Application of gas chromatography-ion mobility spectrometry in the analysis of food volatile components

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ABSTRACT

Gas chromatography-ion mobility spectrometry (GC-IMS) is an emerging analytical technique that has the advantages of fast response, high sensitivity, simple operation, and low cost. The combination of the fast speed and resolution of GC with the high sensitivity of IMS makes GC-IMS play an important role in the detection of food volatile substances. This paper focuses on the basic principles and future development trend, and the comparative analysis of the functions, similarities and differences of GC-IMS, GC-MS and electronic nose in the detection of common volatile compounds. A comprehensive introduction to the main application of GC-IMS in food volatile components: fingerprint identification of sample differences and detection of characteristic compounds. On the basis of perfecting the spectral library, GC-IMS will have broad development prospects in food authentication, origin identification, process optimization and product classification, especially in the analysis and identification of trace volatile food flavor substances.

KEYWORDS

GC-IMS, food volatile components, trace volatile substances detection

INTRODUCTION

Ion mobility spectrometer is a powerful analytical tool for identifying, detecting and analyzing trace compounds. It can complete the separation and analysis of the test object within a few milliseconds. The IMS device has a simple structure and high sensitivity (ng pg\textsuperscript{-1}), and is particularly suitable for the detection of volatile organic compounds such as explosives \cite{1}, illegal drugs \cite{2} and air contaminants \cite{3}. At present, IMS has been widely used in various fields, such as security field \cite{4}, medical field \cite{5} and environmental field \cite{6}. In recent years, IMS technology has made great progress, Waters (to TWIMS), Thermo Fisher Scientific (to FAIMS), SCIEX (to DMS) and Bruker Daltonics (to time OF-TOF) \cite{7}. The company has completed the commercialization of IMS, and Gesellschaft für Analytische Sensorsysteme mbH (G.A.S.) has completed the commercialization of GC-IMS and IMS-time-of-flight (TOF) mass spectrometry. However, when IMS analyzes complex compounds, there is a defect of competitive ionization between different components. This makes it difficult to distinguish components with similar ionic mobility, such as 3-methyl-1-butanol and 1-pentanol \cite{8, 9}. Later, people combined the high-efficiency separation of gas chromatography with the trace detection of IMS, and gave birth to the combined technology of GC and IMS, which effectively
combined the retention time and the changes of ion mobility signal response, and superimposed the advantages of the two to achieve rapid, sensitive detection effect.

There are many types of food and the matrix is often very complicated. The analysis of food volatile components is of great significance for understanding food flavor, food safety, food quality classification, and identification of the source of food raw materials. At present, commonly used instrumental analysis techniques in the analysis of volatile components in the food industry, including gas chromatography-mass spectrometry, gas chromatography-olfactometry technology, and electronic nose technology, have their own advantages and disadvantages in terms of detection speed, sensitivity and convenience. The development of the combined technology of GC and IMS has effectively increased the ability of rapid analysis of complex volatile compounds, which is very suitable for the detection of trace volatile substances in food. In recent years, it has set off a research boom. In this paper, it introduces the working principle of GC-IMS and the development status of the instrument, focusing on comparing the advantages and disadvantages of GC-IMS and other traditional volatile compound detection instruments, and introduces the use of GC-IMS in the fields of food flavor analysis and quality detection in recent years. The latest research and application examples of GC-IMS promote readers to understand and use GC-IMS technology.

**GC–IMS TECHNOLOGY**

**Development process and status quo**

In 1970, Cohen and Karasek (1970) [10] took the lead to couple IMS and GC, and used the advantages of IMS to analyze trace organics. The ion mobility spectrum with GC separation was obtained for the first time in 1972, marking the birth of the first generation of GC-IMS [11].

