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I-CReST 2025:104-069 – Advancement in *Halalan Toyyiban* Laboratory Chemical Instrumentation for Sustainable Food Product Analysis

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ABSTRACT

The *halalan toyyiban* (HT) concept is crucial in ensuring food products adhere to both *halal* (permissible) and *toyyiban* (wholesome) Islamic dietary principal, addressing ethical, safety, and quality considerations in the global food industry. However, challenges such as complex food matrices and the presence of adulterants necessitate advanced analytical techniques for robust detection. This comprehensive review explores the latest laboratory instrumentation for HT assurance, focusing on spectroscopic techniques such as Fourier Transform Infrared Spectroscopy (FTIR) for rapid, non-destructive analysis, chromatographic methods such as High-Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC) for precise quantification, respectively. Beyond the analytical advancements, sustainability is increasingly integral for HT compliance, necessitating environmentally friendly detection methods, efficient resource utilization and reduced the chemical waste in food product testing laboratories. Furthermore, this review also highlights the role of multivariate data analysis (MVDA) in managing complex datasets, enhancing pattern recognition and improving predictive modelling for more accurate decision-making for the HT aspects based on aforementioned laboratory instrumentations. While these methodologies offer significant advancements, challenges such as high-cost, lack of standardization and technical expertise remain key limitations. This study emphasizes the need for cost-effective, automated and standardized detection laboratory system that align with sustainability goals, ensuring more efficient, accessible and environmentally responsible HT compliance framework for a reliable and ethical food product laboratory results.

Keywords: Analytical detection; food safety and quality; *halalan toyyiban* authentication; laboratory instrumentation; multivariate data analysis

1. INTRODUCTION

The rapid evolution of food science and technology, coupled with increasing global demand for *halal* certification, has necessitated significant advancements in laboratory instrumentation for comprehensive food product analysis. The *halalan toyyiban* (HT), which derived from Islamic concept that encompasses both the permissibility (*halal*) and wholesomeness (*toyyiban*) of food products, requires sophisticated analytical tools to ensure compliance with Islamic dietary requirements while maintaining food safety and quality standards [1]. The HT compliance is needed to ensure that the food products are safe and allowed to be consumed. Moreover, the HT is not only related to religious issues, but also to fulfil the Muslim right. Issues related to *halal* such as healthy, organic, cruelty-free animal welfare, ethical which have made the HT concept popular and highly accepted by all societies as such non-Muslim consumers such as jews (*kosher* consumers), Americans, European and Asians, as well as natural and organic consumers, to consume the HT food products [2]. Thus, recent developments in advanced analytical instrumentation have revolutionized the ability to detect, quantify, and authenticate food components, particularly in addressing complex challenges such as trace contamination detection and verification of processing methods. These technologies, such as mass spectrometry (MS) and high-performance liquid chromatography (HPLC), enable precise detection of trace contaminants, including non-*halal* substances like pork derivatives and alcohol, ensuring food products remain free from *najs* and forbidden elements. Additionally, techniques like spectroscopy and chromatography help verify *halal*-compliant processing methods, ensuring that food production adheres to Islamic dietary laws. Beyond *halal* authentication, laboratory instrumentation also supports the *toyyiban* aspect by detecting harmful substances such as pesticides, heavy metals, and microbial contamination, guaranteeing food safety and quality [3].

Meanwhile, modern instrumentation must not only provide accurate results but also optimize resource utilization, reduce waste generation, and employ eco-friendly methodologies. This paradigm shift towards sustainable laboratory practices aligns with global environmental initiatives while supporting the stringent requirements of HT certification processes. Despite these technological advances, there remains a critical need to bridge the gap between HT principles and contemporary analytical methodologies in a way that modern instrumentation provides precise and reliable means of detecting contaminants, verifying ingredients, and ensuring food safety, aligning these scientific approaches with traditional Islamic dietary laws requires continuous research, standardization, and collaboration between scholars, scientists, and regulatory bodies [4]. This review examines recent laboratory instrumentation specifically designed for HT food analysis, with particular emphasis on sustainable technologies that promote environmental stewardship without compromising analytical accuracy or religious compliance. Understanding these developments is essential for stakeholders in the *halal* food industry, regulatory bodies, and research institutions working towards establishing more efficient and sustainable food testing protocols.

