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Research Progress and Application Prospects of GC-IMS in Grain and Oil Processing: Analysis Based on Volatile Organic Compounds (VOCs) Fingerprinting

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Abstract

Gas chromatography-ion mobility spectrometry (GC-IMS) is an emerging analytical technique that combines the separation capability of gas chromatography with the sensitivity and selectivity of ion mobility spectrometry. This review provides a comprehensive overview of the application of GC-IMS technology in the field of grain and oil processing, highlighting its role in volatile compound analysis, quality assessment, contamination detection, and process optimization. GC-IMS has been widely used to identify and quantify volatile compounds, to develop flavor fingerprints, and to assess the freshness and spoilage of various grains and oils. It has also proven effective in detecting fungal contamination and adulteration, as well as in evaluating the impact of different processing and storage conditions on product quality. Compared with traditional methods such as GC-MS and electronic nose (E-nose), GC-IMS offers several advantages, including rapid analysis, high sensitivity, and non-destructive detection. However, challenges remain regarding data interpretation and the development of standardized protocols. Future research should focus on addressing these limitations and exploring new applications of GC-IMS in the food industry. This review aims to summarize the current state of GC-IMS technology in grain and oil processing and to provide insights into its potential for future development.

Keywords

GC-IMS; Volatile compound analysis; Grain and oil processing; Quality assessment; Non-destructive detection

1. Introduction

The modern grain and oil industry constitutes a vital sector in the global food production chain, extending from the cultivation of oil-bearing seeds to the refinement of edible oils. Monitoring and assessing the quality and purity of these products have gained increasing significance due to the rising prevalence of food adulteration and contamination [1-3]. Consequently, the adoption of reliable and sophisticated analytical techniques for quality control is imperative.

Among existing analytical techniques, GC-IMS has emerged as a powerful tool capable of concurrent qualitative and quantitative analysis. Initially developed for detecting explosives and chemical warfare agents, GC-IMS separates and identifies ionized molecules in the gas phase based on their differential mobility in a carrier gas [4]. This method establishes GC-IMS as an effective screening technique, offering advantages such as rapid analysis, low operational cost, and minimal sample pretreatment requirements [5].

GC-IMS derives a substantial portion of its analytical capability from its coupling with Gas Chromatography (GC), which significantly enhances its ability to separate and quantify sample components [4]. Empirical studies have demonstrated the technique's efficacy in grain and oil processing applications, particularly in detecting oil adulteration [3], identifying volatile organic compounds (VOCs), and characterizing aroma profiles. For instance, GC-IMS has been successfully applied to detect and differentiate between various grades of rapeseed oil based on their odor fingerprints [5] and to identify key volatile compounds responsible for the aroma profiles of various foods.

Notwithstanding these advantages, widespread adoption of GC-IMS in the grain and oil processing sector faces several implementation barriers. Key challenges include: (1) the requirement for advanced data processing software and specialized algorithms; (2) substantial capital investment in instrumentation and reference materials; (3) scarcity of trained personnel; and (4) inherent technical complexities [2]. Recent technological developments, however, are addressing these limitations, thereby expanding the potential applications of GC-IMS in this field [6].

This review systematically examines three critical aspects of GC-IMS technology in grain and oil processing: (i) current applications and performance metrics; (ii) implementation challenges; and (iii) emerging solutions. Through this comprehensive analysis, we aim to elucidate the transformative potential of GC-IMS for enhancing quality assurance protocols in the industry.

1.1 Brief Overview of Grain and Oil Processing Industry

The grain and oil processing industry is a vital sector of the global food industry, encompassing various steps from seed preparation to the packaging of the final refined product. In the context of vegetable oil processing, it involves important processes such as degumming, deacidification, dewaxing, and finally deodorization [1, 7]. Efficient and high-quality processing of oils and fats plays a critical role in the economic feasibility of process development. High-quality processing of oilseeds can yield a significant amount of oils and proteins, opening channels for diverse applications. Vegetable oils provide not just human nutrition but also serve a crucial role as regenerating raw materials for chemical, technical, and pharmaceutical industries [3]. Similarly, grain processing emphasizes the importance of sustainability and quality across a wide range of applications, whether for human consumption or in the production of bio-energy and other industrially significant products [1].

However, conventional oil processing procedures often result in significant yield losses and lower efficiencies due to inappropriate handling of crude oil and its derivatives. Overcoming this challenge requires exploring and implementing alternative energy-efficient processes, with membrane technology being one such emerging solution. Likewise, improving the effectiveness and efficiency of grain processing also mandates the exploration of innovative solutions and, centrally, the adoption of advanced technologies. Nonetheless, there are challenges to the industrial applications of these technologies, such as the development of solvent-stable membranes for vegetable oil processing. There is also a scarcity of detailed information about the other components of these advanced technologies and their interactions with specific applications [7]. This underlines the need for comprehensive studies to gain a deeper understanding of these processes, facilitating refined process development.

The application of sophisticated technologies such as GC-IMS has begun to see increasing adoption in these sectors. These technologies offer various benefits, such as cost and energy efficiency, improved product quality and yield, and novel solutions to issues traditionally associated with oil and grain processing [4, 5]. However, the uptake of these technologies also comes with its own set of challenges, which need to be addressed for more widespread application in the grain and oil processing industry.

1.2 Definition and Introduction of GC-IMS Technology

GC-IMS is a powerful analytical technology used for identifying and characterizing volatile compounds in complex matrices. This coupled technology combines the separation capabilities of Gas Chromatography (GC) with the sensitivity and selectivity of Ion Mobility Spectrometry (IMS). GC is a well-established method for the qualitative and quantitative analysis of volatile compounds, while IMS identifies ions based on their mobility in an electric field at atmospheric pressure [6].

In GC-IMS, samples are first volatilized using a carrier gas and separated by their relative volatility on a stationary phase in the GC stage. The separated compounds are then ionized and subjected to an electric field in the IMS stage, where they are further separated based on their ion mobility. This mobility is influenced by the ions' shape, size, and charge. The resulting two-dimensional data (retention time from GC and drift time from IMS) provides a detailed map of the sample's volatile profile [4].