In the 1980s, the carrier-coated diatomaceous earth-filled chromatographic column was replaced by a stationary phase of a high-efficiency capillary column chemically cross-linked and bonded to the surface of the fused silica tube, eliminating the pollution caused by the stationary phase of the IMS analytical instrument. Baim and Hill (1984) [12] improved the IMS equipment, such as implementing one-way airflow, closing the drift tube, reducing the volume of the ionization chamber, and adding sample conduits. It effectively solves the problems of instability of retention time and peak width expansion in the early GC-IMS drift tube, and improves the resolution of the instrument.

The flow rate of the capillary column in the GC stationary phase is extremely small, and a good connection is required to complete the effective transfer of the sample and the matching of the flow rate between GC and IMS [9]. At present, the connection between GC and IMS is mainly divided into side injection mode (the column enters from the side of the IMS ionization zone); and axis injection mode (the column enters vertically from the center of the ion shutter) (Fig. 1). The side injection mode does not affect the detection sensitivity due to the deviation of the distance between the chromatographic column and the ion source, however, requires high airtight connection between the chromatographic column and the ionization zone, the structure is relatively complicated, and the installation and maintenance of the drift tube are inconvenient. The axial injection mode can eliminate the peak broadening caused by the interface connection line, and the neutral molecules can be quickly purged out of the detector, but the sensitivity and resolution of the detection will be affected by the position of the capillary column in the ionization source [13].

The ionization source is the core component of the IMS, which has a great influence on the degree of ionization of the component to be measured. Non-radioactive sources include photoionization source, corona discharge ionization source, electrospray ionization source, flame ionization source, and electronic pulse ionization source. Different non-radioactive sources have their own characteristics, and the applicable detection objects are different, they are generally targeted for the difference of the object to select the appropriate non-radioactive ionization source. In contrast, the radioactive ionization source has the characteristics of simple structure, stable operation, long-lasting durability, low energy consumption, and no need for external power supply. Common radioactive ionization sources use $^{63}$Ni, $^{241}$Am, and $^3$H as radioactive isotopes, and $^{63}$Ni ionization sources are particularly common. However, high temperature can easily lead to the oxidation of nickel precursors and the release of radioactive nickel into the environment, the use of $^{63}$Ni ionization sources poses a threat to the environment. In addition, the post-processing of waste nickel precursors is quite complicated. At present, Tritium source is increasingly recognized by the market, with excellent performance, exempt from the management of regulatory authorities, and has been commercialized in the GC-IMS series of instruments.

The development of GC-IMS presents a diversified trend. On the one hand, it improves the separation effect of the gas phase and increases the resolution. For example, the Sielemann group used the high flow rate of MCC carrier gas to apply multi-capillary columns (MCC) to GC-IMS to achieve...
rapid analysis of volatile organic compounds (VOCs) [14], its structure is shown in Fig. 2 [15]. However, for complex samples, longer MCC are needed to improve separation, which will increase analysis time. On the other hand, different types of IMS detectors are developed to realize two-dimensional analysis. For example, 2D-GC-IMS and 2D-GC-DMS can obtain four-dimensional information (retention time, ion signal intensity, drift time, and compensation voltage) of the measured object, thereby providing important support for the analysis of complex mixtures.

Compared with other analytical techniques, the convenience and miniaturization of GC-IMS are particularly eye-catching. It does not require vacuum, operates under normal pressure, and has a simple structure. The advancement of IMS miniaturization technology has made it more widely applicable, especially for on-site analysis, which provides a reliable solution for the rapid and immediate detection of volatile components in food. The focus of IMS miniaturization is to reduce the size of the migration tube while minimizing the loss of resolution. However, components that are too small often result in a greater loss of resolution. For example, a drift tube that is too small will limit the migration of ions, resulting in uneven drift field, charging of the channel surface, enhanced space charge effect, and a relatively large reaction area. In recent years, the FAIMS migration tube has broken through the limitation of the traditional migration tube structure and is easier to miniaturize. Eiceman et al. developed a new type of FAIMS using MEMs technology, which consists of a $3 \times 1 \times 0.2$ cm$^3$ cuboid migration tube and a set of parallel plate electrodes. The detection limit of the system for toluene can reach 100 ng g$^{-1}$ [16]. Herrador [17] proposed a new type of miniaturized IMS, which overcomes the resolution problems associated with miniaturization and can be directly coupled to MCC, which can effectively pre-separate the introduced VOC mixture.