2. MOLECULAR SPECTROSCOPY

Over the past decade, molecular spectroscopy has gained interest in the analysis of food and pharmaceutical products, including in the stages of production and quality control as this methodology offers ease in sample preparation, low cost, less time analysis, less solvent usage (green analytical chemistry) and ability to monitor compounds. Moreover, molecular spectroscopy has been widely used for the *halal* analysis due this method capability of detecting non-*halal* contaminants mostly in food samples. The most common type of molecular spectroscopy used for *halal* analysis is vibrational spectroscopy mainly the Fourier transform infrared (FTIR) spectroscopy [5].

It is known that infrared (IR) spectroscopy is a non-destructive analytical technique offering fast analysis and cost effective which makes it an excellent analytical method in food and pharmaceutical product analysis. The IR spectroscopy either in the mid-infrared (4000 – 400 cm^{-1}) and near-infrared (14000 – 4000 cm^{-1}) is most common used method in food analysis. The principle of IR spectroscopy is based on the interactions between samples with electromagnetic radiation at the IR region, resulting in vibrational transitions of molecules in the sample. The most usable FTIR using the attenuated total reflectance (ATR) spectroscopy technique for obtaining spectra of samples offers advantage as such the sample can directly placed on an ATR crystal for measurement, with less time analysis and requiring less solvent, nevertheless. Recently, some researchers have been used the FTIR spectroscopy in the field of *halal* food authentication and authentication of meat or meat-based products. For example, Che Man and co-workers used FTIR-ATR spectroscopy for the identification and confirmation of lard and other edible fats and oils in the normal FTIR spectra of wavenumber 6000 – 650 cm^{-1}, respectively [6]. Rohman and Che Man also used the FTIR spectroscopy for the simultaneous analysis of lard in the quaternary mixtures of chicken, mutton and beef fats. The findings are typical characteristics of absorption bands of triacylglycerols. However, with detailed investigation, the peak intensities of lard can be differentiated at wavenumber of 1160(a), 1117(b) and 1098(c) cm^{-1} as shown in Fig. 1. The findings are typical characteristics of absorption bands of triacylglycerols of the aforementioned animal fats. The findings are the presence of peak which corresponds to stretching of vinylic C–H at 3007 cm^{-1} wavenumber. Moreover, stretching vibrations of methylene (–CH_2–) and methyl (–CH_3) groups can be observed at the frequencies of 2922, 1465, 2853 and 1377 cm^{-1}, respectively. The strong intensity of C=O absorption of ester linkage is observed at 1743 cm^{-1} and the bands of 1237, 1160, 1117, 1098 and 721 cm^{-1} also contribute to the overlapping of the CH_2-rocking vibrations and the out-of-plane bending vibration of *cis*-disubstituted olefins [7,8].

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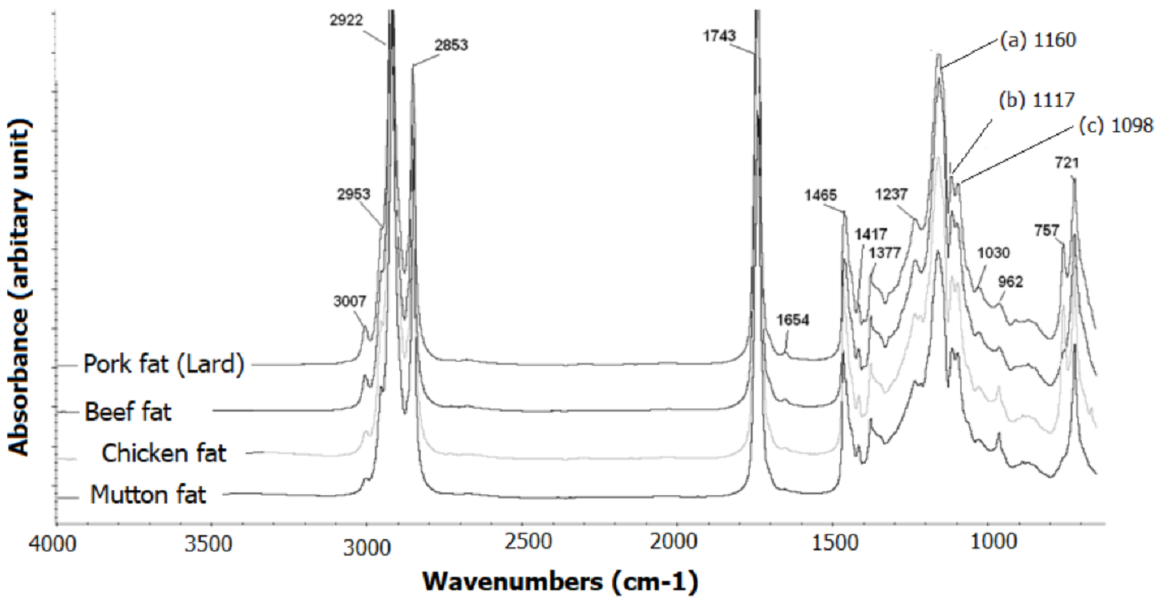

