are easier to interpret but may lack the sensitivity and robustness that needed for the complex for matrices as an example (Rohman & Windarsih, 2020). Meanwhile, the implementation of MVDA also requires specialized software tools such as MATLAb, SIMCA, XLSTAT, MetaboAnalyst that which may involve significant licencing costs and steep learning curves for the end users to understand and master all the necessary software's interferences which may takes ages (Chong & Jia, 2020). Next, the integration of MVDA tools with laboratory instruments, such as FTIR, GC, HPLC and so on, demands the significant initial investments of the infrastructure and training. It is also known that the aforesaid advanced instrumentations generate large, complex datasets that can only be fully leveraged through the MVDA techniques and often necessitates

customized the hardware and software integration, adding to the initial setup cost (Hupp *et al.*, 2024).

For some reason, the MVDA able to covers a wide range of data analysis principles and data types. By linked to the diversity of the challenges originating from the analytical procedures as well the research questions, these methods can be used for different purposes such as data exploration, prediction and classification or interference. In addition to that, MVDA is an active field of research in which methods are being develop or improved frequently (Jiang *et al.*, 2024). Furthermore, it is not straightforward to propose a general methodology for a MVDA that is applicable for all acquired data. As such, related to the main steps of MVDA, a number of questions should be considered by researchers before start of the analysis in order to make very important decisions. The decisions to be made are related to the type of analysis as well as the pre-processing method to be applied. Next to the point addressed below, it is noteworthy to mention that prior to the actual analysis, researchers should also think about the experimental design, sample selection and data collection as they are critically importance for the actual data analysis (Mishra *et al.*, 2021). Conversely, this review section will specifically focus on a particular number of methods of MVDA toward the HT such as the principal component analysis (PCA), discriminant analysis (DA) and partial least squares discriminant analysis (PLS-DA) respectively. These data analysis techniques were selected based on the number of publications in which they were used, their applicability to the wide range of common problem mainly in the authentication and verification hence their potential for the HT laboratory instrumentation, independently. The integration of MVDA techniques, such as PCA, has greatly advanced the analytical precision and reliability of *halal* authentication methods through laboratories instrumentations. The PCA, as one of the most widely utilized techniques, plays a crucial role in reducing the dimensionality of complex datasets obtained from sophisticated analytical instruments, such as FTIR spectroscopy, Nuclear Magnetic Resonance (NMR), and GC-MS, respectively (Dayananda *et al.*, 2024). These instruments often generate extensive data, often comprising numerous variables, which can be difficult to interpret directly. Thus, by applying the PCA, researchers can condense this data into principal components (PC) that capture the maximum variance, thereby simplifying the analysis and highlighting key patterns and relationships within the data. An example of PCA's application in *halal* authentication utilizing the laboratory instrumentation detection can be seen in its use for differentiating *halal* and non-*halal* samples in various food matrices. In 2016, Ahda *et al.* (2016) reported the application of HPLC-UV combined with PCA for analysis lard that presence in both beef and pork meatball. The result indeed proved that beef and pork meatball indeed can be distinguished by the PCA, respectively. Next, Ahda *et al.* (2021) also reported in 2021 that the usage of PCA to differentiate *halal* and non-*halal* meatballs derived from wild boar, pork and beef through comparing saturated and unsaturated fatty acids composition examined by GC-MS. By 2023, Windarsih *et al.* (2023) published an article mentioning the use of liquid chromatography equipped with high-resolution mass spectrometry (LC-HRMS) methodology to determine the *halal* authenticity of beef sausage and beef sausage that containing pork through

untargeted metabolomics approach. Meanwhile, the use of PCA by SIMCA and Metaboanalyst software able to discriminate the sausage with high accuracy in hope to use the certain metabolites as the biomarkers. Recently, Nazri *et al.* (2024) also uses the PCA with the aid of FTIR-ATR spectroscopy by the wavenumber of 4000 – 650 cm^{-1}, respectively. The PCA result revealed clear clustering of samples of animal fatty acids comprising beef, chicken, mutton, and pork based on the specific bands at functional and fingerprint regions.

For instance, in a study whereas the FTIR spectra were collected from various food products, the PCA was employed to distinguish between *halal* and non-*halal* samples by identifying specific chemical fingerprinting patterns associated with different ingredients or contamination (Windarsih *et al.*, 2023). In this case, the multivariate approach enabled the classification of the samples based on subtle chemical differences, such as the presence of non-*halal* animal-derived ingredients, contaminants or any adulterations, while simultaneously reducing the computational complexity involved in analysing large amounts of spectral data. It has been reported by Irnawati *et al.* (2023) in recently, the use of combination of FTIR-ATR spectroscopy for the rapid detection of lard in high-quality tuna fish oil with the aid of chemometric as such the PCA not only for authentication but also to warrant the quality and the *halal* status of tuna fish oil for the consumers. Furthermore, this technique findings not only proved an effective discrimination of *halal* and non-*halal* contaminants but also supports the implementation of Indonesian Act No. 33 (2014) which concerning the Halal Assurance system (HAS). Nevertheless, although the FTIR and PCA are widely utilized in the detection of non-*halal* contaminants or adulterations due to their effectiveness and versatility, they are limitations that need to be considerate (Nazri *et al.*, 2025). For example, Badrul *et al.* (2023) highlighted the use of FTIR and PCA as a rapid and cost-effective method for detecting pork gelatine in hard-shell capsules used in supplement products. However, they concluded that PCA has limitations in differentiating adulteration within the capsule shells. This is evident from the irregular PCA score plot for the capsule shell samples, which closely resembled the profile of bovine gelatine, making clear distinction challenging (Mubarok & Rohman, 2022). Thus, the PCA indeed has demonstrated its value in processing and interpreting such large datasets efficiently, improving the overall accuracy of *halal* authentication in food products. So, this approach not only enhances the reliability of detection but also supports the development of more effective, data-driven methods for HT verification in food safety laboratories. Pranata *et al.* (2021) reported the approach of solid-phase microextraction-gas chromatography-mass spectrometry (SPME/GC-MS) and MVDA of PCA to classify the meatball product of beef, chicken and wild boar (non-*halal* species) based on their volatile compound contents of acids, aldehydes, aliphatic hydrocarbons, cyclic aromatic hydrocarbon, heterocyclics and many more compounds respectively.