The basic structure and working principle of GC-IMS

GC-IMS consists of two parts: gas chromatography system and ion transfer tube. The basic principle is as follows (Fig. 3). During the analysis, the sample components are separated by GC and enter the IMS ionization zone. After ionization, the product enters a drift tube through intermittently opening the ion gate under the action of a constant electric field, loses energy by colliding with the reverse inert drift gas, and is received by the Faraday disk at the other end. Different ions have different mobility after collision, so they are separated. This separation is the basis of gas chromatography-ion mobility spectrometry analysis method [18]. When the electric field intensity $E$ is less than 1000 V cm$^{-1}$, the ion drift rate $V_d$ is proportional to the electric field intensity $E$ and the ion mobility coefficient $K$:
VOCS DETECTION EQUIPMENT

COMPARISON OF GC-IMS AND TRADITIONAL VOCs DETECTION EQUIPMENT

At present, the main instruments used for the analysis of food volatile substances are electronic nose and gas chromatography-mass spectrometry (GC-MS). For the detection and analysis of odor active substances, GC-O and GC-O-MS are also commonly used methods.

The electronic nose (e-nose) consists of an odor sampling manipulator, a gas sensor array and a signal processing system. It mainly classifies and recognizes unknown odors based on sensor signals. The analysis speed is fast and it overcomes the influences of subjective factors that may occur in the sniffing. It is more suitable for the qualitative and distinguishing discrimination of the components of volatile substances in food, such as product classification, traceability, identification, etc. This is similar to the GC-IMS function. The difference is that with the help of the built-in statistical software, the GC-IMS data has a higher degree of visualization and can quantitatively analyze almost all volatile compounds in the response, that is, on the basis of identification and classification, it can also visually show the difference in the content of some volatile compounds. A variety of sampling systems have been developed to improve the efficiency of introducing volatile compounds into the electronic nose detection system, such as purge and trap, dynamic headspace, solid phase microextraction, stirring rod adsorption extraction, internal needle dynamic extraction, static headspace, etc. Among them, static headspace is more commonly used because of its simplicity and convenience, but its detection sensitivity is low. In contrast, GC-IMS uses static headspace sampling or even direct sampling can reach the level of trace detection.

GC-MS provides precise qualitative quantification of food flavor substances based on retention time and ion mass with the help of the NIST database. It is currently the main volatile flavor substance identification method. GC-O uses the human nose to screen odor active compounds and ranks the contribution of different odor active compounds to the overall flavor of the food. Due to the high sensitivity of the human nose, there are often some strong odor active compounds detected by GC-O, because the content is lower than the detection limit of GC-MS, and structural information of the compound cannot be given. Therefore, GC-MS instrument analysis is challenging and difficult for those volatile flavor substances that have a low odor threshold, exist at trace (ppb level) and ultra-trace levels in food. People often select and optimize sample pretreatment methods to increase the concentration of volatile flavor substances in samples to achieve the purpose of GC-MS analysis of those trace flavor substances. At present, the commonly used sample pretreatment methods include simultaneous distillation extraction method, solvent-assisted evaporation method, solid phase microextraction method, and purge and trap method. However, the use of various pre-treatment methods on the one hand significantly increases the analysis time of the sample. The main time in the flavor analysis of a sample is used for the pretreatment, while a small amount of time (less than 1 h) for GC-MS analysis; on the other hand, different pre-treatment methods have their own advantages and disadvantages, and the obtained flavors of the samples are different. The flavor of the original sample is the only criterion to measure the quality of the sample processing method. Otherwise, the significance of GC-MS analysis will be compromised. However, in most cases, it is not easy for researchers to obtain a better sample pretreatment method to make it representative of the original sample flavor. Relatively speaking, GC-IMS does not require sample pre-treatment and adopts static headspace sampling, which preserves the original flavor of the sample to the greatest extent. It also does not require the harsh working environment of vacuum and helium like GC-MS. It uses high-purity nitrogen.
or self-circulating air as the carrier gas. The general analysis time is only 3–10 min, which is much shorter than 30 min required by GC-MS. The efficiency is higher, and the sample analysis cost is lower. This greatly reduces the probability of changes in the volatile substances in the sample, and the result is obviously closer to the real situation. In the future, due to the high sensitivity and short-term characteristics of GC-IMS, the combination of sniffing technology with it is expected to realize accurate analysis and screening of active aroma compounds. However, the number of qualitative substances in the current GC-IMS database is small, so it cannot be widely used for the identification of volatile substances. But users can expand the database in the professional field by themselves, and the database will continue to be improved and developed in the course of use (Table 1).