Fig. 1. The example of FTIR spectra of lard, beef, chicken and muttons fats at wavenumber of 4000 – 650 cm^{-1} according to Rohman [8]

Furthermore, the FTIR spectra also can be used to provides the reliable tool for characterization for gelatines from different sources by investigating the fingerprint profile of gelatines especially the peaks that related to the amide bonds [9]. Noteworthy, the Amide I band which can be found between 1700 – 1600 cm^{-1} proved as the most effective for signature for protein analysis of the FTIR spectroscopy reported by Al-Saidi and co-workers [10]. Table 1 compiled the combination of FTIR spectroscopy for analysis of porcine gelatine in several matrices of foods products reported beforehand, respectively.

Table 1. The application of FTIR spectroscopy analysis of non-halal components in food products

Non-halal components	Issue	Infrared spectroscopy condition	Results	References
Lard	Adulteration of lard in palm oil	Near IR at wavelength 1650 – 950 nm using transflectance and transmission sampling techniques	The classification of adulterated palm oil and lard with model accuracy of 0.93 (transflectance) and 0.95 (transmission).	[11]
Lard	Adulteration of beef with pork through analysis of lard	The FTIR normal spectra at 1/λ of 1200 – 1000 cm^{-1} using ATR technique	The FTIR spectra can classify sausage with pork and beef.	[12]
Lard	Analysis of crackers "rambak" containing pig and cow skins.	The FTIR normal spectra at 1/λ of 1200 – 1000 cm^{-1} using ATR technique	The FTIR spectra can classify crackers based on skin origin using oils as the medium	[13]
Pork	Adulteration of beef meatball with pork	Normal FTIR spectra of 1200 – 1000 cm-1 using ATR technique	The FTIR spectra can classify the beef meatball and beef meatball mixed with pork	[14]
Porcine gelatine	Detection of porcine gelatine in edible bird's nest	Measurement of FTIR-ATR at 4000 – 650 cm^{-1}	Discriminate of wavenumbers of amide groups; 1240 – 650 cm-1 (Amide III), 1560 – 1335 cm-1 (Amide II) and 1600 – 1700 (Amide I)	[15]
Porcine gelatine	Detection of porcine gelatine in jelly soft candy	Measurement of FTIR-ATR at 4000 – 400 cm^{-1}	The differences of gelatines were determined based on the unique wavenumbers observed for type of gelatine.	[16]
Porcine gelatine	Identification of gelatine sources from bovine, porcine and fish gelatines	Measurement of FTIR-ATR at 4000 – 400 cm^{-1}	The qualitative and quantitative analysis of porcine gelatine can be successfully carried out.	[17]

3. CHROMATOGRAPHY TECHNIQUE

In the context of HT food analysis, the chromatographic techniques serve as fundamental analytical tools that bridge the gap between religious compliance and scientific verification and authentication. These sophisticated methods not only ensure adherence to Islamic dietary law but also validate the food product's wholesomeness, cleanliness and safety, thereby fulfilling both religious and quality assurance requirements. The significance of chromatography in HT analysis lies in its ability to detect trace amounts of non-*halal* substances as such porcine derivatives, alcohol residues and unauthorized additives, which is crucial for maintaining the integrity of the *halal* status of authentication, respectively [18]. Furthermore, these analytical techniques also support the growing *halal* food industry by providing reliable scientific evidence for food product authentication, which is essential for building consumer confidence and meeting international trade requirements.