DA is another critical technique extensively utilized in *halal* authentication studies. By establishing classification boundaries, DA aids in identifying and distinguishing *halal* products from non-*halal* ones based on physicochemical properties and spectral profiles. In

conjunction with instrumentation such as FTIR, LC-MS and Raman spectroscopy, DA has shown remarkable performance in accurately classifying meat and processed food samples. It has been reported by Lestari *et al.* (2022) the use of DA to predict the class membership of unknown samples of beef, rat and beef-rat meatballs from fat extraction and FTIR spectra measurement at specific wavenumber region as variables. It is found that the DA was successfully able to classify lipid components extracted from all meatballs through Bligh and Dyer, Folch and Soxhlet methods with 100% accuracy levels, respectively. Next, Wirnawati *et al.* (2023) reported the FTIR analysis with DA to analysis adulteration of dog meat by the lipid in beef sausage. The outcome of this research is with DA about 100% accuracy of success to discriminate the lipid elements which used to from beef, dog and mixture of beef and dog sausages based on the detection and measurement of dog meat in beef sausage formulation. Moreover, the application of DA has also been extended to the detection and quantification of adulterants in food matrixes, amplified by HT scope which referring to the wholesomeness to the Muslim, respectively. It has been reported by Tan *et al.* (2023) the leveraging of MVDA as such DA demonstrated the capability to discriminate the quantify urea as adulterant in UHT milk. The findings showed 100% correct classification of UHT milk with a sensitivity as low as 1 *w/v*% of rendering urea in the UHT milk and due to this result, it is suitable for commercial applications and as a routine analysis for analytical laboratories, nevertheless.

PLS-DA extends the application of multivariate analysis by modelling the relationship between instrumental variables and categorical *halal* labels. Moreover, many researchers frequently utilize PLS-DA in HT food product research due to its effectiveness in handling complex, multidimensional data and its ability to model relationships between observed variables and latent constructs (Maritha *et al.*, 2023). The PLS-DA is particularly advantageous when dealing with small sample sizes and when the primary objective is predictive modelling rather than hypothesis testing. Unlike PCA, which focuses on variance, PLS-DA maximizes the separation between *halal* and non-*halal* groups by integrating latent variable information, thus offering superior classification accuracy. Next, Ali *et al.* (2020) performed metabolite profile of *halal* and non-*halal* broiler chicken using FTIR spectroscopy and ultra-high performance liquid chromatography-time of flight-mass spectrometry (UHPLC-ToF-MS) coupled with PLS-DA using MetaboAnalyst, respectively. It is found that through the PLS-DA model data the lower intensity of histidine in chicken which slaughter by Islamic way as compare conventional slaughtering method. Moreover, the *halal* slaughtering process imposes increased metabolic demands on the chicken, leading to an enhanced breakdown of amino acids to meet energy requirements. The study suggests that the prolonged period before death in *halal* slaughtered chicken's results in a lower concentration of amino acids, as they are catabolized to provide essential energy substrates for cellular functions.

The application of multivariate data analysis techniques, such as PCA, DA, and PLS-DA has significantly enhanced the accuracy and reliability of HT laboratory instrumentation for food

product detection through suggested pipeline in Figure 1, respectively. These techniques facilitate the differentiation of *halal* and non-*halal* food components by efficiently handling complex, high-dimensional datasets obtained from spectroscopic, chromatographic, and mass spectrometry-based methods. The PCA plays a crucial role in reducing data dimensionality while preserving essential variance, allowing researchers to identify key patterns and variations in food composition. DA further strengthens classification by distinguishing between *halal*-compliant and non-compliant samples based on predefined groups, making it a valuable tool for authentication studies. Meanwhile, the PLS-DA provides superior predictive modelling capabilities by establishing correlations between spectral data and halal classification, enabling robust and reliable food product verification. By integrating these multivariate approaches, HT laboratories can enhance food authentication and verification, improve quality assurance processes, and ensure compliance with *halal* standards through recommended workflow shown in Figure 2. The combination of PCA, DA and PLS-DA not only optimizes analytical workflows but also strengthens the credibility and efficiency of modern halal food testing, reinforcing consumer confidence in HT-certified products.

