The role of gas chromatography in halal food authentication: Principles, applications, and challenges – A systematic literature review

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ABSTRACT

The global demand for halal products continues to rise, driving the need for accurate scientific analytical methods to ensure authenticity and compliance with halal standards. This systematic review aims to examine the application of gas chromatography, including its role, applications, and challenges, in halal food authentication. However, existing studies are mostly fragmented and focus on specific products or individual analytical approaches, and a comprehensive evaluation of GC applications, methodological challenges, and future directions in halal authentication remains limited. The research method used was a systematic literature review using the PRISMA approach, with scientific publications from 2015 – 2025 obtained from five major databases: ScienceDirect, PubMed, Semantic Scholar, OpenAlex, and Google Scholar. Of the 1,121 articles identified, 33 met the inclusion criteria and were analyzed in depth. The analysis revealed that GC techniques, particularly GC–MS, GC–FID, HS-SPME–GC–MS, and GC–FAMEs, have been extensively applied for the authentication of meat, fat, gelatin, and fermented beverages through the identification of marker compounds such as aldehydes, ketones, alcohols, and fatty acid methyl esters (FAMEs). These techniques proved effective in differentiating halal and non-halal meat species, detecting pork fat adulteration, and verifying ethanol content in beverages. The conclusion shows that GC has high sensitivity and selectivity in halal authentication, but still faces limitations such as matrix complexity, operational costs, and the need for expert personnel. Research gaps identified include the lack of standardized GC protocols, limited studies on complex processed products, and minimal integration with chemometric analysis, necessitating the development of more standardized and applicable methods.

INTRODUCTION

The global demand for halal products is increasing in line with growing awareness among Muslim consumers about food safety and halal integrity (IMARC Group, 2023). The global halal food market is projected to reach USD 5.92 trillion by 2030, driven by the large Muslim population in the Asia–Pacific region and by increasing consumer attention to ethical, health, and quality considerations (Next Move Strategy Consulting, 2025). Halal products not only fulfill religious requirements but also

serve as indicators of food quality and safety that are increasingly valued by consumers. This awareness has also extended to non-Muslim consumers who seek transparency in supply chains and product authenticity, implementing consistent and trustworthy halal standards, which is critically important (Al-Mahmood & Fraser, 2023). However, halal verification faces complex technical and operational challenges, as the identification of non-halal components such as pork fat, alcohol, or meat not slaughtered according to Islamic law cannot be reliably performed through product labeling alone (Usman et al., 2024). Moreover, variations in certification standards among countries and limited supply chain transparency further complicate the process, emphasizing the need for verification mechanisms that are accurate, efficient, and reliable (Sunmola et al., 2025). These challenges highlight the importance of applying scientific analytical methods that can precisely and objectively detect non-halal substances, thereby bridging the gap in halal verification systems.

Modern chemical analytical techniques play a crucial role in ensuring the halal integrity of food products by detecting contamination or adulteration with non-halal materials. These methods can identify prohibited components such as pork fat or alcohol, even at trace concentrations, making them essential tools for halal verification (Prihandiwati et al., 2024). Various analytical approaches have been developed for halal food authentication, including DNA-based methods such as polymerase chain reaction (PCR) for species identification, immunoassays such as enzyme-linked immunosorbent assay (ELISA) for protein detection (Sani et al., 2025), spectroscopic techniques including Fourier-transform infrared (FTIR) and near-infrared (NIR) spectroscopy for rapid fingerprint analysis, as well as liquid chromatography (LC/HPLC) for non-volatile compounds (Lestari et al., 2025). Each technique offers distinct advantages in terms of sensitivity, specificity, and rapid detection; however, limitations remain regarding matrix interference, complex sample preparation, and compound selectivity. Among these approaches, gas chromatography–mass spectrometry (GC–MS) has become one of the most widely applied techniques due to its superior capability to separate and identify complex volatile and lipid compounds with high precision and sensitivity (Kanwal & Musharraf, 2024). GC–MS provides detailed compositional information and reliable chemical fingerprinting for halal authentication. Nevertheless, GC–MS also presents several drawbacks, including costly instrumentation, time-consuming sample preparation, and the requirement for skilled operators, which may limit its routine application in some laboratories. Furthermore, GC–MS primarily evaluates chemical composition and therefore cannot directly determine whether meat originates from animals slaughtered according to Islamic law, as slaughtering practices do not necessarily produce distinct chemical markers. Verification of halal slaughter compliance thus requires certification systems, traceability, and halal assurance protocols in addition to laboratory-based analysis (Lestari et al., 2024; Syafri et al., 2022).

Gas Chromatography (GC) has emerged as a primary method for halal authentication owing to its ability to detect specific compounds that serve as indicators of halal or non-halal status. When combined with advanced detectors such as Flame Ionization Detector (FID) or Mass Spectrometry (MS), GC significantly improves the accuracy of identifying volatile and non-volatile compounds in food matrices (Ahamed et al., 2025; Reyrolle et al., 2024). This approach enables faster and more accurate detection, allowing for clear differentiation between halal and non-halal sources across diverse food systems (Windarsih et al., 2022). Consequently, GC functions not only as an analytical instrument but also as a strategic component in maintaining the integrity of halal products within an increasingly complex and globalized food market.