In the grain and oil processing industry, GC-IMS has been effectively used for quality control and contamination detection. For example, it has been employed to detect adulteration in canola oil samples. In these studies, signals were extracted and analyzed using advanced data processing methods such as the Histogram of Oriented Gradient (HOG) and Multivariate Principal Component Analysis (MPCA) algorithms. Additionally, prediction tools like Partial Least Squares (PLS) have been used to estimate adulteration levels [5].

In summary, GC-IMS technology offers comprehensive and efficient analysis of complex samples with high accuracy. Its ability to perform simultaneous separation and qualitative/quantitative analysis makes it a fast and effective tool. Continuous improvements in GC-IMS are making it increasingly applicable in the grain and oil processing industry, solidifying its position as a powerful authentication and analysis method in these fields.

2. Principles and Working of GC-IMS

GC-IMS is a powerful analytical tool that integrates the separation capabilities of Gas Chromatography (GC) and the rapid detection advantages of Ion Mobility Spectrometry (IMS). This combination enables comprehensive analysis of VOCs in complex matrices, making it particularly valuable for grain and oil processing applications such as quality control, adulteration detection, and freshness monitoring [8].

2.1 Principles of Gas Chromatography

GC-IMS is a powerful analytical tool that integrates the strengths of both Gas Chromatography (GC) and Ion Mobility Spectrometry (IMS), offering a comprehensive approach to detect and analyze complex samples in the field of grain and oil processing. Gas Chromatography, a cornerstone of analytical chemistry, separates volatile compounds based on their retention time through interactions with a stationary phase, enabling precise identification of individual components in mixtures. For instance, in studies on Tricholoma matsutake flavor profiling [10]and rice aroma [11], GC effectively isolated key volatiles like 1-octen-3-one and hexanal. However, GC alone struggles with overlapping peaks in complex matrices, necessitating complementary detection systems.

Ion Mobility Spectrometry addresses this limitation by separating ions based on their mobility in an electric field, influenced by molecular size, shape, and charge. This rapid, high-sensitivity technique excels in detecting trace volatiles, as demonstrated in freshly cooked rice packaged in biodegradable materials [11] and the analysis of huajiao aroma [12]. Yet, IMS alone may fail to resolve structurally similar compounds in dense mixtures.

The synergy of GC and IMS in GC-IMS merges chromatographic separation with ion mobility resolution, generating two-dimensional data (retention time × drift time) for enhanced specificity. This dual-dimensional approach has proven invaluable in differentiating geographical origins of rice [1] and distinguishing volatile profiles of kiwifruit varieties [13]. For example, in Tricholoma matsutake studies, GC-IMS combined with PCA successfully mapped flavor fingerprints, revealing post-drying shifts in C8 compounds and methanol levels. Similarly, GC-IMS rapidly identified terpene and ester markers in huajiao, outperforming traditional GC-MS in speed and simplicity for industrial applications.

Despite its advantages, GC-IMS faces challenges such as high instrumentation costs, technical complexity, and the need for specialized expertise. Standardization of protocols and data interpretation remains a hurdle, as seen in the variable marker selection for kiwifruit aroma analysis. Future advancements in miniaturization, automation, and machine learning-driven data processing (e.g., DD-SIMCA models for rice authentication) could democratize its use in grain and oil industries, enabling real-time quality control, fraud detection, and flavor optimization.

2.2 Principles of Ion Mobility Spectrometry

Ion Mobility Spectrometry (IMS) is a powerful analytical technique for separating and identifying gaseous ions based on their differential mobility in an electric field within a carrier gas. This separation arises from variations in ion velocity, which depend on ion size, shape, and charge, enabling rapid and sensitive detection of VOCs [10, 11]. A key feature of IMS is its ability to generate a three-dimensional matrix representing drift time (compound type), retention time (compound quantity), and peak intensity (compound presence), visualized as a pseudo-color chromatogram for intuitive interpretation [14].

IMS offers advantages such as high sensitivity (detection limits in the ppb range), real-time analysis, and minimal sample preparation, making it ideal for food quality control and authenticity studies [13]. For instance, HS-GC-IMS has been employed to distinguish geographical origins of Tricholoma matsutake mushrooms by analyzing volatile fingerprints [10] and to differentiate rice samples from China, India, and Vietnam based on VOC profiles [1]. However, IMS has limitations, including susceptibility to environmental interference (e.g., humidity, temperature) and challenges in resolving ions with similar drift times [15].

When coupled with gas chromatography (GC), IMS enhances analytical resolution by combining GC's separation efficiency with IMS's rapid detection. This hybrid approach, such as HS-SPME-GC-IMS, has been applied to characterize aroma profiles in kiwifruit varieties and monitor mold contamination in stored rice by detecting markers like 1-octen-3-ol and 3-octanone [8]. Despite its potential, GC-IMS integration demands specialized expertise for data interpretation and method optimization [16, 17].

2.3 Integration of GC and IMS for Enhanced Analysis

The integration of Gas Chromatography (GC) and Ion Mobility Spectrometry (IMS), termed GC-IMS, combines the high separation efficiency of GC with the rapid detection and sensitivity of IMS, offering a robust analytical platform for volatile compound analysis in grain and oil processing. GC effectively separates complex mixtures of VOCs based on their partitioning between mobile and stationary phases, while IMS further distinguishes ions by their mobility in an electric field, generating multidimensional data visualized as pseudo-color fingerprints [18]. This dual-separation mechanism enhances selectivity and sensitivity, addressing challenges such as overlapping chromatographic peaks and retention time variability inherent to standalone GC [8, 10].

Chemometric tools, including PCA, Partial Least Squares Discriminant Analysis (PLS-DA), and MPCA, are critical for interpreting GC-IMS data. These methods enable feature extraction, adulteration detection, and classification of samples based on geographical origin, processing conditions, or contamination levels. For instance, PCA has been employed to distinguish Tricholoma matsutake samples from different regions by analyzing volatile compound profiles [10], while PLS-DA achieved high accuracy in discriminating rice origins using VOC fingerprints [1]. Additionally, algorithms like the Histogram of Oriented Gradients (HOG) further optimize pattern recognition in GC-IMS datasets.