**APPLICATION OF GC-IMS IN THE FOOD INDUSTRY**

In recent years, the research of GC-IMS in food flavor analysis, detection, and process control has developed rapidly, and related papers have shown a significant growth trend (Fig. 4). The application of GC-IMS is mainly focused on extracting/establishing fingerprints on the basis of full-component analysis for the analysis of differences between samples, as well as the identification and analysis of characteristic compounds.

| Table 1. Comparison of e-nose, GC-MS, GC-IMS |
|-----------------------------------------------|
| **Detection limit** | **Electronic nose** | Below the ppm level | **GC-MS** | It can be as low as ppb | **G.A.S GC-IMS** | May be as low as the ppb (v) level, some substances may be as low as the ppt level |
| **Detection matrix** | **Gas, liquid, solid** | Substances can be broadly distinguished, such as alkanes, H2, etc | **Gas, liquid, solid** | Accurate qualitative based on GC retention time and ion mass | **Gas, liquid, solid** | Each component can be accurately qualitative and two-dimensional qualitative (GC retention time + IMS drift time) |
| **Qualitative** | **Uncomplicated software, self-contained statistical software to analyze samples, such as PCA, LDA, etc.** | **Establishment of a standard curve for Trace material quantification** | **Uncomplicated software, self-contained software can give sample ion chromatogram, total ion flow diagram, etc., which requires researchers to analyze the spectrum according to NIST database** | **Establishment of a Standard curve for trace material quantification** | **Powerful analysis software, can give the volatile organic fingerprint spectrum and the sample difference plot, which is convenient for sample differentiation analysis, PCA software can classify samples according to principal components, according to which can classify sample origin, quality grade, years of storage and so on.** |
| **Quantitative** | **Cannot be accurately quantified** | **Direct injection or headspace injection** | **Partially required** | **A harsh working environment (vacuum, helium) is required** | **No pretreatment required** | **No harsh work environment is required** |
| **Main injection mode** | **Headspace injection** | **Partially required** | **>30 min** | **Samples varied with analysis times, generally within 3–10min** | **Yes** | **Yes** |
| **Sample pretreatment** | **No harsh work environment is required** | **A harsh working environment (vacuum, helium) is required** | **No harsh work environment is required** | **Samples varied with analysis times, generally within 3–10min** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** |
| **Environmental requirements** | **<2min** | **>30 min** | **No harsh work environment is required** | **Samples varied with analysis times, generally within 3–10min** | **No** | **Yes** |
| **Sample analysis time** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** | **Food sensory quality control (food flavor), environmental, agriculture and other fields** | **No** | **Yes** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** |
| **Portability** | **Yes** | **No** | **Yes** | **Yes** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** |
| **Application area** | **Yes** | **No** | **Yes** | **Yes** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** | **Food sensory quality control (food flavor), environmental monitoring, disease diagnosis, etc.** |