High-performance liquid chromatography (HPLC) plays a crucial role in HT laboratory analysis by enabling precise detection and quantification of non-*halal* substances in food products. This HPLC excels at separating and analysing heat-sensitive compounds particularly traces of ethanol, non-*halal* derived compounds, as well as amino acids (AA) contents in food products which sometimes can be adulterated with non-*halal* ingredients. HPLC's versatility allows for both reversed-phase and normal-phase separations, making it invaluable for analysing preservatives and colorants. Norakasha and co-workers used reversed phase-liquid chromatography (RP-LC) to differentiate porcine and bovine gelatines in pure forms using amino acid composition. It found that three amino acids of glycine, proline and hydroxyproline are contributed to separate the type of gelatines of bovine and porcine [19]. For advanced liquid chromatography, it reported by Zhang and co-workers the difference between bovine and porcine extracted from skins and bones collagen. The gelatines then subjected to separation using HPLC with tandem mass spectrometry (HPLC-MS/MS). The result showed that the hydroxylated proline was a key factor affecting the peptide identification and there are small differences in the sequence of amino acids which yield 39 pairs of polypeptides [20]. Furthermore, tt is reported that Azilawati and co-workers able to identify and quantified 17 AA from gelatine of bovine, porcine skins, fish and carrageenan using HPLC which attached with a fluorescence detector (HPLC-FLD). In note, the findings were reproducible and accurately defined as the method was found to be suited to routine analysis of AA through the composition of gelatine-based ingredients suitable for HT detection in food products [21].

Other than liquid chromatography, the gas chromatography especially flame ionization detector (FID) and mass spectrometer (MS) play a crucial role in HT laboratory instrumentation. Recently, Mansur and co-workers validated method for ethanol analysis using GC-FID in foods and beverages from South Korea local market. The result show that the validated method was suitable for quantitative analysis of ethanol in various processed foods and beverages as for *halal* verification [22]. Also reported by Pranata and co-workers utilized GC-MS analysis for adulteration of beef meatballs with wild boar in Indonesia and it is found that the aforesaid GC-MS analysis is possible preliminary to classify meatball products that contain *halal* and non-*halal* contaminants based on animal volatile profile (biomarker) as wild boar contains more aldehydes and terpenes compare to beef and chicken (Fig. 2) [23].