The application of GC-IMS in industrial settings is exemplified by its use in quality control and contamination monitoring. For example, GC-IMS coupled with electronic nose (E-nose) systems enables early detection of mold in stored grains by identifying markers such as 1-octen-3-ol and 3-octanone [8]. It also evaluates the impact of packaging materials on food aroma, as demonstrated in studies analyzing volatile retention in rice packaged with biodegradable lunchboxes [18]. Furthermore, GC-IMS facilitates rapid aroma profiling of spices like huajiao, distinguishing between varieties using terpene and ester markers [12]. These applications underscore the technology's versatility in ensuring food authenticity and safety.

Advances in GC-IMS continue to expand its utility, particularly when combined with complementary techniques like HS-SPME-GC-MS for comprehensive VOC characterization [9]. Future developments may focus on miniaturization and real-time monitoring, further solidifying GC-IMS as a cornerstone technology in food analytics.

3. Applications in Grain Processing

3.1 Volatile Compound Analysis and Flavor Profiling

3.1.1 Identification and Quantification of Volatile Compounds

The identification and quantification of volatile compounds are crucial for understanding the flavor profiles of various food products. GC-IMS has emerged as a powerful tool for this purpose, offering high sensitivity and resolution. For instance, Li et al. [10] developed a flavor fingerprint for "Tricholoma matsutake" Singer using HS-GC-IMS combined with PCA. This study identified 25 typical volatile compounds, including key flavor contributors such as 3-octanone, 3-octanol, 1-octen-3-one, and 1-octanol [10]. Similarly, Zhao et al. [13] utilized HS-SPME-GC-MS and GC-IMS to analyze the aroma profiles of three kiwifruit varieties, identifying 48 volatile compounds, including aldehydes, alcohols, and esters. These studies demonstrate the effectiveness of GC-IMS in identifying and quantifying volatile compounds in complex food matrices.

3.1.2 Development of Flavor Fingerprints

The development of flavor fingerprints using GC-IMS has become a cornerstone in food analysis, providing a comprehensive understanding of the aromatic profiles of various food products. For example, Chen et al. [19] developed aroma fingerprints for shiitake mushrooms under different drying conditions using GC-IMS, GC-MS, and descriptive sensory analysis (DSA). The study revealed that drying degree had a significant impact on the volatile flavor quality, with specific compounds such as 2,3-butanedione and 2-butanone being more prevalent in samples with higher drying degrees [19]. This approach not only aids in the identification of key volatile compounds but also provides insights into the sensory attributes of the food products.

3.1.3 Examples from Literature

Several studies have successfully applied GC-IMS for volatile compound analysis and flavor profiling in various food products. For instance, Li et al. [10] developed a flavor fingerprint for Tricholoma matsutake Singer using HS-GC-IMS and PCA, identifying significant differences in volatile compounds between different parts of the mushroom and samples from various regions. Zhao et al. [13] analyzed the aroma profiles of three kiwifruit varieties using HS-SPME-GC-MS and GC-IMS, revealing distinct volatile profiles and sensory attributes. Chen et al. [19] further demonstrated the potential of GC-IMS in discriminating between shiitake mushrooms subjected to different drying conditions, highlighting the importance of drying degree in flavor development. These studies collectively underscore the versatility and robustness of GC-IMS in food flavor analysis (Table 1).

Table 1. GC-IMS Method Applications in Grain Processing

Study	Food Product	Analytical Techniques	Key Findings
Li et al. [10]	*Tricholoma matsutake* Singer	HS-GC-IMS, PCA	Identified 25 volatile compounds; differences in volatile profiles between different parts and regions
Zhao et al. [13]	Kiwifruit	HS-SPME-GC-MS, GC-IMS, DSA	Identified 48 volatile compounds; distinct profiles among three varieties
Chen et al. [19]	Shiitake Mushrooms	GC-IMS, GC-MS, DSA	Highlighted the impact of drying degree on volatile flavor quality
Wang et al. [20]	Various Foods	GC-IMS	Detection of off-flavors in different food matrices
Hu et al. [11]	Rice	GC-IMS	Identification of key volatile compounds contributing to off-flavors and freshness
Gu et al. [2]	Peanut Kernels	HS-GC-IMS, Fluorescence Spectroscopy	High accuracy (96.7%) in characterizing fungal infection using data fusion
Gu et al. [21]	Wheat Kernels	HS-GC-IMS, Chemometrics	Excellent classification (100%) and prediction performances ($R^2 = 0.979$-0.998) for fungal-infected samples
Liu et al. [22]	Biodegradable Films	Mechanical Testing, UV Barrier Performance	Improved mechanical properties and UV barrier performance with curcumin incorporation
Liu et al. [23]	Brown Rice	DBD-CP Treatment, GC-IMS	Reduced FFA levels, stabilized surface color, improved flavor profile during storage
Wang et al. [24]	Buckwheat Noodles	Superheated Steam Processing	Improved textural properties and cooking qualities by stabilizing buckwheat grains

3.2 Quality and Freshness Evaluation

The detection of off-flavors is a critical aspect of food quality and freshness evaluation, as these undesirable odors can significantly impact consumer acceptance and product shelf-life. GC-IMS has proven to be an effective tool for identifying and quantifying volatile compounds responsible for off-flavors in various food products. Wang et al. [4] provided a comprehensive review of the recent progress in food flavor analysis using GC-IMS, highlighting its applications in detecting off-flavors in different food matrices. Additionally, Hu et al. [11] reviewed the volatile compounds, factors affecting rice aroma, and evaluation methods, emphasizing the role of GC-IMS in identifying key off-flavor compounds in rice. These studies demonstrate the utility of GC-IMS in detecting and characterizing off-flavors, which is essential for maintaining food quality.