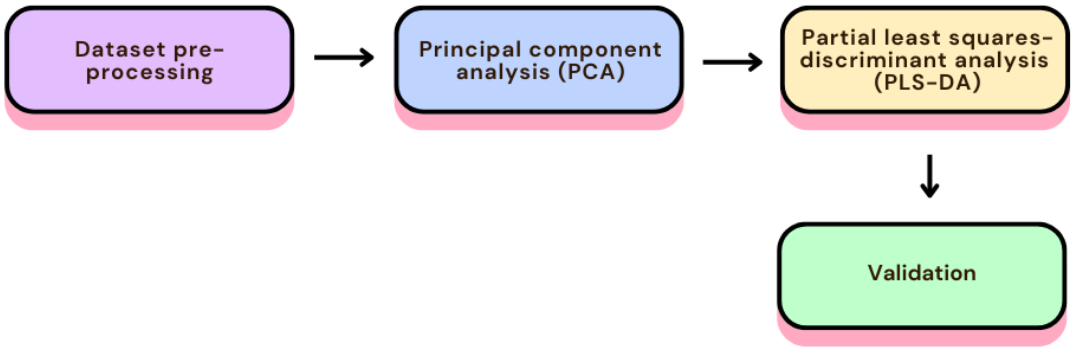

Figure 1. The example multivariate data analysis (MVDA) pipeline for HT authentication.

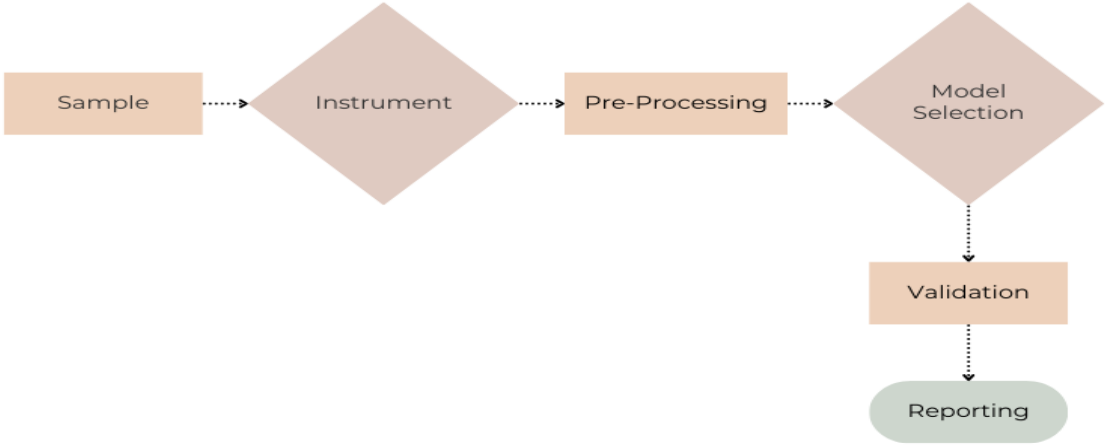

Figure 2. The flowchart of recommended workflow for HT integrating instrumentation and multivariate data analysis.

7. Validation, Accreditation and Practical Laboratory Implementation

A structured and transparent approach to method validation is central to ensure that laboratory instrumentation applied for HT authentication delivers results that are scientifically defensible, legally robust and fit for regulatory decision-making (Nazri *et al.*, 2025). Laboratories are generally expected to operate under the overarching framework of ISO/IEC 17025, which sets requirements for analytical competence, impartiality and metrological traceability, while validation of individual methods is guided by ISO 5725 and dedicated Eurachem guidance documents (Umar & Parakkasi, 2015). Within this framework, analytical performance characteristics including limit of detection (LOD), limit of quantification (LOQ), repeatability, reproducibility, trueness, robustness and measurement uncertainty are not merely technical indicators but underpin the credibility of analytical claims in halal authentication settings. For example, reporting LOD and LOQ is essential when determining trace levels of prohibited materials such as porcine fat, alcohol, or specific proteins, where small analytical differences may translate to significant religious and regulatory implications (Al Olan & Yossouf, 2023). Similarly, demonstrating repeatability and reproducibility ensures that a method is not only capable of detecting adulteration in controlled research settings but can perform consistently across operators, instruments, batches and laboratories, which is critical for multi-site surveillance or certification schemes.

Trueness and robustness also carry specific importance in HT contexts, where food matrices are chemically complex and may be influenced by thermal processing, fermentation, lipid oxidation or formulation variability. Robustness testing acts as a safeguard against false classifications by confirming that minor variations in experimental conditions such as extraction temperature, solvent purity, or instrumental parameters do not compromise classification accuracy (Mustapha *et al.*, 2024). Equally, the estimation and reporting of measurement uncertainty is necessary for laboratories intending to issue test reports for regulatory, certification or judicial purposes, as it quantifies the degree of confidence in analytical results and supports defensible decision-making when analyte levels fall near regulatory or religious thresholds. Accreditation under ISO/IEC 17025 therefore requires more than numerical performance outcomes; laboratories must document standard operating procedures, ensure traceable calibrations, participate in proficiency testing, monitor quality control metrics, and maintain a culture of continuous improvement to sustain validity over time.

In the context of modern HT analytics, validation challenges are increasingly connected to the adoption of advanced instrumental platforms such as FTIR, GC, HPLC, MS-based lipidomics and proteomics, as well as chemometrics-driven classification models. These techniques require additional performance evaluation strategies that move beyond conventional univariate validation to multivariate model validation, including cross-validation, external validation, sensitivity/specificity assessment, model transferability, overfitting detection and class prediction uncertainty. In authentication workflows, model performance is often judged not only by analytical accuracy but by classification accuracy

its ability to assign samples correctly as *halal* or non-*halal*. Ensuring reproducible spectral signatures, stable feature selection, and robust model behaviour across different instrument types and food matrices is a prerequisite for deploying chemometric models in certification laboratories or industry settings (Amid, 2024). A recurring concern in validation of chemometric methods is that incomplete assessment of model generalisability may lead to false positives or false negatives, thereby undermining the religious integrity of *halal* assurance systems.