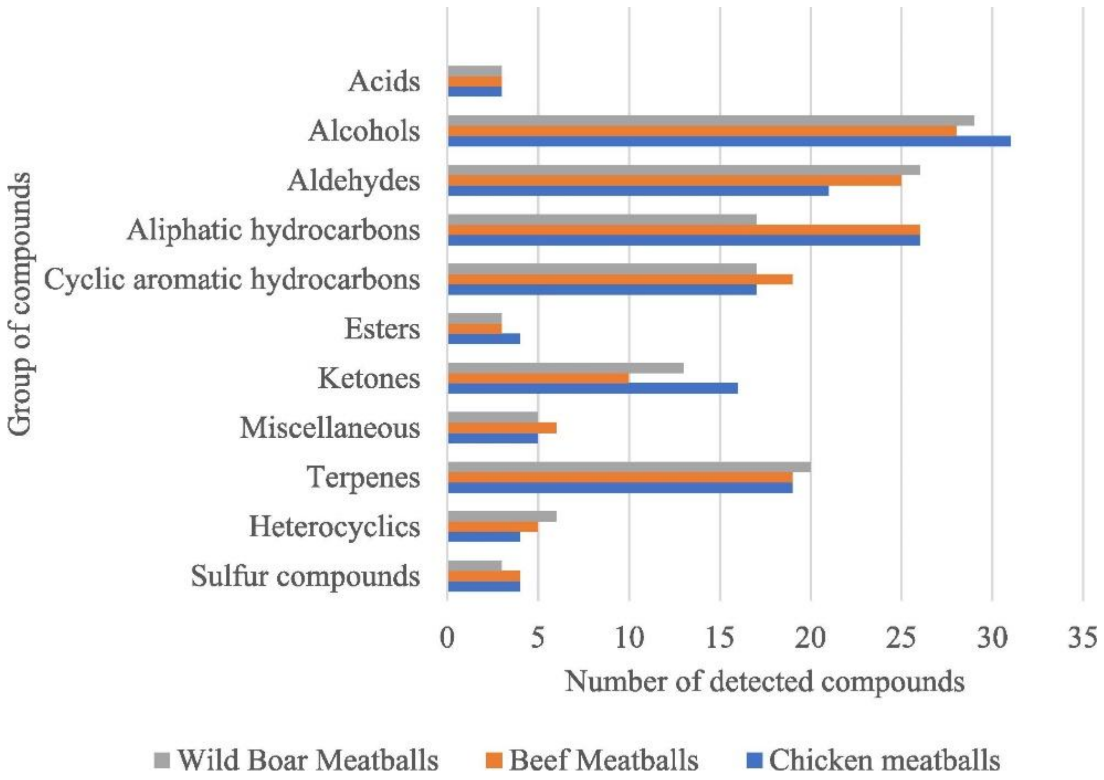

Fig. 2. Chemical composition of the volatile compounds detected through GC-MS in wild boar, beef and chicken meatballs [23]

4. MULTIVARIATE DATA ANALYSIS

According to Wold and Sjostrom, multivariate data analysis (MVDA) or chemometrics can be defined as "information aspects of chemistry" where statistical and mathematical methods are used (i) to produce "good data" and (ii) to extract relevant information from the measured dataset [24]. The first approach can be achieved by using design of experiment which to provide a small number of information-rich experiments. The MVDA can be employed for the second purpose whereby additional visualization of the data represents an important issue. The methods used in MVDA are fully applicable in various field such as analytical chemistry, pharmaceutical, environmental science, agriculture and even the marketing and psychology, respectively [25]. Furthermore, the classification of MVDA comprising of three approaches such as exploratory data analysis, unsupervised and supervised pattern recognition techniques as shown in Fig. 3. Exploratory data analysis and unsupervised pattern recognition are widely used to simplify group of samples by reducing the amount of original data and gaining better understanding of chemical datasets [26]. These approaches are employed to uncover the hidden structures, patterns or trends within the data without prior knowledge of sample classification. By reducing the dimensionality of the original dataset which often through methods such as principal component analysis (PCA), hierarchical cluster analysis (HCA) or t-distributed stochastic neighbor embedding (t-SNE), researchers can effectively visualise similarities and dissimilarities among samples. This simplification not only facilitates the interpretation of high-dimensional chemical information but also enhances the identification of natural grouping, outliers and underlying variables that contribute most to the variance in the dataset.