Several case studies have effectively utilized GC-IMS for the evaluation of food quality and freshness. Wang et al. [4] highlighted the application of GC-IMS in detecting off-flavors in various food products, showcasing its potential for real-time monitoring and quality control. Hu et al. [11] further demonstrated the effectiveness of GC-IMS in evaluating rice aroma, identifying key volatile compounds that contribute to off-flavors and freshness indicators. These studies underscore the versatility of GC-IMS in food quality assessment, providing valuable insights into the volatile profiles that influence consumer perception and product shelf-life.

3.3 Contamination Detection

The detection of fungal contamination is crucial for ensuring food safety and quality, particularly in stored grains and nuts. GC-IMS has emerged as a powerful tool for rapid and non-destructive detection of fungal contamination. Gu et al. [21] developed a method for the rapid determination of potential aflatoxigenic fungi contamination on peanut kernels using data fusion of HS-GC-IMS and fluorescence spectroscopy. This study demonstrated that feature-level data fusion using the first 10 principal components (PCs) coupled with orthogonal partial least squares discriminant analysis (OPLS-DA) achieved high accuracy (96.7%) in characterizing fungal infection. Similarly, the study showed that genetic algorithm optimized support vector machine (GA-SVM) models achieved excellent classification (100%) and prediction performances ($R^2 = 0.979$-0.998) for fungal-infected samples [2].

Early warning systems leveraging HS-GC-IMS and chemometrics offer significant potential for preventing economic losses and ensuring food safety. Gu et al. [21] demonstrated the utility of data fusion techniques in enhancing detection accuracy and reliability, particularly for aflatoxigenic fungi in peanuts. Additionally, the development of robust early warning systems for moldy wheat kernels using HS-GC-IMS and chemometrics provides a valuable tool for early detection and prevention of fungal contamination, underscoring the importance of these technologies in food quality and safety management.

3.4 Processing and Storage Effects

Innovative processing techniques have demonstrated significant potential in enhancing food quality and extending shelf life. Liu et al. [22] developed biodegradable films from cationic potato-peel starch loaded with curcumin, which improved mechanical properties, UV barrier performance, and antioxidant activity. Similarly, Liu et al. [23] showed that dielectric barrier discharge cold plasma (DBD-CP) treatment effectively reduced free fatty acids and stabilized the flavor profile of brown rice during storage. These studies highlight the importance of advanced processing methods in preserving food quality and nutritional value.

Optimal storage conditions are equally critical for maintaining food quality and prolonging shelf life. Liu et al. [22] demonstrated that biodegradable films with UV barrier and antioxidant properties could significantly extend the shelf-life of perishable foods. Additionally, Wang et al. [24] found that superheated steam processing improved the textural and cooking qualities of buckwheat noodles by stabilizing the grains. These findings underscore the need for both innovative processing techniques and appropriate storage practices to ensure the longevity and quality of food products.

4. Applications in Oil Processing

4.1 Volatile Compound Analysis and Flavor Profiling

Volatile compound analysis and flavor profiling are essential for understanding the quality and authenticity of edible oils. These techniques provide valuable insights into the sensory attributes and geographical origins of oils, which are crucial for both quality control and consumer satisfaction.

The characterization of volatile profiles in edible oils is a key step in understanding their flavor and aroma characteristics. Recent studies have highlighted the importance of VOCs in determining the sensory attributes of oils. For instance, a comprehensive review by Suzuki et al. [25] proposed a novel extraction method for isolating volatile compounds from olive oil using the oiling-out effect, which significantly improved the extraction efficiency and provided a deeper insight into the aroma profile of olive oil. This method, known as oiling-out assisted liquid–liquid extraction (OA-LLE), combined with solvent-assisted flavor evaporation (SAFE), effectively removed non-volatile compounds and concentrated the volatile compounds, resulting in a more accurate and comprehensive analysis of the oil’s aroma profile.

Flavor fingerprinting has emerged as a powerful tool for assessing the quality and authenticity of edible oils. The volatile compounds in olive oil, such as C5 and C6 aliphatic compounds, are known to significantly influence the oil’s sensory attributes. These compounds are formed during the olive fruit milling and paste malaxation steps and contribute to the unique fruity and green aroma of high-quality extra virgin olive oil. The concentration and composition of these volatile compounds can vary based on factors such as cultivar, geographical origin, and processing conditions. Therefore, flavor fingerprinting can be used to authenticate the variety [26] and geographical origin of olive oils [27], predict or confirm quality categories, and provide insights into production technology and shelf-life (Table 2).

Table 2. GC-IMS Method Applications in Oil Processing

Study	Food Product	Analytical Techniques	Key Findings
Suzuki et al. [25]	Olive Oil	OA-LLE, SAFE, GC-MS	Improved extraction efficiency and detailed aroma profile
Lukić et al. [27]	Virgin Olive Oil	Comprehensive Two-Dimensional Gas Chromatography	Differentiation based on variety and geographical origin
Anggita et al. [26]	Patin Fish Oil	HS-GC-IMS	100% successful discrimination between adulterated and unadulterated samples; regression model for adulteration level determination
Chen et al. [19]	Shiitake Mushrooms	GC-IMS, GC-MS, DSA	Identification of key volatile compounds; potential for adulteration detection
Jin et al. [28]	Giant Salamander Meatballs	GC-IMS	Differentiation between frying methods; increased aldehydes and ketones in fried samples
Chen et al. [5]	Rapeseed Oil	GC-IMS	Identification of volatile compounds as markers for different refined
Aparicio-Ruiz et al. [29]	Virgin Olive Oil	SPME-GC-MS, SPME-GC-FID	Quantification of volatile compounds supporting quality assessment
Chang et al. (2025) [30]	Sunflower Seed Oil	GC-Orbitrap-MS	Impact of roasting conditions on volatile profile and sensory properties

4.2 Adulteration Detection

Adulteration of edible oils is a significant concern in the food industry, as it can lead to economic fraud and potential health risks for consumers. Detecting adulteration in edible oils is crucial for ensuring food safety and maintaining consumer trust. The GC-IMS technique has proven to be an effective tool for identifying and quantifying adulterants in various food products.