![Fig. 4. Number of documents related to GC-IMS and food in recent years](image-url)
Application of GC-IMS fingerprint in the analysis of food difference

Using GC-IMS to analyze the difference of samples is one of the main applications of GC-IMS in food flavor analysis. GC-IMS can quickly give the chromatographic and spectral response signals of each VOCs, and compare the spectral library to realize the qualitative analysis of specific VOCs. The Reporter and Gallery-Plot plug-ins that come with the instrument can generate visualized sample signal difference maps and fingerprints of trace volatile compounds. According to the difference of the GC-IMS fingerprint of the sample, the difference in quality and characteristic flavor of the sample can be judged. Combined with chemometrics techniques such as principal component analysis (PCA), GC-IMS fingerprints have been widely used in food authentication [21], quality discrimination [22], grease grading [23], origin traceability [24], process improvement [25] and other fields (Table 2).

Application of fingerprint technology in grease. The rapid development of GC-IMS technology has played an important role in olive oil classification and identification. Rocío Garrido-Delgado [26] used MCC-IMS to analyze 98 samples of olive oil. The results of the study showed that 97% of samples were successfully classified by using full spectrum applied chemometric method, and the prediction success rate could reach 87%. Compared with selecting some signal peaks applied chemometric method, the prediction rate increased by 8%. The team used CC instead of MCC to conduct research and found [27] that CC-IMS can better distinguish olive oil categories, with a discrimination rate of 92%, but in terms of efficiency, MCC is higher than CC. Gerhardt et al. (2017) [28] et al. coupled the temperature compensated GC separation to the DTIMS device to generate a 3D fingerprint at a higher resolution. The analysis of non-targeted VOCs in olive oil successfully distinguished the differences of extra virgin olive oil (EVOO) samples from different geographical sources and varieties, and has a higher recognition quality than ordinary commercial GC-IMS systems. The team used GC-IMS and FT-MIR to distinguish olive oils from different geographic sources, and used PCA-LDA or PLS-DA for low-level data fusion and multivariate classification. The verification results of the

| Table 2: Partial application of fingerprint in food |
|---|---|---|---|
| Food category | Research object | Research results | Reference |
| Grease | Olive oil | Compared with some signal peaks, the classification prediction rate of full spectrum is improved, CC-IMS can better distinguish, MCC has higher efficiency. Geographical sources and varieties are successfully distinguished | [26–29] |
|  | Refined sunflower oil and rapeseed oil | Established the volatile fingerprints, it can accurately identify the refining grade | [30, 31] |
| Meat products | Beef, lamb, chicken | Characteristic flavor compounds were effectively characterized | [32] |
|  | *Cordyceps militaris* chicken soup | Enzymolysis promoted the volatilization of typical flavor compounds, cordyceps militaris inhibited some flavor substances | [33] |
|  | Iberian ham | Identified the feeding methods and classified the samples | [34] |
| Fruit and vegetable products | Matsutake | Established the volatile fingerprints, hot air drying affects the formation of carbon volatile substances | [35] |
|  | Kumquat, strawberry | Explored their flavor substances | [36, 37] |
| Wine | Brandy | Established a brandy age identification model | [40] |
|  | Raspberry wine | Sequential inoculation can impart “fruity” and “sweetness” | [41] |
| Aquatic products | Silver carp | Found the dominant bacterial groups for the putrefaction of cold silver carp | [42] |
|  | Dried salted fish | The difference of volatile components at different temperatures, the main markers of microbial deterioration were determined. | [43] |
| Others | Honey, egg products, cheese | Traceability, counterfeiting, classification, detection of freshness, identification of flora | [44–47] |
classification model compared with the results obtained by using separate data blocks, the cross-validation error rate is reduced and the model is more robust [29].