Although Gas Chromatography (GC) has proven to be an effective tool for halal authentication, its application faces several technical challenges and operational limitations. The complexity of food matrices, which often comprise fats, proteins, and volatile compounds, can affect the accuracy of compound separation and detection (Nevistić & Tomas, 2023). In addition, the high cost of equipment and the need for skilled operators for sample preparation, instrument operation, and data interpretation limit the accessibility of this technique in many laboratories (Fracaro et al., 2021; Zampetti et al., 2020). GC encompasses several variants, including GC–FID (Flame Ionization Detector), GC–MS (Mass Spectrometry), Headspace GC, and SPME–GC, each with distinct advantages and limitations in terms of sensitivity, analyte type, and sample complexity (Corbally et al., 2023; Luong et al., 2019). However, some GC-based approaches remain specific to sample types and are not yet universally applicable to all categories of halal food products. This situation highlights the need for standardized analytical protocols

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and the development of more adaptive methods to ensure that GC can be applied consistently and effectively across diverse product types.

These challenges reveal a significant knowledge gap in the application of GC for halal authentication, particularly concerning the selection of analytical methods, sample types, detectors, and protocol optimization. Existing studies remain fragmented, lacking unified standards, and are predominantly focused on simple sample matrices, leaving the performance of GC in complex and processed food products underexplored (Nurani et al., 2022). Therefore, a systematic review is required to synthesize, evaluate, and integrate current findings related to the role of Gas Chromatography (GC) in halal food authentication, including comparisons among GC techniques, detector types, and analytical outcomes across various food matrices. Such an approach enables the identification of trends, research gaps, and opportunities for developing more accurate, efficient, and reliable GC-based methods. Consequently, the findings of this systematic review are expected to provide not only a comprehensive scientific understanding but also a strategic framework for developing standardized GC protocols, thereby supporting supply chain integrity and strengthening consumer trust in halal products globally.

## RESEARCH METHOD
Literature search strategy

A systematic literature search was conducted to collect and access both national and international scientific articles from databases including ScienceDirect, PubMed, Semantic Scholar, OpenAlex, and Google Scholar. The references used to gather information on the role of gas chromatography in halal food authentication were restricted to publications between 2015 and 2025. The primary search terms applied were "Gas Chromatography" AND "Halal Food Authentication." To ensure comprehensive coverage, additional keywords such as "volatile compounds," "GC-MS," and "halal authentication techniques" were incorporated in the advanced search process.

Inclusion and exclusion criteria

The inclusion criteria comprised scientific articles published between 2015 and 2025, written in English, and classified as original research papers that specifically examined the application of gas chromatography in halal food authentication. Studies involving the analysis of volatile compounds, as well as GC-MS applications and integrated gas chromatography-based techniques, were also included. The exclusion criteria encompassed publications focusing on non-halal authentication methods, such as genetic or immunological approaches without the use of gas chromatography, studies unrelated to food systems, and papers in the form of reviews, editorials, opinion pieces, conference summaries, or abstracts without full text. Articles that were inaccessible in full-text format or that did not directly address the use of gas chromatography for halal authentication were also excluded from the analysis.

Data screening and selection process

The screening process was systematically carried out across five major databases: PubMed, Google Scholar, ScienceDirect, OpenAlex, and Semantic Scholar. Initially, a total of 1,121 articles were retrieved. After applying the publication year restriction of 2015 to 2025, 780 articles met the preliminary eligibility criteria. Of these, 32 were identified as duplicates, leaving 748 unique articles for further evaluation. The keyword-based screening using "Gas Chromatography" AND "Halal Food Authentication" yielded 120 potentially relevant studies. A subsequent content evaluation and full-text availability assessment led to the exclusion of several articles, including five that were inaccessible, twenty-three that were unrelated to halal food authentication, six that did not involve gas chromatography, eight that were not original research, and fifteen that were excluded due to methodological inconsistency with the scope of this study. After completing all screening stages, a total of 33 articles met all inclusion criteria and were selected for in-depth analysis. The entire process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, as illustrated in the PRISMA flow diagram (Figure 1).
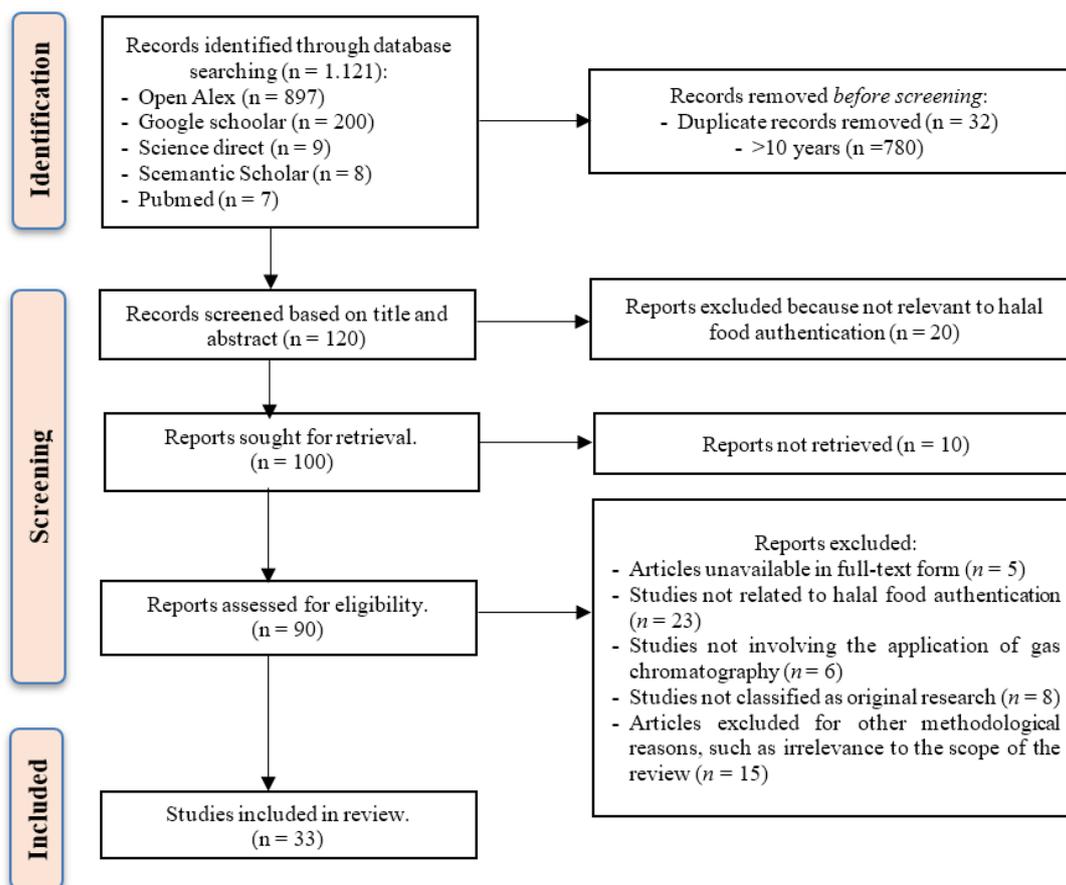
Figure 1. PRISMA 2020 flow diagram illustrating the systematic process of literature selection for studies on the application of gas chromatography in halal food authentication.