The broader accreditation ecosystem plays a pivotal role in translating validated methods into routine practice. Laboratories seeking recognition from national or Islamic authorities must integrate validation data into quality management systems, align reporting formats with regulatory expectations, and ensure that analytical capacity is supported by trained personnel and sustainable infrastructure. For countries with established *halal* governance systems, including Malaysia, validated analytical methods are increasingly viewed as part of the technical backbone of *halal* certification, enabling objective verification of conformity to HT principles (Hassan *et al.*, 2018). As the *halal* industry evolves toward high-value, processed, functional, and alternative protein products, the ability to validate advanced instrumental methods and demonstrate compliance with international standards will be crucial to support global trade, consumer confidence, and scholarly accountability. These priorities are consistently reflected in international guidelines such as ISO/IEC 17025, ISO 5725, and Eurachem's method validation and measurement uncertainty guides, which recognise that scientific rigour, metrological traceability, and transparency of uncertainty are foundational to trust in analytical outcomes and accreditation processes (Ling *et al.*, 2025; Hidayati *et al.*, 2024).

Table 2. Suggested checklist for validation/ISO 17025 compliance for HT laboratories.

Requirement/Activity	Status (Yes or No)
Section 1: Governance & Quality Management	
Quality Management System documented	
Quality policy (competence, impartiality, confidentiality)	
Risk assessment & corrective actions	
Document control system	
Internal audits scheduled & recorded	
Management review conducted	
Continuous improvement evidence	
Section 2: Personnel Competency	
Competency matrix for staff	
Role descriptions & authority defined	
Training records maintained	
Halal-relevant competency assessed	
Ongoing professional development	
Authorized signatories listed	

Section 3: Environment & Equipment	
Environmental controls adequate	
Instrument maintenance logs	
Calibrations traceable (SI units)	
Verification for non-calibrated items	
Instrument performance checks	
Backup systems available	
Section 4: Method Validation	
Method scope and purpose defined	
Sample preparation defined	
LOD & LOQ determined	
Repeatability assessed	
Reproducibility assessed	
Trueness evaluated	
Precision evaluated	
Robustness tested	
Selectivity/specificity evaluated	
Recovery/spike recovery evaluated	
Linearity/working range assessed	
Measurement uncertainty estimated	
Statistical analysis documented	
Validation report approved	
Fit for *halal* purpose	
Section 5: Halalan Toyyiban (HT) Requirements	
Target analytes relevant to *halal*	
Threshold limits established	
Decision rule defined	
False positive/negative risk assessed	
Matrix effects evaluated	
Processed foods validated	
Staff trained in *halal* ethics	
Section 6: Chemometric/Spectroscopic Model	
Workflow defined	
Pre-processing validated	
Model optimization documented	
Accuracy, sensitivity, specificity	
Classification rate	
Confusion matrix	
ROC/AUC	
Cross-validation	
External validation	

Independent test set	
Overfitting check	
Model transferability tested	
Version control system	
Section 7: Sample Handling & Traceability	
Sampling plan documented	
Chain of custody implemented	
Unique sample identification	
Storage conditions monitored	
Retention policy defined	
Procedure for suspect samples	
Section 8: Calibration & Quality Control	
Traceable calibration procedures	
Use of CRMs when applicable	
Calibration intervals justified	
Control charts implemented	
QC samples included per batch	
Acceptance criteria defined	
Out-of-spec results investigated	
Section 9: Measurement Uncertainty	
Sources of uncertainty identified	
Methodology documented	
Uncertainty budget prepared	
Propagation calculated	
Uncertainty reported	
Decision rule *halal*-aligned	
Section 10: Documentation & Reporting	
SOPs approved & version controlled	
Electronic records secured	
Reports include method & standard	
Results & uncertainty reported	
Decision rule stated	
Halal conformity stated	
Record retention policy	
Section 11: Proficiency Testing	
Participation in proficiency testing schemes	
Proficiency testing performance evaluated	
Corrective actions implemented	
Inter-lab comparisons planned	
Section 12: Regulatory & Religious Compliance	
Compliance with ISO/Codex	

Alignment with *halal* standards (MS/OIC)	
Decision rules documented	
Consultation with authorities	
Updates monitored & integrated	
Section 13: Risk Management	
Risk register maintained	
Non-conformance system in place	
Root-cause analysis performed	
Preventive/corrective actions	
Effectiveness verified	

8. Conclusions

Ensuring compliance with HT standards in food products requires a tiered analytical strategy in which rapid spectroscopic tools such as FTIR serve as first-line screening platforms for high-throughput assessment, while chromatographic methods (HPLC) and molecular assays (PCR) provide confirmatory, quantitative identification of specific adulterants, supported by microbiological testing to verify hygiene and safety. To translate these capabilities into routine practice, immediate priorities include standardization of analytical protocols, establishment of validated performance criteria, and coordinated ring trials to enable inter-laboratory comparability, reproducibility and accreditation readiness. A forward-looking research agenda should target the development of verified peptide markers for species authentication, harmonized spectral libraries and reference materials for FTIR-based profiling, and interoperable chemometric models that are shareable, transferable, and transparent across different instruments and laboratories. Advancing these initiatives through collaborative, cross-institutional efforts will accelerate method maturation, reduce operational barriers, and create a scalable, data-driven ecosystem capable of delivering reliable, cost-effective, and globally aligned HT assurance.