In addition, Chen Tong et al. established the volatile fingerprints of refined sunflower oil [30] and refined rape-seed oil [31], using the two-dimensional difference spectrum method and the color difference method to screen out 22 and 34 characteristic peaks respectively as a variable that characterizes the difference in the degree of refining, combined with the k-proximity algorithm, it can accurately identify vegetable oils of different refining grades. The former’s successful discrimination rate for samples can reach 97.3%.

**Application of fingerprint technology in meat products.** The GC-IMS fingerprint can effectively characterize the characteristic flavor substances of meat (beef, lamb and chicken), and is classified by PCA, with an accuracy rate of 98.3% [32], which provides a reliable means of identification for meat adulteration. When meat is being processed, its characteristic flavor substances will change accordingly. The GC-IMS fingerprint provides great convenience for exploring the influence of different processing methods on the changes of flavor substances. When using GC-IMS to study the cordyceps militaris chicken soup, Zeng et al. [33] found through the volatile flavor fingerprint that enzymolysis could promote the volatilization of typical flavor compounds in the soup, analyzed that cordyceps militaris may have an inhibitory effect on some substances.

Judging the feeding method according to the meat products can effectively combat label fraud. Arroyo-Manzanares [34] and others used GC-IMS to detect cured Iberian ham (acorns, feed fed). In the first step, PCA-LDA technology is adopted for the full spectrum to classify the samples, and the identification efficiency reaches 90%. The second step is to select characteristic markers in the entire spectrum, using the selected markers combined with principal component analysis and orthogonal partial least squares discriminant analysis (OPLS-DA), which can achieve good separation between groups and the discrimination rate of the sample set can reach 100%.

**Application of fingerprint technology in fruit and vegetable products.** The research on characteristic flavor substances of fruits and vegetables has always been a hot spot in the field of food research. At present, there are still many characteristic flavor substances of fruits and vegetables that need to be explored urgently. Li et al. [35] used GC-IMS to study fresh and dried matsutake from different regions, identified 25 signal peaks, and found that hot air drying would affect the generation of eight kinds of carbon volatile substances. There are significant differences in the volatile substances in the pili and stipe of matsutake samples from different regions, and PCA can clearly distinguish them. The author established the volatile fingerprint of matsutake, which provides data support for the identification of the origin of matsutake. Hu et al. [36] used GC-IMS to explore the difference in flavor substances between fresh kumquats, kumquat treated with vacuum saccharification infiltration and hot air drying, and kumquat treated with normal pressure saccharification infiltration and drying. The fingerprint results showed that hexanal, 2-hexen-1-ol and ethyl acetate are the main markers of VS-ADKs. Benzaldehyde and furfural are the main components of AS-ADKs. Compared with FKs, the content of valeraldehyde and acetone in VS-ADKs and AS-ADKs increased significantly ($P < 0.05$), while the change of ethanol showed a downward trend ($P < 0.05$). The change of flavor substances is often closely related to the deterioration of food quality. Van-dendriesche [37] used HS-MCC-IMS to detect volatile substances in strawberries, and estimated the shelf life of strawberries based on the partial least squares. The correlation coefficient was as high as 0.99.

**Application of fingerprint technology in wine.** GC-IMS fingerprints are widely used in wine classification [38] and origin traceability [39]. Li et al. [40] used GC-MS and GC-IMS to analyze brandy volatile compounds, based on fingerprints combined with PLSR analysis method, studied the correlation between brandy volatiles and brandy age, and established a brandy age identification model. The predictive ability and goodness of fit of the PLSR model established by GC-IMS are 0.943 and 0.996, and the model index ability is better than the model established by GC-MS.