Analysis Data

Data analysis in this systematic literature review was conducted descriptively based on a single comprehensive table that summarizes the extracted information from all selected studies. The table includes essential details such as references, sample types, gas chromatography (GC) methods employed, identified marker compounds, key findings, and the strengths and limitations of each study. The data were analyzed to identify emerging patterns, methodological trends, and differences in the performance of various GC approaches in halal food authentication. This analytical approach provides a comprehensive overview of the development and application of GC techniques across diverse food matrices, while also highlighting existing research gaps that need to be addressed to establish a more accurate and standardized halal verification system.

RESULT AND DISCUSSION

Research on halal food authentication has advanced rapidly over the past decade in line with the development of analytical techniques based on Gas Chromatography (GC). This method has been widely applied to various food matrices to detect volatile and semi-volatile compounds that serve as markers of product halalness. The literature review results indicate a wide diversity of instrumental approaches, sample types, and chemical parameters used in the verification process. A summary of the systematic literature review (SLR) findings on the application of GC in halal food and beverage authentication, including the sample types, GC methods, identified marker compounds, and the main findings of each study, is presented in Table 1.

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Table 1. Systematic literature review (SLR), summary of gas chromatography (GC) applications for halal authentication (2015 – 2025).

Reference	Sample Analyzed	GC Method Used	Identified Compounds/Markers	Key Findings
Amalia et al. (2025)	Wild boar meat (boiled, fried, roasted)	SPME–GC-MS	– Boiled: 2-Octenal, 1-Octen-3-ol. – Fried: Longifolene, Phenylcyclohexane. Roasted: Cyclopropyl carbinol, 2-Decenal.	PCA clearly separated cooking treatments; volatile profiles were strongly affected by the cooking method.
Pertiwi et al. (2025)	Beef, pork, chicken (raw/cooked/mix); rat, wild boar; meatballs; satay	SPME–GC-MS	– Beef: Nonanal, hexanal, heptanal. – Pork: Hexanal, 1-octen-3-ol. – Chicken: Benzeneacetaldehyde, aldehydes. – Rat & wild boar: Thiazoles, pyrazines, aldehydes (distinct). – Mixtures: Intermediate volatile profiles.	Clear species classification: beef separated from pork/chicken; mixtures clustered between parents. Accuracy ~82.7%.
Lestari et al. (2025)	Gabus fish oil, pork oil, palm oil	GC (ethanol standard)	– Gabus fish oil: Caprylic acid, Pentadecanoic acid, Arachidic acid. – Pork oil: Distinct fatty acid profile, no caprylic/arachidic acid. – Palm oil: Rich in long-chain fatty acids.	PCA clearly separated Gabus fish oil from pork oil and palm oil using specific markers.
Ahamed et al. (2024)	Cooked beef, pork, and admixtures (80:20; 60:40)	HS-SPME–GC-MS	– Beef: Nonanal, octanal, hexadecanal, benzaldehyde, 1-octanol, hexanoic acid, 2-acetylpyrrole. – Pork: Hexanal, 1-octen-3-ol. – Mixtures: Showed combined volatile profiles between beef and pork, indicating partial overlap of both markers.	Distinct clustering of beef, pork, and mixtures; adulteration influenced volatile profiles. PCA (80% variance), PLS-DA (72.1%). Random Forest confirmed robust biomarkers.
Putri et al. (2024)	Beef, chicken, goat fat adulterated with lard (0–80%)	SPME–GC-MS	– Lard adulteration markers: Hexanal, Nonanal, Heptanal, 1-Hexanol, Diallyl disulfide, 2-Pentyl furan, D-Limonene.	Lard detectable at 10% adulteration in all fat types; OPLS-DA produced robust classification.
Elsabagh et al. (2024)	Beef, pork, donkey, dog meat; beef mixtures	GC-MS (FAMEs)	– Beef: Stearic acid, Oleic acid. – Pork: Linoleic acid, Linolenic acid. – Donkey: Higher proportion of unsaturated fatty acids. – Dog: trans-Vaccenic acid, Oleic acid.	Beef had the highest saturated fatty acids; adulterant meats were richer in unsaturated fatty acids. GC-MS/MS and PCR confirmed species differentiation.
Darmawan et al. (2024)	Porcine, bovine, and mixed gelatin	SPME–GC–MS with chemometrics	– Aldehydes (nonanal, hexanal, heptanal), Alcohols (1-octen-3-ol, 1-octanol), FAMEs, Sulfur compounds, Ketones	Porcine, bovine, and mixed gelatin can be accurately distinguished based on volatile and FAMEs profiles. Mixed gelatin samples were clearly detected.