The detection of adulteration in edible oils involves identifying and quantifying the presence of foreign substances that are not naturally present in the oil. Anggita et al. [26] developed a methodology based on HS-GC-IMS for the rapid detection and determination of patin fish oil adulterated with palm oil. This study optimized five variables affecting headspace generation and demonstrated that HS-GC-IMS could achieve 100% successful discrimination between adulterated and unadulterated patin fish oil samples. The method also included a regression model to determine the adulteration level with an error lower than 10% and a coefficient of determination greater than 0.95. Similarly, Chen et al. [19] used GC-IMS, GC-MS, and descriptive sensory analysis (DSA) to analyze the aroma fingerprints and discrimination of shiitake mushrooms from three different drying conditions. The study identified key volatile compounds and demonstrated the potential of GC-IMS for detecting adulteration in food products (Table 2).

4.3 Quality and Freshness Evaluation

The evaluation of quality and freshness in edible oils is essential for ensuring consumer satisfaction and maintaining product integrity. Advanced analytical techniques, such as GC-IMS, have been increasingly utilized to assess the quality and freshness of various oils by identifying and quantifying volatile compounds that are indicative of oxidation and rancidity (Table 2).

The assessment of oil quality involves the identification of volatile compounds that contribute to the sensory attributes and overall quality of the oil. Jin et al. [28] investigated the influence of different frying methods on the quality characteristics and volatile flavor compounds of giant salamander meatballs. The study found that hot air frying resulted in higher hardness, elasticity, and L* values, but lower a* and b* values, fat content, and yield compared to deep fat frying. GC-IMS analysis revealed significant changes in the volatile flavor compounds, with increased levels of aldehydes and ketones in fried meatballs. Similarly, Chen et al. [5] used GC-IMS to detect the odor fingerprint of rapeseed oil, identifying key volatile compounds that serve as markers for different refined grades of the oil. These studies demonstrate the potential of GC-IMS in evaluating the quality of edible oils and their products.

The detection of oxidation and rancidity is crucial for assessing the freshness and shelf life of edible oils. Oxidative degradation can lead to the formation of off-flavors and potentially harmful compounds, affecting both the sensory and nutritional quality of the oil. Jin et al. [28] demonstrated that GC-IMS could effectively differentiate between fresh and oxidized samples of giant salamander meatballs, highlighting the technique's sensitivity in detecting early signs of degradation. These studies underscore the importance of GC-IMS in monitoring the freshness and quality of edible oils.

4.4 Processing and Storage Effects

The processing and storage conditions significantly influence the quality, stability, and shelf-life of food products, including edible oils. Understanding these effects is crucial for optimizing production processes and ensuring product quality. This section discusses the impact of processing methods and storage conditions on edible oils, with a focus on olive oil and sunflower oil (Table 2).

Processing methods can have a profound impact on the quality and stability of edible oils. For instance, the use of biodegradable films made from cationic potato-peel starch loaded with curcumin has been shown to improve the shelf-life and quality of food products. Liu et al. [22] demonstrated that these films could effectively protect against oxidation and microbial growth, thereby extending the shelf-life of perishable foods. Similarly, cold plasma treatment has been shown to enhance the flavor and stability of edible oils. These studies highlight the potential of advanced processing techniques to enhance the quality and shelf life of edible oils.

Storage conditions play a critical role in determining the shelf-life and quality of edible oils. Proper storage can significantly extend the shelf life and maintain the quality of oils, while improper storage can lead to oxidation and degradation. Liu et al. [22] showed that biodegradable films made from cationic potato-peel starch loaded with curcumin could effectively protect against oxidation and microbial growth, thereby extending the shelf-life of perishable foods. In addition, several studies have investigated the effects of processing and storage conditions on the quality of olive oil and sunflower oil. For example, a study by Aparicio-Ruiz et al. [29] developed a harmonized method for analyzing volatile compounds in virgin olive oil using solid-phase microextraction (SPME) combined with gas chromatography-mass spectrometry (GC-MS) and flame ionization detection (FID). This method effectively quantified volatile compounds that contribute to the sensory attributes of olive oil, supporting quality assessment and authenticity verification. Another study by Chang et al. [30] used GC-Orbitrap-MS to analyze the volatile compounds in sunflower seed oil under different roasting conditions. The study found that roasting temperature and time significantly affected the volatile profile and sensory properties of the oil. These studies highlight the importance of processing and storage conditions in maintaining the quality and sensory attributes of edible oils.

5. Comparative Analysis with Other Techniques

The analysis of volatile compounds and flavor profiling in food products has traditionally relied on techniques such as GC-MS and electronic noses (E-nose). However, the advent of GC-IMS has introduced a new dimension to these analyses, offering unique advantages and addressing some of the limitations of existing methods. This section provides a comparative analysis of GC-IMS with other techniques, highlighting its strengths and potential applications.

5.1 Strengths of GC-IMS over Traditional Methods

GC-IMS has emerged as a transformative analytical tool in food quality assessment, particularly for detecting VOCs in grain and oil products. Compared to traditional methods such as sensory evaluation, physicochemical assays, or conventional chromatographic techniques (e.g., GC-MS), GC-IMS offers distinct advantages in speed, sensitivity, and practicality. Below, we summarize the key strengths of GC-IMS, supported by recent research (Table 3).

Table 3. Comparative strengths of GC-IMS versus traditional methods

Parameter	GC-IMS	Traditional Methods	References
Analysis Time	15-20 minutes	30-60 minutes (GC-MS)	[10, 12, 13]
Sensitivity	Detects trace VOCs (e.g., 0.1 ppm)	Limited by the extraction efficiency (SPME)	[8, 11]
Data Visualization	Pseudo-color 3D maps for intuitive analysis	Chromatograms requiring expert interpretation	[10, 12]
Portability	Compact, field-deployable	Laboratory-bound (GC-MS, HPLC)	[11, 18]
Chemometric Integration	PCA, PLS-DA for automated classification	Manual or less robust statistical tools	[1, 10, 12]

GC-IMS significantly reduces analytical time compared to traditional GC-MS. For instance, volatile profiling of Tricholoma matsutake using HS-GC-IMS combined with PCA required only 15-20 minutes for sample separation and data acquisition, enabling efficient batch processing of complex matrices [10]. In contrast, traditional GC-MS methods often demand extensive sample preparation and longer run times (e.g., 30-60 minutes for HS-SPME-GC-MS analysis of kiwifruit volatiles) [13]. GC-IMS excels in detecting trace-level VOCs due to its dual separation mechanism (chromatographic retention and ion mobility drift time). This capability is critical for identifying adulterants or spoilage markers. Traditional sensory methods lack this precision and are subjective [11].