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References

Abdul Mokti, H., Kamri, N. A., & Mohd Balwi, M. A. W. F. (2024). *Tayyiban* in *halal* food production: A systematic literature review. *Journal of Islamic Marketing*, *15*(2), 397–417.

Abdul Rahman, F. A., & Sahari, N. H. (2022). The conceptual analysis of the *halalan toyyiban* for practices of food handling in food truck business. *Journal of Contempory Islamic Studies (JCIS)*, *8*(2), 55–66.

Ahda, M., & Guntarti, A. (2023). *Halal* food analysis using FTIR spectroscopy combined with chemometrics: A Review. *Current Nutrition & Food Science*, *19*(2), 125–135.

Ahda, M., Guntarti, A., & Kusbandari, A. (2016). Application of high-pressure liquid chromatography for analysis of lard in the meatball product combined with principal component analysis. *Asian Journal of Pharmaceutical and Clinical Research*, *9*(6), 120–123.

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. *Songklanarin Journal of Science and Technology*, *43*(2), 352–355.

Ahmad, A. N., Hashim, Y. Z. Y., Latif, N. H. M., Jaiyeoba, H. B., Samsudin, N., & Said, N. M. (2021). Positioning *halalan toyyiban* in *halal* food system: Production, processing, consumption, marketing, logistic and waste management. *Halalsphere*, *1*(2), 17–40.

Al Olan, M. S. M., & Yossouf, A. A. P. (2023). Laboratory methods for authenticating the conformity of halal foods. In *Halal and Kosher Food: Integration of Quality and Safety for Global Market Trends* (pp. 77–92). Cham: Springer International Publishing.

Al-Mazrouei, M. A., Al-Kharousi, Z. S., Al-Kharousi, J. M., & Al-Barashdi, H. M. (2024). Microbiological evaluation of local and imported raw beef meat at retail sites in Oman with emphasis on spoilage and pathogenic psychrotrophic bacteria. *Microorganisms*, *12*(12), 2545.

Al-saari, N., Sani, W. A., Azmi, N. S. A., Fujiyoshi, S., & Maruyama, F. (2024). Emerging microbial intervention technologies and innovations for enhanced food quality and safety from a *halalan toyyiban* perspective and one health approach. In *Solving Halal Industry Issues Through Research in Halal Sciences* (pp. 145–169). Singapore: Springer Nature Singapore.

Albaseer, S. S., & Dören, L. (2023). Simultaneous determination of ethanol and methanol in non-alcoholic beverages by precolumn derivatization and liquid chromatography with fluorescence detection. *Journal of Food and Bioprocess Engineering*, *6*(1), 81–86.

Ali, N. S. M., Zabidi, A. R., Manap, M. N. A., M. N., Zahari, S. M. S. N. S., & Yahaya, N. (2020). Identification of metabolite profile in *halal* and non-*halal* broiler chickens using Fourier-transform infrared spectroscopy (FTIR) and ultra high-performance liquid chromatography-time of flight-mass spectrometry (UHPLC-TOF-MS). *Malaysian Applied Biology*, *49*(3), 87–93.

Alijagić, A., Čaklovica, F., Čaklovica, K., Rahmanović, B., Hrustemović, E., Fazlović, N., Hojkurić-Rahmanović, Z. (2023). Microbiological correctness of fish with reference to *Listeria monocytogenes* in the context of importance to *halal* production. In *Congress of Halal Quality 2023*. Islamic Comunity in Bosnia and Herzegovina, Agency for Halal Quality Certification.

Alsaqri, S. N., Mabood, F., Boqué, R., Jabeen, F., Ahmad, A., Hussain, J., Sohail, M., Syed, M. G., Melhi, S., Shahzad, A., Khan, M. N., Al-Amri, I., Shah, R., & Din, I. U. (2023). Rapid detection of pork gelatin in ice cream samples by using non-destructive FT-NIR spectroscopy and partial least squares-discriminant analysis. *Food Chemistry Advances*, *2*, 100215.

Amid, A. (2024). Halal Detection Technologies. *Solving Halal Industry Issues Through Research in Halal Sciences*, 41–54.

Azahar, N. N., Muhammad, N., Abdul Rahim, N. F., & Leong, Y. S. (2023). Formulation of *halalan toyyiban* radish effervescent tablet. *International Food Research Journal*, *30*(3).

Azmi, N. A. N., Noor, N. M., Elgharbawy, A., & Darmawan, N. (2024). Combining science and faith for better quality and safety in *halalan toyyiban* products. *Halal Studies and Society*, *1*(3), 12–14.

Badrul, A. I., Munir, M. A., Riani, I. G., & Sa'adah, R. (2023). The rapid detection of pork gelatin in hard shell capsule on supplement products using FTIR and PCA. *AJARCDE (Asian Journal of Applied Research for Community Development and Empowerment)*, 23–27.

Berthold-Pluta, A., Pluta, A., Garbowska, M., & Stefańska, I. (2019). Prevalence and toxicity characterization of *Bacillus cereus* in food products from poland. *Foods*, *8*(7), 269.

Biswas, A. K., Kondaiah, N., Anjaneyulu, A. S. R., & Mandal, P. K. (2011). Causes, concerns, consequences and control of microbial contaminants in meat – A review. *International Journal of Meat Science*, 1, 27–35.

Bonne, K., & Verbeke, W. (2008) Muslim consumer trust in *halal* meat status and control in Belgium. *Meat Science*, 79(1), 113–123.

Brereton, R. G. (2014). A short history of chemometrics: A personal view. *Journal of Chemometrics*, *28*(10), 749–760.