Reference	Sample Analyzed	GC Method Used	Identified Compounds/Markers	Key Findings
Yulirohyami et al. (2023)	Vinegar and beverages	GC-FID	– Ethanol	Validated GC-FID method detected ethanol in vinegar and beverages down to 0.05–1% v/v; LOD: 4.89 × 10⁻⁴%, LOQ: 1.48 × 10⁻³%. The method ensures halal compliance by accurately quantifying ethanol levels.
Dewi et al. (2023)	Meat & bone broth (beef, pork, goat, lamb, chicken)	HS-SPME–GC-MS	– Pork meat broth: Dioctyl hexanedioate, (E)-2-undecenal, 2-decenal, 1-hexanol, diethyl phthalate, tetradecamethylcycloheptasiloxane. – Pork bone broth: 1,3-dichlorobenzene, 2-octenal, 2,4-decadienal, 2-decenal, hexyl oxirane. – Other broths (beef, goat, lamb, chicken): Different aldehyde/alcohol profiles.	Physical traits, pH, viscosity, and density could not differentiate between halal/non-halal; volatile profiles provided distinct separation, with pork broth being highest in nonanal & hexanal.
Rachmaniah et al. (2023)	Javanese wine & Balinese wine	GC-MS (derivatization)	– Both wines: Ethanol (detected at high levels).	Both samples contained ethanol exceeding halal thresholds.
Ahamed et al. (2023)	Cooked beef, pork, chicken	GC-FID	– Beef: Undecanal, 2-undecanone, 1-octanol, 2-undecenal. – Pork: Hexanal, 1-octen-3-ol, 4-methyl phenol. – Chicken: Benzeneacetaldehyde, aldehydes, pyrazines.	Aldehydes are dominant in all species; PLS-DA separated beef from pork and chicken; 8 key discriminant compounds were identified.
Abdelrahman et al. (2023)	Mutton meat, beef meat, and their mixtures (various adulteration levels)	GC–MS/MS (FAMEs)	– Beef: Palmitic acid (C16:0), Stearic acid (C18:0) → lebih tinggi (SFA). – Mutton: Oleic acid (C18:1), Linoleic acid (C18:2), Linolenic acid (C18:3), Trans-vaccenic acid (C18:1 trans-11) → lebih tinggi (USFA). – Rasio SFA: USFA lebih tinggi pada beef dibanding mutton.	GC–MS/MS successfully differentiated beef vs mutton despite genetic closeness; adulteration changed fatty acid composition (increase in USFA for mutton, higher SFA for beef).
Yulirohyami et al. (2023)	Pork fat in food products	GC–MS (FAMEs)	– Fatty acids: Oleic acid, Linoleic acid, Palmitic acid, Stearic acid	GC–MS differentiated pork fat from other fats using FAME profiles, enabling halal authentication.

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Reference	Sample Analyzed	GC Method Used	Identified Compounds/Markers	Key Findings
Salamah et al. (2022)	House rat (R. tanezumi), lard, chicken, goat, meatballs	GC-MS (Rtx-5ms)	– House rat fat: Methyl myristate, Palmitoleic acid, Palmitic acid, Oleic acid, Stearic acid. – Lard: Oleic acid, Palmitic acid. – Chicken: Palmitoleic acid. Goat: Stearic acid, Oleic acid. – Meatballs: Profile closer to goat fat than rat fat.	Rat fat: 48.21% unsaturated, 31.49% saturated fatty acids; PCA clustered rat closest to chicken.
Amalia, Yuliana, et al. (2022)	Meatballs (beef, rat, wild boar, mixtures)	HS-SPME–GC-MS	– Beef meatballs: 2-amino-5-methyl benzoic acid, Heptanal, Benzaldehyde. – Rat meatballs: (Z)-2-heptenal, 3-methyl-3-butenol, Caproic acid. – Wild boar meatballs: Cyclobutanol, Lauric acid, Undecane. – Mixtures: Nonanal, 1-pentanol, 1-octen-3-ol, Dimethyl trisulfide, Indole.	Clear discrimination between beef, rat, and wild boar meatballs even at 20% adulteration. Nonanal consistent marker across mixtures.
Amalia, Kusnandar, et al. (2022)	Beef, rat, wild boar, mixtures	GC-MS (FAMEs, BF$_3$)	– Beef: Dimethylfulvene. – Rat: Benzyl alcohol. Wild boar: 1,3,5-Cycloheptatriene. – Beef–rat mixtures: Benzaldehyde. – Beef–wild boar mixtures: 2,6-Dimethyldecane.	Each type of meat exhibited unique volatile markers; the mixtures clustered closer to those of wild boar.
Mansur et al. (2022)	108 commercial food & beverages	GC-MS (DMSO extraction)	– All samples: Ethanol (target analyte).	14 out of 108 products exceeded halal ethanol thresholds; the method is highly sensitive and precise.
Ismarti et al. (2022)	Gelatin (bovine, porcine, fish, poultry)	GC-MS (FAMEs)	– Bovine gelatin: Aldehydes, ketones. – Porcine gelatin: Higher esters, pyrazines. – Fish gelatin: Alcohols, furfural. – Poultry gelatin: Mixed aldehydes and alcohols.	Distinct volatile profiles among species; Maillard reaction increased complexity; potential for halal authentication.
Pranata et al. (2021)	Meatball products (beef, chicken vs wild boar)	SPME–GC-MS	– Beef & chicken meatballs: β-cymene, 3-methyl-butanal, 2-pentanol, benzaldehyde, pentanal, hexanal, nonanal, pyrazines. – Wild boar meatballs: distinct volatile differences, lower in some aldehydes.	Volatilomics successfully discriminated between halal (beef, chicken) and non-halal (wild boar) meatballs, proposing volatile markers for authentication.
Guntarti et al. (2021)	Fat of Sprague Dawley rats, wild boar, goat, cow, and meatballs	GC-MS (DB1-MS)	– Rat fat: Oleic acid, Linoleic acid, Palmitic acid, Palmitoleic acid, Stearic acid, Myristic acid, Margaric acid, Pentadecanoic acid. – Wild boar, goat, cow, meatballs: no linoleic acid.	Rat fat is dominated by Oleic & Linoleic acids; Linoleic acid is unique to rat fat. PCA clearly separated rats from other species.