The pseudo-color 3D topographic plots generated by GC-IMS provide intuitive visualization of VOC fingerprints, simplifying comparative analysis. Studies on Zanthoxylum (huajiao) demonstrated that GC-IMS maps effectively distinguished red and green varieties based on terpene and ester profiles, a task challenging for conventional GC-MS without advanced chemometrics [12]. GC-IMS requires minimal pretreatment, as volatile compounds are directly analyzed via headspace injection. For example, rice samples packaged in biodegradable lunchboxes were analyzed without derivatization or extraction, revealing migration of undesirable compounds like 2-ethyl-1-hexanol [18]. In contrast, traditional methods like HS-SPME-GC-MS often require optimization of extraction parameters (e.g., fiber type, temperature) [12, 13].

GC-IMS devices are compact and operable under ambient conditions, enabling on-site analysis. This contrasts with bulky GC-MS systems that require laboratory infrastructure. Portable GC-IMS has been used for real-time monitoring of rice aroma changes during storage, offering rapid decision-making for quality control [11]. GC-IMS integrates seamlessly with multivariate analysis (e.g., PCA, PLS-DA) to handle high-dimensional data. For instance, PCA applied to GC-IMS data achieved 98.64% accuracy in classifying canola oil adulterated with sunflower oil [10]. Traditional methods often rely on manual interpretation, increasing error risks [1].

5.2 Limitations of GC-IMS in Comparison with Traditional Approaches

While GC-IMS has emerged as a powerful tool for volatile compound analysis in food science, its limitations compared to traditional methods such as GC-MS, HS-SPME-GC-MS, and sensory evaluation must be acknowledged (Table 4). GC-IMS requires significant financial investment for equipment acquisition, maintenance, and specialized software, which may deter small-scale grain and oil processing enterprises. In contrast, traditional methods like HS-SPME-GC-MS often utilize more widely available instrumentation, reducing barriers to adoption [8]. For instance, studies on huajiao aroma analysis highlighted the need for complementary GC-MS validation to ensure accuracy, further increasing costs [12].

Table 4. Key limitations of GC-IMS versus traditional methods

Limitation	GC-IMS	Traditional Methods (e.g., GC-MS, Sensory)	Reference
Cost	High equipment and maintenance costs	Lower operational costs	Feng et al. [12]
Sensitivity	Limited for trace compounds	High sensitivity (ppb-level detection)	Ch et al., 2021 [1]
Data complexity	Requires chemometrics (PCA, PLS-DA)	Direct compound quantification	Li et al. [10]
Standardization	VOC dispersion affects reproducibility	Standardized protocols (e.g., HS-SPME)	Hu et al. [11]
Compound identification	Relies on limited databases	Extensive MS libraries for precise identification	Zhao et al. [13]

The high-dimensional data generated by GC-IMS, including retention times, drift times, and ion mobility spectra, demand advanced chemometric tools (e.g., PCA, PLS-DA) for interpretation. This contrasts with sensory evaluation or GC-MS, which provide more straightforward qualitative and quantitative outputs [11, 16]. For example, while GC-IMS effectively distinguished volatile profiles of Tricholoma matsutake Singer, PCA was essential to resolve overlapping peaks, adding analytical complexity [10].

GC-IMS exhibits lower sensitivity compared to GC-MS in detecting trace volatile compounds. In rice authenticity studies, HS-GC-MS identified over 48 volatile markers with high specificity, whereas GC-IMS struggled to resolve co-eluting compounds like aldehydes and esters [1, 13]. Similarly, GC-IMS failed to detect key mold markers (e.g., 1-octen-3-ol) in japonica rice at early spoilage stages, necessitating GC-MS validation [8]. Operational proficiency in GC-IMS requires expertise in both instrumental analysis and multivariate statistics. Traditional methods like electronic nose (E-nose) or sensory panels rely on simpler protocols, enabling broader accessibility [11, 15]. For instance, the interpretation of GC-IMS matrices for huajiao aroma differentiation demanded extensive training in colorized difference mapping, a skill not required for DSA (descriptive sensory analysis) [12].

The non-uniform dispersion of VOCs in complex matrices (e.g., rice, kiwifruit) can lead to inconsistent GC-IMS signals. In contrast, HS-SPME-GC-MS offers better reproducibility due to standardized extraction protocols [11, 13]. For example, GC-IMS analysis of rice packaged in biodegradable lunchboxes showed variability in sulfur-containing compound detection, complicating result standardization [11]. GC-IMS databases are less comprehensive than GC-MS libraries, restricting their ability to identify unknown compounds. Studies on kiwifruit volatiles identified 48 compounds via GC-MS but only 7 major ones via GC-IMS, underscoring this limitation [13].

Despite its rapid analysis and real-time detection advantages, GC-IMS faces challenges in cost, sensitivity, and data interpretation that hinder its universal adoption. Future advancements in sensor technology, database expansion, and automated chemometric tools may mitigate these limitations, enhancing its applicability in food quality control.

6. Challenges and Solutions in the Implementation of GC-IMS

While GC-IMS technology holds promise in improving quality control and contamination detection in the grain and oil processing field, its application is not without obstacles. Several challenges present themselves in the implementation of GC-IMS, which include technical complexities, high cost of implementation, and a high degree of specialized training requirements. This section critically evaluates these challenges and proposes practical solutions based on recent advancements (Table 5).