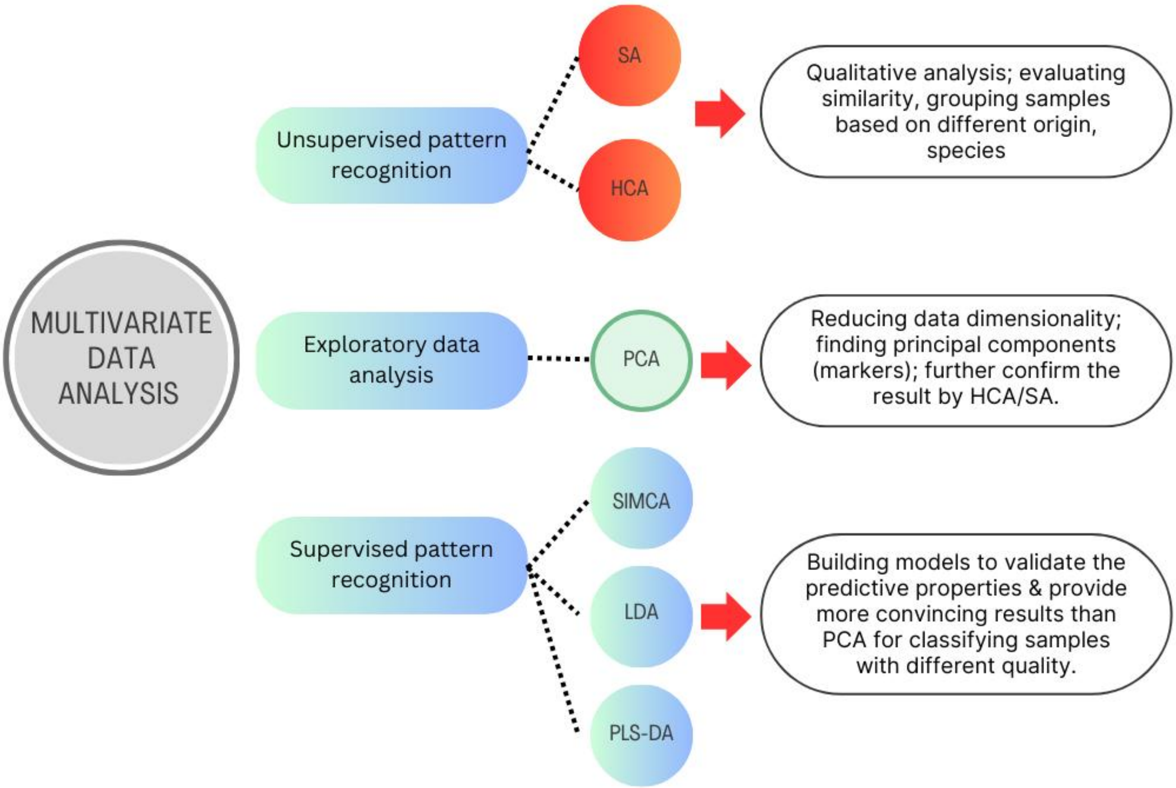

Fig. 3. The MVDA techniques widely used for the classification of datasets. SA = similarity analysis, HCA = hierarchical clustering analysis, PCA = principal component analysis, SIMCA = soft independent modelling of class analogy, LDA = linear discriminant analysis and PLS-DA = partial least squares discriminant analysis [27]

In HT applications, various MVDA techniques are commonly applied and provide an alternative way to analyse the complex chemical data, namely classification analysis and multivariate calibration. Some data pre-processing such as mean centering, Savitzy-Golay-based derivatization, standard normal variate, baseline corrections, signal correction and compression, spectra normalizations are also used in molecular spectra before being subject to MVDA [28]. The most widely used of MVDA in HT was principal component analysis (PCA) which has greatly advanced the analytical precision and reliability of HT methods through laboratory instrumentations. Recently, Nazri and co-workers utilized the PCA with FTIR-ATR spectroscopy of the wavenumber 4000 – 650 cm^{-1} which then showed clear clustering of animal fatty acids comprising of *halal* (beef, mutton and chicken) with *haram* (pork) meats based on specific bands of at both functional and fingerprint regions [29].

Not only that, but the discriminant analysis (DA) also shown remarkable performance in accurately classifying in meat and processed food samples. It has been reported by Lestari and co-workers 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, based on the DA was successfully able to classify the lipid components extracted from all meatballs through Bligh and Dyer, Folch and Soxhlet methods with 100% accuracy levels [30]. Other than that, the partial least squares discriminant analysis also (PLS-DA) extends to the application of multivariate data analysis by modelling the relationship between instrumental variables and categorical *halal* labels. Nurfatin and co-workers 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 [31].