Reference	Sample Analyzed	GC Method Used	Identified Compounds/Markers	Key Findings
J. Li et al. (2021)	Chinese black pork breeds (Beijing Heiliu, Laiwu)	HS-SPME–GC-MS	– Both breeds: Aldehydes (hexanal, nonanal, octanal). – Beijing Heiliu: Higher phosphatidylcholines (PCs). – Laiwu: Higher phosphatidylethanolamines (PEs), sphingomyelins.	Differences in lipid composition and volatile profiles enabled breed discrimination.
Ahda et al. (2021)	Meatballs (beef, pork, wild boar), fats (beef, lard, commercial)	GC-MS (retention time)	– Beef: Palmitic acid, Stearic acid (SFA-rich). – Pork: Oleic acid (MUFA-rich). – Wild boar: Oleic acid (MUFA-rich). – Lard: Oleic acid, Linoleic acid (MUFA + PUFA). – Commercial meatball: Oleic acid dominant.	The ratio of saturated to unsaturated fatty acids differentiated between halal and non-halal samples; PCA grouped the samples accordingly.
Azizan et al. (2021)	Pure wheat biscuits, pure lard, and wheat biscuits adulterated with lard (lab-prepared)	GC–MS of Fatty Acid Methyl Esters (FAMEs) after Soxhlet extraction	– Fatty acids, C18:3n6, highlighted as a dose-dependent marker for lard adulteration	PCA and HCA clustered pure biscuits, pure lard, and adulterated biscuits; Random Forest outperformed PLS-DA; C18:3n6 was proposed as a key biomarker
Guntarti et al. (2019)	Pork sausage, beef sausage, commercial sausages	HS-SPME–GC-MS (DB-WAX)	– Pork sausage: Myristic acid, Palmitic acid. – Beef sausage: Palmitic acid, Oleic acid. – Commercial sausages: Closer to a beef profile.	PCA effectively distinguished pork vs beef sausages.
Guntarti et al. (2020)	Fats (rat, pig, beef, chicken, goat, dog, wild boar)	GC-MS (FAMEs)	– Rat fat: Oleic acid, Linoleic acid, Palmitic acid, Stearic acid, Palmitoleic acid, Myristic acid. – Pig fat: Oleic acid, Linoleic acid. – Beef fat: Palmitic acid, Stearic acid. – Chicken fat: Palmitoleic acid, Oleic acid. – Goat fat: Oleic acid, Stearic acid. – Dog fat: Oleic acid, Palmitic acid. – Wild boar fat: Oleic acid.	PCA differentiated species; rat fat clustered close to chicken and pork.
Pavlidis et al. (2019)	Minced beef, pork, mixtures	GC-MS + E-nose	– Beef: Aldehydes (nonanal, hexanal), 1-octen-3-ol. – Pork: Higher hydrocarbons and ketones. – Mixtures: Intermediate volatile profiles.	Clear discrimination of beef, pork, and mixtures; OPLS-DA gave the best classification.
Q. Wang et al. (2019)	Mutton adulterated with duck	GC-MS (FAMEs)	– Mutton: Aldehydes, ketones, alcohols (baseline). – Duck meat: Additional volatiles, changed aldehyde ratios.	Duck adulteration is detectable at ~10%. E-nose predictions aligned well with GC-MS profiles.

Reference	Sample Analyzed	GC Method Used	Identified Compounds/Markers	Key Findings
Guntarti (2018)	Dog fat vs beef, chicken, goat, lard, wild boar	SPME–GC-MS (DB-WAX)	– Dog fat: Lauric acid, Myristic acid, Pentadecanoic acid, Palmitoleic acid, Palmitic acid, Margaric acid, Oleic acid, Stearic acid, Arachidonic acid. Beef fat: Palmitic acid, Stearic acid. – Chicken fat: Palmitoleic acid. Goat fat: Stearic acid, Oleic acid. – Lard: Palmitic acid, Oleic acid. – Wild boar fat: Oleic acid.	Dog fat is dominated by Oleic acid; PCA clustered dog fat close to lard, chicken, and wild boar.
Rahayu et al. (2018)	Dog fat, beef fat, goat fat, chicken fat, pork fat	GC–MS of FAMEs after lipid extraction (Bligh & Dyer method)	– Oleic acid, Palmitic acid, Linoleic acid, Stearic acid, Palmitoleic acid; discriminants: 8,11-eicosadienoic, 11-eicosenoic, Nonadecanoic acid, Methyl γ-linoleate	GC–MS FAME profiles differentiated dog fat from beef, goat, chicken, and pork; PCA score plots showed dog fat clustered closer to chicken/pork but separable based on specific fatty acids
Witjaksono et al. (2017)	Pig fat (lard), chicken, cow	GC-TOF MS	– Lard: 1,2,3-trimethyl-benzene, indane, undecane, p-cymene, bis(2-ethylhexyl) hexanedioate (very high concentrations). Chicken & cow fats: much lower hydrocarbon content.	Lard contained 250× more trimethyl benzene than chicken, 91× more than cow; hydrocarbons proposed as markers.
Trivedi et al. (2016)	Minced beef & pork; mixtures (0–50%)	GC-MS (volatiles)	– Beef: Glycine, Myo-inositol, Pyroglutamic acid, Citric acid, Creatinine. – Pork: Heptadecane, Pentadecane, Arabitol. – Mixtures: Intermediate metabolite profiles.	PCA/PLS-DA distinguished beef, pork, and mixtures; adulteration detectable at 10%.
Park et al. (2016)	Korean fermented foods (soy sauce, kimchi, vinegar, etc.)	SPME–GC-MS	– Detected: Ethanol, Methanol, 1-Propanol, Isobutanol, Isoamyl alcohol.	Simple method for simultaneous detection of alcohols; relevant for halal certification.
Suparman et al. (2015)	Imported chocolates	GC-MS (FAMEs)	– All samples: Eicosadienoic acid (C20:2) identified as a lard marker.	All six chocolate samples tested positive for lard; FTIR confirmed the presence of specific peaks.