Bujang, A., Noor, Z. M., & Abdullah, N. (2018). An overview of *toyyib* aspect of *halal* food production in meat and meat products. In *Proceedings of the 3rd International Halal Conference (INHAC 2016)* (pp. 467–478). Springer Singapore.

Carrasco, C., Pérez-Palacios, T., Luengo, L. M., Gómez, S., Fajardo, M., de los Ángeles Gómez, M., & Rodríguez, A. B. (2022). Nutritional quality and physiological effects of *halal* meat: A pilot study in non-muslim consumers. *Food Bioscience*, *49*, 101935.

Cheah, H. Y., Merican, S. E., Bakar, A. Z. A., Omar, S., & Sanny, M. (2021). Assessing the performance of food safety management system using food safety management system diagnostic tools and microbial assessment scheme: A case of powdered beverage manufacturers. *The Malaysian Journal of Medical Sciences: MJMS*, *28*(3), 129.

Chessler, S. D., & Lee, D. E. (2018). Alarming increase in HbA1c and near misdiagnosis of diabetes mellitus resulting from a clinical laboratory instrument upgrade and haemoglobin variant. *Case Reports*, *2018*, bcr-2018.

Chong, J., & Xia, J. (2020). Using MetaboAnalyst 4.0 for metabolomics data analysis, interpretation, and integration with other omics data. *Computational Methods and Data Analysis for Metabolomics*, 337–360.

Cohen, L., Cui, N., Cai, Y., Garden, P. M., Li, X., Weitz, D. A., & Walt, D. R. (2020). Single molecule protein detection with attomolar sensitivity using droplet digital enzyme-linked immunosorbent assay. *ACS Nano*, *14*(8), 9491–9501.

Daher, R. K., Stewart, G., Boissinot, M., & Bergeron, M. G. (2016). Recombinase polymerase amplification for diagnostic applications. *Clinical Chemistry*, *62*(7), 947–958.

Dahlal, N. M. (2021). An ideal *halalan toyyiban* food quality management (HTFQM) principles. *Halalsphere*, *1*(2), 76–85.

Dayananda, B., Owen, S., Kolobaric, A., Chapman, J., & Cozzolino, D. (2024). Pre-processing applied to instrumental data in analytical chemistry: A brief review of the methods and examples. *Critical Reviews in Analytical Chemistry*, *54*(8), 2745–2753.

Demirci, M. N., Soon, J. M., & Wallace, C. A. (2016). Positioning food safety in *halal* assurance. *Food Control*, *70*, 257–270.

Djenane, D., Gómez, D., Yangüela, J., Roncalés, P., & Ariño, A. (2018). Olive leaves extract from Algerian oleaster (*Olea europaea* var. *Sylvestris*) on microbiological safety and shelf-life stability of raw *halal* minced beef during display. *Foods*, *8*(1), 10.

Fayyaz, K., Nawaz, A., Olaimat, A. N., Akram, K., Farooq, U., Fatima, M., Siddiqui, A. S., Rana, I. S., Mahnoor, & Shahbaz, H. M. (2022). Microbial toxins in fermented foods: health implications and analytical techniques for detection. *Journal of Food and Drug Analysis*, *30*(4), 523.

Fong, F. L. Y., Lam, K. Y., San Lau, C., Ho, K. H., Kan, Y. H., Poon, M. Y., El-Nezami, H., & Sze, E. T. P. (2020). Reduction in biogenic amines in douchi fermented by probiotic bacteria. *PLoS One*, *15*(3), e0230916.

Gong, Y., Chen, X., & Wu, W. (2024). Application of Fourier transform infrared (FTIR) spectroscopy in sample preparation: material characterization and mechanism investigation. *Advances in Sample Preparation*, *11*, 100122.

Gorris, H. H., & Soukka, T. (2022). What digital immunoassays can learn from ambient analyte theory: A perspective. *Analytical Chemistry*, *94*(16), 6073–6083.

Güngör, Ö. Y., Yalçın, E., Çavuşoğlu, K., & Özkan, B. (2025). Chemical profiling by LC–MS/MS and GC–MS and biological activity assessment of different extracts of Portulaca oleracea through in-vitro and in-silico approaches. *Scientific Reports*, *15*(1), 40511.

Hassan, N., Ahmad, T., & Zain, N. M. (2018). Chemical and chemometric methods for *halal* authentication of gelatin: An overview. *Journal of Food Science*, *83*(12), 2903–2911.

Herdiana, Y., Sofian, F. F., Shamsuddin, S., & Rusdiana, T. (2024). Towards *halal* pharmaceutical: Exploring alternatives to animal-based ingredients. *Heliyon*, *10*(1), e23624.

Hidayati, L., Sucipto, S., Cheumar, M. T., & Juliana, J. (2024). Integrating *halal* assurance and quality management: A strategic framework for sustainable growth in the food industry. *Industria: Jurnal Teknologi dan Manajemen Agroindustri*, *13*(2), 239–254.

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.

Hupp, A. M., Kovarik, M. L., & McCurry, D. A. (2024). Emerging areas in undergraduate analytical chemistry education: microfluidics, microcontrollers, and chemometrics. *Annual Review of Analytical Chemistry*, *17*, 197–219.

Irnawati, I., Windarsih, A., Indrianingsih, A. W., Apriyana, W., Ratnawati, Y. A., & Rohman, A. (2023). Rapid detection of tuna fish oil adulteration using FTIR-ATR spectroscopy and chemometrics for *halal* authentication. *Journal of Applied Pharmaceutical Science*, *13*(4), 231–239.