The latest research has shown [41] that fermentation strains and fermentation methods affect the aroma substances produced by wine fermentation. Li et al. used GC-IMS to study the effects of sequential inoculation, natural fermentation in co-fermentation mode under the combination of Saccharomyces cerevisiae/Torulaspora delbrueckii and single inoculation of S. cerevisiae on the fermentation flavor of raspberry wine. Volatile fingerprints indicate that sequential inoculation can impart “fruity” and “sweetness” to the wine. Compared with other modes, sequential inoculation has greater potential for the production of raspberry wine.

**Application of fingerprint technology in aquatic products.** Using GC-IMS to study the flavor difference of aquatic products during storage can better infer the effect of different spoilage microorganisms, and provide help for inhibiting related microorganisms and extending shelf life. Jia et al. [42] explored the spoilage potential of three spoilage microorganisms (Aeromonas allosacharophila, Pseudomonas psychrophila, Shewanella putrefaciens) in silver carp, compared the volatile fingerprints of inoculated silver carp with different strains, and found that Pseudomonas psychrophile and S. putrefaciens are the dominant bacterial groups for the putrefaction of cold silver carp. Zhang et al. [43] used HS-GC-IMS fingerprints combined with principal component analysis (PCA) to study the volatile component changes of dried salted fish, an important traditional salted aquatic product in China, at 4°C and 25°C. The samples were clearly classified according to storage temperature and time. In addition, heat map cluster analysis further reveals the differences and similarities between different samples. These results are consistent with the results of principal component analysis. According to the difference of volatile
components at different temperatures, butyl methyl ketone was determined to be the main marker of microbial deterioration in dried salted fish at 25°C.

**Application of fingerprint technology in other food fields.** In addition to the above-mentioned fields, GC-IMS fingerprints have also been widely used in other food systems, such as honey traceability, counterfeit identification and variety classification [44, 45]. Cavanna et al. [46] established a stoichiometric model for detecting egg freshness based on the volatile substance fingerprints of different batches of egg products, and the accuracy of the model’s prediction was 97%. Gallegos [47] used GC-IMS analysis to obtain fingerprints of volatile metabolites of lactic acid bacteria when researching fermented cheese products. Using PCA technology, 4 clusters could be identified and successfully distinguished *Lactobacillus casei*, *Lactobacillus paracasei*, *Lactococcus lactis* subsp. Lactis and Lactococcus cremoris subsp. The change of the IMS signal intensity of VOCs during the growth of strains helps to analyze the growth and decline of strains, further affects the sensory evaluation of cheese, and can be used as reference data for process control in industrial fermentation. At the same time, according to the obtained GC-IMS characteristic fingerprint, the screening of excellent strains with similar fermentation performance can be realized, or the physiological state during the growth of bacteria can be controlled online.

**Application of GC-IMS to the analysis of monomer compounds**

In addition to the application in classification and distinguishing differences, GC-IMS is like GC-MS, which can complete the qualitative and quantitative analysis of key flavor substances. The difference is that GC-IMS has higher sensitivity and faster detection speed. It can not only supplement the verification of GC-MS results, but also highlights its advantages in online monitoring and product process control. Vautz [48] used GC-UV-IMS to detect diacetyl and 2,3-pentanedione in beer whose detection limit was below the odor threshold, and the results were consistent with the GC-MS results. Diacetyl and 2,3-pentanedione are the key flavor substances that control the fermentation time, and the best effect is to terminate the fermentation when the degradation reached below the odor threshold. However, in practice, the lack of online monitoring methods for the two substances often prolongs the fermentation time and reduces the efficiency [48]. GC-IMS is fast and highly sensitive, which can solve the problem of online monitoring of key flavor substances and improve production efficiency. Marquez-Sillerro et al. [49, 50] used single drop ionic liquid microextraction-multicapillary column (MCC) and ion mobility spectrometry (IMS) to determine trace key flavor substances produced by odor in wine, 2,4, 6-trichloroanisole, which is due to the use of polluted materials in cellars or corks. In the detection process, no pre-treatment is required except for dilution. The multicapillary column avoids the interference of ethanol on the ion mobility spectrum, and the detection limit of the sample is as low as 0.01 μg L⁻¹.