The fundamental principle of gas chromatography in halal food authentication

Gas Chromatography (GC) is an analytical technique that separates volatile compounds based on their volatility and interaction with the stationary phase. Compounds with higher volatility elute more rapidly, whereas those with greater affinity for the stationary phase exhibit longer retention times, producing distinct chromatographic profiles for each sample. This capability enables GC to generate specific chemical fingerprints, making it a highly reliable tool for authenticating halal food. GC–MS serves as the primary analytical method to distinguish volatile and lipid components among species. When integrated with sample preparation techniques such as headspace solid-phase microextraction (HS-SPME) or fatty acid methyl ester (FAME) derivatization, GC–MS effectively identifies non-halal markers, particularly those derived from pork (Ahamed et al., 2024; Pranata et al., 2021). Volatilomic

investigations have revealed aldehydes, ketones, and alcohols such as hexanal, nonanal, and 1-octen-3-ol as potential species-specific markers (Ahamed et al., 2025; Indrasti & Ramadhina, 2025). Furthermore, GC–FAMEs analysis can differentiate fat sources, for example, identifying linoleic acid as a specific marker for rat fat (Guntarti et al., 2021). Advanced instruments, such as GC–TOF MS and GC×GC–TOF MS, offer enhanced sensitivity, enabling the detection of characteristic hydrocarbons in lard and improving the accuracy of identifying non-halal adulterants that are often undetectable by conventional GC–MS (Prihandiwati et al., 2024; Witjaksono et al., 2017).

Based on the findings of this systematic literature review (SLR), studies applying GC for halal authentication encompass a diverse range of food matrices, as summarized in Table 1. The analyzed samples were categorized into five major groups, including fresh and processed meats (beef, pork, chicken, mutton, goat, lamb, wild boar, dog, rat, and derivative products such as meatballs, sausages, and satay), gelatin from bovine, porcine, fish, and poultry sources, and various oils and fats such as lard, beef fat, goat fat, chicken fat, dog fat, rat fat, wild boar fat, gabus fish oil, and palm oil. Across these matrices, SPME–GC–MS, HS-SPME–GC–MS, and GC–FAMEs were the most frequently employed techniques. The reviewed studies consistently identified species-specific volatile compounds and fatty acid profiles as chemical markers for differentiating halal and non-halal sources, enabling the detection of pork adulteration, mixed meat products, and fat substitution. Chemometric tools such as principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) were commonly integrated to enhance classification accuracy and sample discrimination. These findings demonstrate the high sensitivity, selectivity, and reliability of GC–MS for trace-level detection and routine halal screening. Nevertheless, several limitations were reported, including the need for derivatization, matrix interference, sensitivity to processing or storage conditions, and relatively high instrumentation and operational costs. Therefore, while GC-based methods provide strong analytical evidence for chemical authentication, they should be complemented by traceability systems and halal certification to ensure comprehensive halal verification

Separation mechanism of volatile compounds by gas chromatography

Gas Chromatography (GC) operates based on differences in the volatility and interaction of analytes with the stationary phase inside the chromatographic column. During analysis, the sample is injected into a heated inlet where volatile compounds are vaporized and carried by an inert gas (helium, nitrogen, or hydrogen) through a capillary column. Compounds with higher volatility and weaker interactions with the stationary phase elute more rapidly, while those with stronger affinities exhibit longer retention times, resulting in distinct chromatographic patterns for each analyte. This fundamental principle makes GC highly effective in distinguishing chemical profiles of food matrices, particularly for halal authentication (Ng et al., 2022; Nurani et al., 2022).

The separation efficiency in GC is influenced by the type of capillary column and the use of temperature programming. Nonpolar columns based on dimethylpolysiloxane are suitable for separating hydrocarbons and fatty acids, whereas polar columns, such as polyethylene glycol, are ideal for oxygenated compounds like aldehydes, ketones, and alcohols. Temperature programming allows efficient separation of compounds with a wide range of volatilities within a single run. Detector selection also plays a crucial role in analytical precision. The Flame Ionization Detector (FID) is widely used for lipid quantification, while Gas Chromatography–Mass Spectrometry (GC–MS) enables the identification of specific molecules based on their unique ion fragmentation patterns. Recent studies have shown that GC–MS, particularly when combined with sample preparation techniques such as fatty acid methyl ester (FAME) derivatization or headspace solid-phase microextraction (HS-SPME), is highly effective for detecting pork fat adulteration and distinguishing species-specific volatile profiles (Mortas et al., 2022). Therefore, GC's separation mechanism not only provides analytical accuracy but also serves as a fundamental approach for reliable halal food authentication.