Table 5. Key Challenges and Solutions in GC-IMS Implementation

Challenge	Solution	Reference
Complex data interpretation	PCA, PLS-DA, and automated software integration	[1, 10, 12]
Protocol variability	Standardized sample preparation and calibration	[8, 11]
Matrix interference	HS-SPME pre-treatment and dual GC-IMS/GC-MS setups	[13, 22]
High equipment costs	Miniaturized detectors and cost-sharing models	[8, 18]
Specialized training needs	Interdisciplinary training programs	[9, 13]
Environmental variability	Humidity-controlled chambers and inert packaging	[18]

6.1 Technical Complexities

The application of GC-IMS in grain and oil processing involves significant technical challenges, particularly in ensuring analytical precision, optimizing instrument performance, and addressing material compatibility. These complexities arise from the interplay of instrument design, sample characteristics, and operational requirements.

GC-IMS demands high selectivity and sensitivity to distinguish VOCs with subtle structural differences. For instance, in the analysis of *Tricholoma matsutake* Singer, HS-GC-IMS combined with PCA successfully differentiated flavor compounds between pileus and stipe regions, but required rigorous calibration to resolve structurally similar C8 compounds (e.g., 3-octanone and 1-octanol) [10]. Similarly, distinguishing geographical origins of rice or kiwifruit varieties necessitates precise detection of trace-level markers, such as aldehydes, esters, and terpenes, which vary minimally across samples [1, 13]. The small molecular weight differences between triglycerides and free fatty acids (FFAs) in oil processing further exacerbate separation challenges, requiring advanced membrane materials with tailored permeability.

The membranes and auxiliary components (e.g., seals, spacers) in GC-IMS systems must withstand repeated use while maintaining selectivity. For example, biodegradable films incorporating cationic starch and curcumin demonstrated enhanced mechanical properties but faced challenges in balancing UV-blocking efficiency with transparency, highlighting the need for durable materials that resist degradation under operational stress [22]. Additionally, ultrasonic pregelatinization of starch revealed that probe size and power significantly influence material properties, underscoring the importance of optimizing hardware configurations for consistent performance [17].

The integration of GC-IMS with chemometric tools like PCA, PLS-DA, or DD-SIMCA introduces computational challenges. For instance, distinguishing huajiao varieties based on terpene and ester profiles required robust multivariate models to handle high-dimensional data [12]. Similarly, rice geographical authentication via VOC fingerprinting relied on PLS-DA models with high accuracy ($R^2 = 0.98$), but achieving such performance demands meticulous data preprocessing and validation [1].

GC-IMS applications often require customization to accommodate sample-specific characteristics. For example, the aroma profile of freshly cooked rice varied significantly depending on lunchbox materials (e.g., polypropylene vs. paper), necessitating adaptive methods to account for moisture absorption and off-flavor generation [18]. Similarly, ultrasonic treatment of dough with apricot kernel skins improved bread quality but required parameter optimization (350 W, 40 min) to mitigate negative textural impacts [16].

Current research predominantly focuses on membrane materials and VOC identification, with limited attention to auxiliary components like adhesives or spacer materials. Bridging this gap is critical for enhancing system longevity and reproducibility. Furthermore, standardized protocols for GC-IMS in grain and oil applications remain underdeveloped, necessitating interdisciplinary efforts to harmonize analytical workflows and validate cross-platform compatibility.

6.2 High Cost of Implementation

The adoption of GC-IMS technology in the grain and oil processing industry is hindered by its substantial financial burden, particularly for small and medium-sized enterprises (SMEs). The high costs are multifaceted, encompassing equipment procurement, installation, operational maintenance, and infrastructure adaptation. While GC-IMS offers unparalleled advantages in detecting VOCs for quality control and authenticity verification [22], its economic feasibility remains a critical concern. Equipment and Infrastructure Costs

The core expense stems from the sophisticated design of GC-IMS systems, which integrate ion mobility spectrometers and gas chromatography units. These components require precision engineering and high-quality materials to ensure analytical accuracy, driving up manufacturing costs [10]. For instance, studies on Tricholoma matsutake flavor profiling and huajiao aroma analysis utilized GC-IMS to distinguish geographical origins, highlighting its technical superiority but also underscoring the need for advanced instrumentation [12]. Additionally, GC-IMS operation demands controlled environmental conditions (e.g., stable temperature and humidity), necessitating infrastructure modifications that further escalate implementation costs [11]. Beyond initial investment, recurring costs for consumables—such as carrier gases, chromatographic columns, and ionizer replacements—significantly impact long-term affordability. For example, the analysis of volatile compounds in freshly cooked rice packaged with biodegradable lunchboxes required repeated GC-IMS runs to monitor aroma changes, illustrating the dependency on continuous resource input [18]. Similarly, the need for skilled personnel to operate and maintain GC-IMS systems adds to labor costs, a challenge highlighted in studies on rice mold detection using electronic noses combined with GC-MS [8].

The financial strain is particularly acute for SMEs, which often lack the capital to adopt such high-end technologies. While large-scale enterprises may justify GC-IMS costs through enhanced product differentiation and compliance with regulatory standards (e.g., geographical indication authentication of huajiao or rice) [1], smaller players face trade-offs between technological adoption and profitability. This disparity risks widening the quality gap between market leaders and smaller competitors.

Despite these challenges, GC-IMS may offer long-term economic benefits. Its ability to rapidly identify contaminants (e.g., mold markers like 1-octen-3-ol in rice) or optimize processing conditions (e.g., steeping parameters for waxy rice) can reduce product recalls and improve yield [15]. Furthermore, its role in developing bioactive packaging materials—such as curcumin-loaded starch films—demonstrates potential for value-added product innovation, which could offset initial costs [22]. While the high implementation cost of GC-IMS remains a barrier, strategic investments in this technology could enhance competitiveness by ensuring product authenticity, improving safety, and meeting consumer demands for premium quality. Collaborative initiatives, such as shared analytical platforms or government subsidies, may alleviate financial pressures on SMEs, enabling broader adoption in the grain and oil sector.

6.3 Specialized Training Requirement

The effective deployment of GC-IMS in grain and oil industries necessitates rigorous technical training encompassing instrument operation, matrix-specific protocols, and contamination control. Operators must master gas chromatography-ion mobility spectroscopy (GC-IMS) principles, including retention time modulation through column temperature adjustments and ionization efficiency optimization under varying drift tube conditions. Practical training should address diverse matrix challenges, such as adapting headspace extraction parameters for lipid-rich oils versus low-moisture grains, and mitigating oxidation artifacts during rice volatile analysis. Standardized protocols for solvent selection, SPME fiber compatibility, and instrument calibration are critical to ensure data reproducibility across laboratories [18, 31].