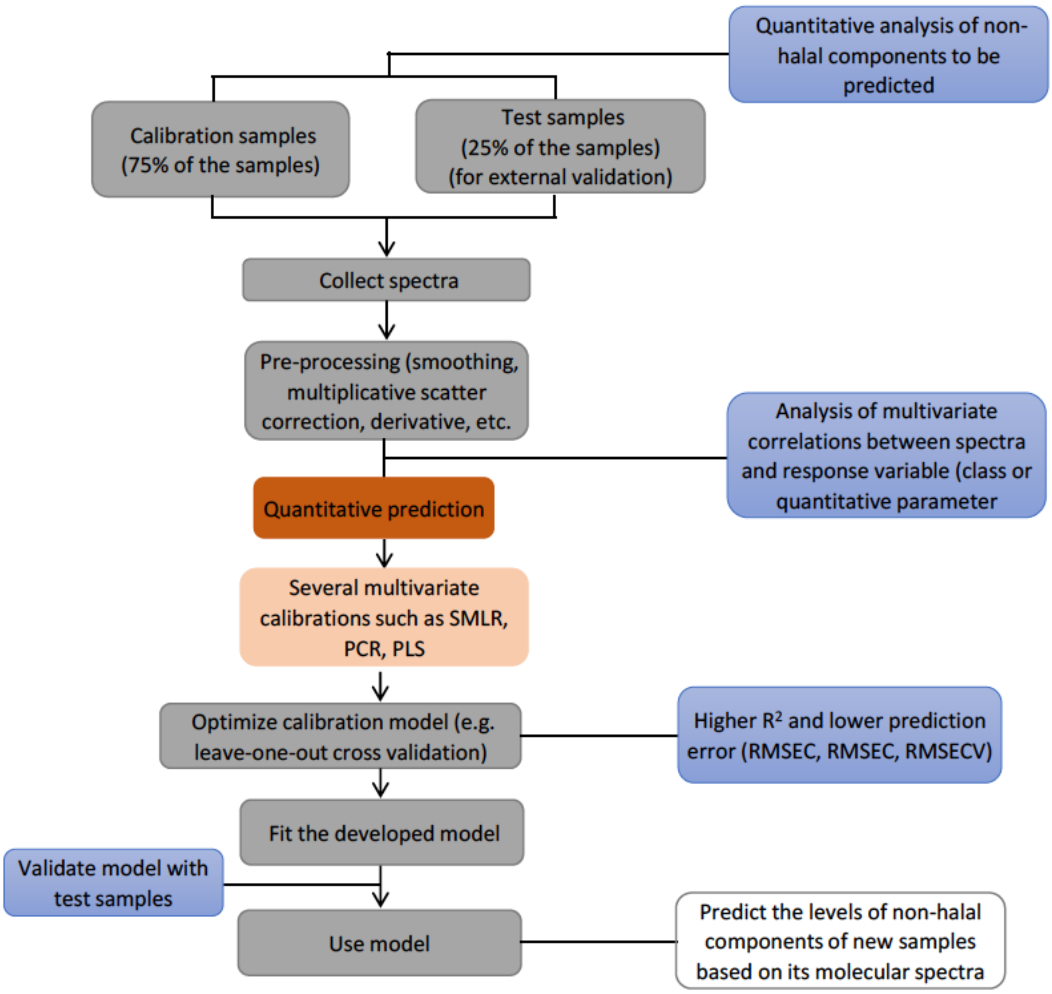

Fig. 4. The scheme of quantitative analysis of non-*halal* components in food products assisted with multivariate calibration [32]

The quantitative analysis of non-*halal* components in food products such as porcine derivatives or ethanol, has been significantly enhanced through the application of multivariate calibration techniques. Spectroscopic methods are widely used as such FTIR, Raman and differential scanning calorimetry (DSC) due to their non-destructive nature and rapid data acquisition. Nevertheless, the complexity of food matrices. This methodology typically begins with acquisition of spectral or chromatographic data, in this case the FTIR spectra which contain overlapping signals from multiple food constituents. Multivariate calibration methods such as PLS or principal component regression (PCR) are then employed to extract meaningful relationships between the spectral data and analyte concentrations. These techniques reduce the data dimensionality and enhance predictive accuracy by extracting latent variables that correlate with the concentration of non-*halal* components [33]. For example, when FTIR combined with PLS it successfully used to quantify lard in adulteration in food products with high precision. Therefore, this integration methods strengthens the *halal* authentication by improving sensitivity, specificity and operational efficiency thus, supporting regulatory enforcement and consumer trust in *halal*-certified food products [34].

5. CONCLUSION

The advancement in HT laboratory chemical instrumentation has significantly improved the analysis of sustainable food products by integrating the molecular, spectroscopic techniques and multivariate data analysis. Molecular approaches such as liquid and gas chromatography enable precise identification of food components, ensuring compliance with *halal* and *toyyiban* principles. Next, the spectroscopic technique of FTIR spectroscopy, provide rapid, non-destructive and high-throughput analysis of food matrices, allowing the detection of adulterants and contaminants at the molecular level. Furthermore, the incorporation of multivariate data analysis, including PCA, DA and PLS-DA enhances the accuracy and reliability of data interpretation which enabling the differentiation of complex food samples thus ensuring their authenticity and safety, respectively. The synergy of these advanced techniques strengthens the integrity of HT food analysis, supporting the development of sustainable, safe and high-quality food products for the local and international market.

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