Application of Gas Chromatography in Halal Food Product Authentication

Understanding the separation mechanism of volatile compounds through Gas Chromatography (GC) forms the analytical foundation for its application in halal food authentication. This principle has been applied in various analytical contexts, including the differentiation of meat species based on

volatile profiles, the identification of fat and oil sources, the distinction between gelatin origins, and the quantification of ethanol in beverages.

1. Authentication of Meat Species Using Volatile Profiles

Headspace Solid Phase Microextraction–Gas Chromatography–Mass Spectrometry (HS-SPME–GC–MS) is an effective approach for distinguishing meat species based on volatile organic compounds (VOCs) generated from lipid oxidation and aroma metabolites. Each species, such as beef, pork, lamb, and goat, produces a unique volatile fingerprint, including aldehydes (nonanal, hexanal, heptanal), ketones (2-heptanone, 3-octanone), alcohols (1-octen-3-ol, 1-pentanol), hydrocarbons, and sulfur compounds (Pavlidis et al., 2019; Pranata et al., 2021). Classification models, such as PCA and PLS–DA, achieve accuracies ranging from 80% to 99%, demonstrating the effectiveness of GC–MS for rapid and sensitive halal authentication (Ahamed et al., 2024; He et al., 2023; X. Li et al., 2022).

GC–MS has also been applied to detect non-halal adulteration in processed products. Specific markers, such as 2-decenal, 1-hexanol, and 2-octenal, characterize pork broth, whereas beef and chicken contain predominantly long-chain aldehydes (Dewi et al., 2023). The method can identify wild boar or rat meat at trace levels and detect pork contamination in beef below 1% (Amalia, Kusnandar, et al., 2022; Trivedi et al., 2016; Zang et al., 2020). GC–MS-based volatilomics provides results consistent with DNA barcoding, offering a highly sensitive, reproducible, and non-destructive tool for halal meat authentication when supported by multivariate analysis and robust mass spectral databases (Akbar et al., 2025).

2. Differentiation of Fats and Oils through Fatty Acid Methyl Ester (FAME) Analysis

Fat and oil authentication in halal food products can be effectively achieved using GC-based Fatty Acid Methyl Ester (FAME) analysis. The methylation process converts fatty acids into FAMEs, which are then separated based on their volatility and polarity, producing characteristic chromatographic fingerprints that differentiate fat sources, such as pork, beef, and vegetable oils (Yulirohyami et al., 2023). Witjaksono et al. (2017) demonstrated that lard contains hydrocarbon compounds, including 1,2,3-trimethylbenzene, at concentrations up to 250 times higher than chicken fat, serving as a distinctive marker. Similarly, Putri et al. (2024) showed that lard adulteration in beef, chicken, or goat fat can be detected at levels as low as 10%, with accurate classification using multivariate models such as OPLS-DA.

Furthermore, GC–FAMEs enables the identification of saturated-to-unsaturated fatty acid ratios as additional authentication indicators. Elsabagh et al. (2024) reported that beef fat typically exhibits a higher proportion of saturated fatty acids, whereas pork and other non-halal sources are richer in unsaturated fatty acids. This technique is highly relevant for halal industries since fats and oils are commonly used as ingredients in processed products such as sausages, chocolates, and pastries. With high sensitivity, reproducibility, and non-destructive capability, GC–FAMEs offers a robust method for detecting non-halal fat adulteration and ensuring product compliance with halal standards (Araújo et al., 2018; Heidari et al., 2020; Lestari et al., 2025).

3. Identification of Gelatin and Derivative Products Using GC–MS

Gelatin, typically derived from animal skin, bones, and connective tissues, is a critical target for halal authentication due to the potential use of non-halal sources such as porcine gelatin. GC–MS analysis has proven effective in distinguishing halal (bovine, fish, or poultry) and non-halal (porcine) gelatin based on volatile compounds derived from peptide hydrolysis and characteristic FAME profiles unique to each animal source (Adebo et al., 2021; Ismarti et al., 2022). Porcine gelatin usually contains specific aldehydes, ketones, and esters that differ significantly from bovine or fish gelatin, while FAME profiles reveal variations in saturated and unsaturated fatty acid proportions, allowing both qualitative and quantitative source identification.

This approach can also be extended to gelatin-derived products such as pharmaceutical capsules, jelly candies, and other processed foods (Darmawan et al., 2024; Moon et al., 2025). The GC–MS method offers high sensitivity, reproducibility, and non-destructive analysis,

making it a reliable tool for halal authentication within the frameworks of volatilomics and lipidomics. When combined with chemometric analyses such as PCA or OPLS-DA, GC–MS further enhances accuracy, especially in complex or blended products where conventional methods often fail to differentiate gelatin sources (Hassan et al., 2025).

4. Detection of Ethanol and Fermentation-Derived Compounds in Beverages

Ethanol detection and the analysis of fermentation metabolites are crucial aspects of halal authentication, particularly in beverages prone to natural fermentation. Gas Chromatography (GC), coupled with either Flame Ionization Detection (GC–FID) or Mass Spectrometry (GC–MS), enables the quantification of ethanol at concentrations below 0.1%, ensuring compliance with halal standards (Abdelrahman et al., 2023). In addition to ethanol, other fermentation metabolites such as acetaldehyde, acetic acid, methanol, and fusel alcohols can be simultaneously analyzed to assess product quality and potential contamination. GC-based methods demonstrate higher sensitivity and selectivity than spectrophotometric or titrimetric techniques, especially in complex matrices (Pizzutti et al., 2016).