Ismail, A. M., Sani, M. S. A., Azid, A., Zaki, N. N. M., Arshad, S., Tukiran, N. A., Abidin, S. A. S. Z., Samsudin, M. S., & Ismail, A. (2021). Food forensics on gelatine source via ultra-high-performance liquid chromatography diode-array detector and principal component analysis. *SN Applied Sciences*, *3*, 1–19.

Jiang, T., Kwofie, F., Attanasio, N., Haas, M., Higgins, J., & Kosanam, H. (2024). Exploring the correlation between LC-MS multi-attribute method and conventional chromatographic product quality assays through multivariate data analysis. *The AAPS Journal*, *27*(1), 1–15.

Kralik, P., & Ricchi, M. (2017). A basic guide to real time PCR in microbial diagnostics: definitions, parameters, and everything. *Frontiers in Microbiology*, *8*, 108.

Kua, J. M., Azizi, M. M. F., Abdul Talib, M. A., & Lau, H. Y. (2022). Adoption of analytical technologies for verification of authenticity of *halal* foods – A review. *Food Additives & Contaminants: Part A*, *39*(12), 1906–1932.

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.

Lin, C., & Wu, W. (2024). An Integrated low-cost automatic pipetting used in nucleic acid detection PCR instrument and clinical detection. *Sensor Review*, *44*(4), 477–485.

Ling, L. H., Hassan, M. S., Ngah, C. W. Z. C. W., & Ozturk, M. (2025). A Maturity Model for the Accredited Food Laboratory in Malaysia: A Case Study. *Malaysian Journal of Science Health & Technology*, *11*(1), 109–121.

Man, Y. C., Aida, A. A., Raha, A. R., & Son, R. (2007). Identification of pork derivatives in food products by species-specific polymerase chain reaction (PCR) for *halal* verification. *Food Control*, *18*(7), 885–889.

Maritha, V., Harlina, P. W., Musfiroh, I., Rafi, M., Geng, F., & Muchtaridi, M. (2023). Exploring untargeted metabolomics for *halal* authentication of *Triceps brachii*, *Longissimus dorsi*, and *Biceps femoris* of meat muscles. *International Journal of Food Properties*, *26*(2), 3148–3159.

Mishra, P., Roger, J. M., Jouan-Rimbaud-Bouveresse, D., Biancolillo, A., Marini, F., Nordon, A., & Rutledge, D. N. (2021). Recent trends in multi-block data analysis in chemometrics for multi-source data integration. *TrAC Trends in Analytical Chemistry*, *137*, 116206.

Mubarok, A., & Rohman, A. (2022). Determination of pork adulteration in roasted beef meatballs using Fourier transform infrared spectroscopy in combination with chemometrics. *Sains Malaysiana*, *51*(8), 2573–2582.

Mustapha, A., Ishak, I., Zaki, N. N. M., Ismail-Fitry, M. R., Arshad, S., & Sazili, A. Q. (2024). Application of machine learning approach on *halal* meat authentication principle, challenges, and prospects: A review. *Heliyon*, *10*(12), e32189.

Nadeem, M., Naveed, T., Rehman, F., & Xu, Z. (2019). Determination of histamine in fish without derivatization by indirect reverse phase-HPLC method. *Microchemical Journal*, *144*, 209–214.

Nakyinsige, K., Man, Y. B. C., & Sazili, A. Q. (2012). *Halal* authenticity issues in meat and meat products. *Meat Science*, *91*(3), 207–214.

Nazri, M. Z. (2025). Application of Fourier transform infrared (FTIR) spectroscopy, gas chromatography and chemometric analyses for *halal* authentication in food products. *Journal of Academia*, *13*(2), 209–223.

Nazri, M. Z., Rashid, S. N. A. 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.

Nazri, M. Z., Rashid, S. N. A. A, Malik, S., A. 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.

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.

Pauzi, N., Man, S., Nawawi, M. S. A. M., & Abu-Hussin, M. F. (2019). Ethanol standard in *halal* dietary product among southeast Asian *halal* governing bodies. *Trends in Food Science & Technology*, *86*, 375–380.

Pimentel-Filho, N. D. J., Mantovani, H. C., de Carvalho, A. F., Dias, R. S., & Vanetti, M. C. D. (2014). Efficacy of Bovicin HC5 and Nisin combination against *Listeria monocytogenes* and *Staphylococcus aureus* in fresh cheese. *International Journal of Food Science and Technology*, *49*(2), 416–422.

Pranata, A. W., Yuliana, N. D., Amalia, L., & Darmawan, N. (2021). Volatilomics for *halal* and non-*halal* meatball authentication using solid-phase microextraction–gas chromatography–mass spectrometry. *Arabian Journal of Chemistry*, *14*(5), 103146.

Rahayu, W. S., Utami, P. I., & Mahardika, B. (2021). *Halal* authentication of toothpaste with FTIR combine with chemometrics. *Indonesian Journal of Chemometrics and Pharmaceutical Analysis*, 78–82.

Rohman, A., & Windarsih, A. (2020). The application of molecular spectroscopy in combination with chemometrics for *halal* authentication analysis: A review. *International Journal of Molecular Sciences*, *21*(14), 5155.

Rohman, A., Gupitasari, I., Purwanto, P., Triyana, K., Rosman, A. S., Ahmad, S. A. S., & Yusof, F. M. (2014). Quantification of lard in the mixture with olive oil in cream cosmetics based on FTIR spectra and chemometrics for *halal* authentication. *Jurnal Teknologi (Sciences & Engineering)*, *69*(1), 113–119.