The high resolution and fast and reliable performance of GC-IMS has been well reflected in food safety prevention, control and detection, especially the identification and quantification of key indicators of pesticide residues. Kermani [51] used GC-IMS to determine three organophosphorus pesticides, fenthion, malathion and chlorpyrifos in water and vegetable samples. The detection limits reached 1.00, 0.46 and 0.85 μg L⁻¹. Fenthion and malathion have a linear relationship in the concentration range of 2–500 μg L⁻¹ and chlorpyrifos in the concentration range of 2–1000 μg L⁻¹, and the determination coefficient is greater than 0.9969. Jafari [52] prepared solid phase microextraction (SPME) fibers based on polypyrrole/montmorillonite nanocomposites, and combined them with gas chromatography-corona discharge-ion mobility spectroscopy (GC-CD-IMS). Diazinon and fenthion were determined, the linear ranges were 0.05–10 μg L⁻¹ and 0.08–10 μg L⁻¹, and the detection limits were 0.020 and 0.035 μg L⁻¹.

In actual commercial applications, Snyder [53] used a handheld GC-IMS instrument to quickly identify the freshness of fish, which shows that this technology can replace the traditional FDA method of determining freshness through smell. In particular, the aforementioned authors can detect changes in the content of characteristic volatile amines such as 1,5-diaminopentane (cadavers) within 0.5–1 min (Table 3).

**Table 3. Application of GC-IMS to the analysis of monomer compounds**

| Equipment       | Research object       | Research results                                      | Reference |
|-----------------|-----------------------|-------------------------------------------------------|-----------|
| GC-UV-IMS       | Beer                  | The detection results of the two substances whose detection limit is lower than the odor threshold are consistent with those of GC-MS | [48]      |
| MCC-IMS         | Wine                  | Trace substances of key odors due to pollution were detected | [49, 50]  |
| GC-IMS          | Water, vegetables     | The concentrations of three organophosphorus pesticides were determined | [51]      |
| GC-CD-IMS       | Water, apple, vegetables | The combination of new SPME and GC-CD-IMS has a good effect on the detection recovery of diazinon and fenthion in samples | [52]      |
| Handheld GC-IMS | Fish                  | Quickly identify freshness                             | [53]      |
CONCLUSIONS AND PROSPECTS

Although mainstream detection methods such as GC-MS, GC-O and electronic nose have played a major role in the identification of food flavor substances and the contribution of odor active substances to flavor composition, there are still some typical problems, not satisfactory. For example, differences in pretreatment methods cause loss of original sample flavor data, and strong odor active compounds below the detection limit cannot be qualitatively determined. The emergence and development of GC-IMS has demonstrated the characteristics of high sensitivity and good separation performance, and has become a good supplement to the above-mentioned instrumental analysis techniques. In recent years, it has been successfully applied to the detection and analysis of volatile substances in various foods. With the help of various model tools and chemometrics software, it shows the strong advantages of various foods. With the help of various model tools and chemometrics software, it shows the strong advantages of various foods.

In the future, GC-IMS equipment will continue to pursue the miniaturization and chipization of IMS, the improvement of GC capillary column separation efficiency and the development of 2D-GC-IMS technology. These improvements will promote the convenience and high efficiency of GC-IMS, and will be better applied to online detection and rapid screening. At the same time, if GC-IMS and olfactory technology can be combined, the screening of odor active flavor components in complex mixtures will be of great help. However, although IMS provides multi-dimensional information on the basis of chromatogram, the construction of the spectral library is not yet complete, and there is still a lot of room for development. In addition, the prediction and evaluation results provided by different mathematical models of discriminant analysis also have different defects related to stability.

With the advancement of commercialization, the application of GC-IMS in food production, manufacturing, scientific research and other fields will be further matured.

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