Yulirohyami et al. (2023) and Pinu & Villas-boas (2017), further demonstrated that GC–MS can detect ethanol and fermentation metabolites in fruit-based beverages at concentrations as low as 0.05%, minimizing the risk of non-compliance with halal regulations. The integration of GC–MS with chemometric approaches enhances the accuracy of compound identification and quantification, providing a comprehensive profile of volatile compounds and overall product quality (Wolfender et al., 2019). With high sensitivity, reproducibility, and non-destructive characteristics, GC–FID and GC–MS serve as key analytical platforms for halal authentication in fermented beverages and fruit-based products, supporting strict quality control and transparent labeling.

Chemical markers for GC-based halal authentication

Gas Chromatography (GC) techniques, including SPME–GC–MS, HS-SPME–GC–MS, GC–FID, and GC–MS/FAMEs, are widely applied for halal authentication of meat and related products. Volatile compounds such as aldehydes (pentanal, hexanal, nonanal), ketones, alcohols, and heterocyclic compounds (pyrazines, thiazoles) effectively distinguish halal (beef, chicken, lamb) from non-halal (pork, wild boar, rat) meats, even in processed forms like meatballs and satay (Ahamed et al., 2024; Pertiwi et al., 2025; Pranata et al., 2021). Integrating volatile profiling with chemometric models enables sensitive, selective, and non-destructive species discrimination; however, factors such as sample processing and storage may impact classification accuracy.

Fat, oil, gelatin, and beverage products are also effectively authenticated using GC–MS and GC–FAMEs, which utilize species-specific chemical markers. Fatty acids such as oleic, linoleic, palmitic, myristic, and linolenic acids differentiate animal fats (beef, pork, chicken, rat, lard) from vegetable oils (Azizan et al., 2021; Guntarti et al., 2020; Witjaksono et al., 2017). Similarly, halal (bovine or fish) and non-halal (porcine) gelatin exhibit distinct volatile, ketone, sulfur, and FAME profiles (Darmawan et al., 2024; Hassan et al., 2025). In fermented and fruit-based beverages, ethanol and metabolites such as acetaldehyde, acetic acid, methanol, and fusel alcohols can be detected at < 0.1% using GC–FID or GC–MS, ensuring halal compliance (Park et al., 2016; Rachmaniah et al., 2023). Integrated with multivariate analysis, GC-based methods offer accurate, reproducible, and rapid authentication across diverse food matrices.

Performance, advantages, and limitations of gas chromatography in halal authentication

Gas Chromatography (GC), including GC–MS, GC–FID, and GC–FAMEs, demonstrates high performance in halal authentication by detecting volatile compounds, fatty acids, and fermentation metabolites at trace levels (< 0.1%). This sensitivity enables accurate identification of meat, fat, gelatin, and ethanol in complex or processed products (Maritha et al., 2022). Integration with headspace or SPME extraction enhances selectivity and reproducibility, generating distinctive chemical fingerprints that differentiate halal and non-halal meats, detect low-level fat adulteration, and verify beverage compliance with halal standards.

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GC offers key advantages, including non-destructive analysis, high reproducibility, and compatibility with multivariate and chemometric methods (PCA, PLS-DA, OPLS-DA), which strengthen species discrimination and adulteration detection (Shi et al., 2021; X. Wang et al., 2019). However, limitations arise from processing and storage effects, feed variability, and the need for extensive sample preparation and spectral libraries. Despite these challenges, the combination of high sensitivity, matrix versatility, and robust quantitative and qualitative capability makes GC a primary platform for halal authentication, providing significant scientific and practical value for food and pharmaceutical quality control.

Challenges and future directions of GC-based halal analysis

Matrix variability, processing effects, and storage conditions have a significant impact on GC sensitivity and selectivity, particularly in cooked or mixed products. Degradation of volatile compounds, Maillard reactions, and alterations in FAME profiles may reduce identification accuracy. The method's constraints also include dependence on comprehensive spectral libraries, complex data interpretation, long analytical times, and high operational costs (Llambrich et al., 2025; Rutkowska et al., 2019).

Future development should focus on enhancing resolution and sensitivity through advanced hyphenated techniques such as GC×GC–MS or GC–TOF MS and optimizing extraction and sample preparation protocols. The integration of chemometrics and multivariate modeling enables the reliable discrimination of species, detection of adulteration, and validation of data. Based on the literature and findings in Table 1, key recommendations include: (1) applying GC-based volatilomics and lipidomics for early adulteration detection; (2) developing non-destructive methods with lower detection limits (< 0.05%) for processed meat, fat, gelatin, and fermented beverages; and (3) establishing a comprehensive halal marker database through analytical chemistry and bioinformatics collaboration. These strategies are expected to enhance accuracy, reproducibility, and standardization in global halal authentication.

CONCLUSION

This systematic review highlights Gas Chromatography (GC) as a highly effective analytical tool for halal food authentication, capable of detecting volatile compounds and fatty acid profiles that differentiate halal from non-halal materials. Techniques such as GC–MS, GC–FID, HS-SPME–GC–MS, and GC–FAMEs enable accurate identification of meat species, detection of pork fat adulteration, and quantification of ethanol in fermented products. GC offers high sensitivity, selectivity, and non-destructive analysis, supporting robust and measurable halal verification. Despite challenges such as complex food matrices, high instrumentation costs, operator expertise requirements, and a lack of global standardization, integrating GC with chemometrics, volatilomics, and lipidomics provides a more efficient, consistent, and universally applicable approach. Overall, GC represents a strategic scientific method for strengthening global halal assurance, enhancing supply chain transparency, and reinforcing consumer trust in the integrity of halal products.

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