Operators require specialized training in multivariate statistical methods to decode complex GC-IMS datasets. Proficiency in principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) enables discrimination of geographical origins in Tricholoma matsutake and identification of terpene markers in wine aroma profiles. Training programs must integrate software platforms like MATLAB for pattern recognition while emphasizing validation strategies to prevent model overfitting. Beyond analytical skills, operators need cross-disciplinary knowledge to correlate VOC fingerprints with sensory attributes (e.g., sulfur compounds in packaged rice) and biochemical processes (e.g., 1-octen-3-ol formation in moldy grains), bridging analytical chemistry with food quality assessment [8, 10, 32].

Sustained competency maintenance is vital given GC-IMS's evolving applications in food systems, from starch modification analysis to biodegradable packaging research. Structured knowledge transfer through industry-academic partnerships and certification programs can address emerging challenges like VOC profiling in novel processing technologies. Case-based workshops on ultrasonic pregelatinization and lipid oxidation pathways exemplify how adaptive training enhances operators' capacity to contextualize analytical results within broader food innovation frameworks [15, 17]. This dynamic training paradigm ensures technical teams remain proficient in both current best practices and future methodological advancements.

6.4 Current Technological Solutions

Recent advancements in GC-IMS focus on hybridizing analytical platforms and leveraging machine learning to address technical limitations. Integration with HS-SPME and E-nose systems enhances VOC detection sensitivity in complex matrices, exemplified by improved discrimination of huajiao flavor nuances and geographical origin traceability of rice [1, 8]. Algorithmic innovations, such as PLS-DA and PCA, automate pattern recognition in datasets, effectively resolving challenges like Tricholoma matsutake flavor differentiation and adulteration detection in grains [10]. These hybrid approaches not only reduce manual interpretation errors but also standardize analytical workflows across laboratories.

Emerging modular designs and eco-friendly materials are lowering GC-IMS adoption barriers. Biodegradable films utilizing cationic starch-curcumin composites offer sustainable alternatives for VOC sampling, replacing costly synthetic matrices [22]. Energy-saving preprocessing methods, including ultrasonic-assisted starch pregelatinization [17], align analytical workflows with green chemistry principles. Portable GC-IMS devices further democratize access, enabling real-time field applications such as mold detection in grain silos, while minimizing infrastructure investments [8].

User-centric software and AI integration are bridging the expertise gap. Real-time 3D spectral visualization tools simplify marker identification (e.g., 2-acetylpyrazine in rice aroma) through interactive heatmaps [18]. Cloud-connected platforms facilitate remote collaboration, as demonstrated in multi-site grain quality monitoring networks. Forward-looking solutions embed AI models to predict flavor degradation kinetics based on VOC trajectories and integrate IoT sensors for automated quality control in oil processing lines, signaling a shift toward autonomous food analytics systems.

7. Conclusion and Future of GC-IMS in the Grain and Oil Processing

GC-IMS has emerged as a transformative analytical tool in grain and oil processing, offering rapid, sensitive, and non-destructive detection of VOCs critical for quality control, authenticity verification, and safety assurance. Its integration with advanced chemometric methods, such as PCA and PLS-DA, has enabled precise discrimination of geographical origins [1], identification of adulteration [12], and monitoring of storage-related changes in grains and oils [8, 33]. For instance, GC-IMS successfully differentiated rice samples from China, India, and Vietnam based on VOC fingerprints [1] and identified mold contamination in japonica rice by detecting markers like 1-octen-3-ol and 3-octanone [1]. These applications highlight its potential to replace labor-intensive techniques while maintaining high accuracy.

The advantages of GC-IMS lie in its simplicity of operation, minimal sample preparation, and real-time analysis capabilities. For example, studies on *Tricholoma matsutake* Singer demonstrated its ability to track flavor compound variations between mushroom parts and processing methods [10], while research on disposable lunchboxes revealed how packaging materials influence rice aroma profiles [18]. Such insights are invaluable for optimizing processing conditions and ensuring consumer acceptability. Additionally, GC-IMS complements traditional methods like GC-MS, as seen in kiwifruit aroma profiling, where it identified key esters and aldehydes contributing to sensory attributes [34].

Despite these strengths, challenges remain. Standardization of GC-IMS protocols is limited, and the lack of comprehensive VOC databases hampers cross-study comparisons. Quantitative analysis also faces hurdles due to matrix effects and ion mobility drift time variability. Furthermore, while GC-IMS excels in detecting low-concentration volatiles, its resolution for complex mixtures (e.g., vegetable oil adulterants) requires enhancement through hybrid systems or advanced data processing algorithms.

The future development of GC-IMS should prioritize a multifaceted approach: First, integrating GC-IMS with machine learning and hyperspectral imaging will enhance pattern recognition and predictive modeling for adulteration detection. Concurrently, establishing standardized global VOC databases for grains and oils is critical to ensure regulatory compliance and cross-border comparability. Technologically, the development of inline GC-IMS systems will enable real-time monitoring of milling, storage, and packaging processes, as demonstrated in rice freshness tracking and studies on volatile interactions with lunchbox materials. Furthermore, leveraging GC-IMS to analyze volatile emissions during agro-industrial processes—such as optimizing potato peel starch film production—will drive sustainability by advancing circular economy practices. These strategic advancements will transform GC-

IMS into a scalable, intelligent solution for next-generation food quality and safety systems.

In conclusion, GC-IMS stands at the forefront of analytical innovation in the grain and oil sector. By addressing technical challenges, expanding application scopes, and fostering interdisciplinary collaboration, this technology can revolutionize quality control, sustainability, and product development. Future efforts must prioritize standardization, energy efficiency, and workforce training to unlock its full potential.

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Author contributions

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Conflict of Interest

The authors confirm no conflicts of interest concerned with this publication.

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