Rohman, A., Windarsih, A., Musfiroh, I., Maritha, V., Lestari, D., Hamidi, D., Susanto, Y., & Bakar, N. K. A. (2025). Recent progress on the application of molecular spectroscopic and chromatographic methods for analysis of *halal* and *kosher* gelatins in food and pharmaceutical products. *Journal of Applied Pharmaceutical Science*, *15*(4), 26–34.

Salipante, S. J., Sengupta, D. J., Rosenthal, C., Costa, G., Spangler, J., Sims, E. H., Jacobs, M. A., Miller, S. I., Hoogestraat, D. R., Cookson, B. T., & Hoffman, N. G. (2013). Rapid 16S rRNA next-generation sequencing of polymicrobial clinical samples for diagnosis of complex bacterial infections. *PloS One*, *8*(5), e65226.

Sani, M. S. A., Nordin, N. F. H., & Elgharbawy, A. A. (2023). *Halal* detection technologies: Analytical method approaches, validation and verification, and multivariate data analysis for *halal* authentication. *Innovation of Food Products in Halal Supply Chain Worldwide*, 253–271.

Singpanomchai, N., Akeda, Y., Tomono, K., Tamaru, A., Santanirand, P., & Ratthawongjirakul, P. (2019). Naked eye detection of the *Mycobacterium tuberculosis* complex by recombinase polymerase amplification—SYBR Green I assay. *Journal of Clinical Laboratory Analysis*, *33*(2), e22655.

Sultana, S., Azlan, A., Mohd Desa, M. N., Mahyudin, N. A., & Anburaj, A. (2024). A review of CRISPR-Cas and PCR-based methods for the detection of animal species in the food chain-current challenges and future prospects. *Food Additives & Contaminants: Part A*, *41*(3), 213–227.

Suparman, S. (2015). The use of Fourier transforms 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.

Taha-Abdelaziz, K., Singh, M., Sharif, S., Sharma, S., Kulkarni, R. R., Alizadeh, M., Yitbarek, A., & Helmy, Y. A. (2023). Intervention strategies to control *Campylobacter* at different stages of the food chain. *Microorganisms*, *11*(1), 113.

Tan, E., Julmohammad, N., Koh, W. Y., Sani, M. S. A., & Rasti, B. (2023). Application of ATR-FTIR incorporated with multivariate data analysis for discrimination and quantification of urea as an adulterant in UHT milk. *Foods*, *12*(15), 2855.

Umar, R., & Parakkasi, I. (2025). A risk-based auditing framework for *halal* certification systems: Bridging gaps in the current *halal* assurance practices. *Formosa Journal of Science and Technology*, *4*(6), 1785–1804.

Walczak, R. (2011). Fluorescence detection by miniaturized instrumentation based on non-cooled CCD minicamera and dedicated for lab-on-a-chip applications. *Biochip Journal*, *5*, 271–279.

Wang, H. P., Chen, P., Dai, J. W., Liu, D., Li, J. Y., Xu, Y. P., & Chu, X. L. (2022). Recent advances of chemometric calibration methods in modern spectroscopy: Algorithms, strategy, and related issues. *TrAC Trends in Analytical Chemistry*, *153*, 116648.

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.

Windarsih, A., Indrianingsih, A. W., Apriyana, W., & Rohman, A. (2023). Rapid detection of pork oil adulteration in snakehead fish oil using FTIR-ATR spectroscopy and chemometrics for *halal* authentication. *Chemical Papers*, *77*(5), 2859–2870.

Windarsih, A., Riswanto, F. D. O., Bakar, N. K. A., Yuliana, N. D., Dachriyanus, & Rohman, A. (2022). Detection of pork in beef meatballs using LC-HRMS based untargeted metabolomics and chemometrics for *halal* authentication. *Molecules*, *27*(23), 8325.

Wirnawati, W., Lestari, D., Rohman, A., Andayani, R., & Hamidi, D. (2023). Analysis of adulteration dog meat in beef sausages using ftir spectroscopy combined with chemometrics, 27 July 2023, PREPRINT (Version 1) available at Research Square.

Witjaksono, G., Saputra, I., Latief, M., Jaswir, I., Akmeliawati, R., & Rabih, A. A. S. (2017). Non-*halal* biomarkers identification based on Fourier transform infrared spectroscopy (FTIR) and gas chromatography-time of flight mass spectroscopy (GC-TOF MS) techniques. In *EPJ Web of Conferences* (Vol. 162, p. 01007). EDP Sciences.

World Health Organisation (WHO). (2019). Estimating the burden of foodborne diseases. Retrieved On March 3, 2025 from https://www.who.int/activities/estimating-the-burden-of-foodborne-diseases.

Xie, C., Wang, H. H., Nie, X. K., Chen, L., Deng, S. L., & Xu, X. L. (2015). Reduction of biogenic amine concentration in fermented sausage by selected starter cultures. *CyTA-Journal of Food*, *13*(4), 491–497.

Xu, L., Cai, C. B., Cui, H. F., Ye, Z. H., & Yu, X. P. (2012). Rapid discrimination of pork in *halal* and non-*halal* Chinese ham sausages by Fourier transform infrared (FTIR) spectroscopy and chemometrics. *Meat science*, *92*(4), 506–510.

Yuswan, M. H., Sani, M. S. A., Manaf, Y. N. A., & Desa, M. N. M. (2020). Basic requirements of laboratory operation for *halal* analysis. *KnE Social Sciences*, 55–65.