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A Comprehensive Review of VOCs as a Key Indicator in Food Authentication

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ABSTRACT

This article presents an in-depth review of the role of volatile organic compounds (VOCs) in food authentication, an area of increasing importance due to the rising complexity of food fraud cases. The inherent and unique profiles of VOCs in different food products serve as chemical fingerprints, enabling the differentiation of authentic food products from fraudulent ones across various food categories such as dairy, fruits, vegetables, meat, seafood, beverages, and grains. The review begins with an overview of the chemical properties and characteristics of VOCs, emphasizing their diversity and significance in the sensory experience of food products. The article explores VOCs' application in food authentication, providing valuable information on origin, variety, quality, ripening stage, and potential adulterations. Advancements in detection and analytical techniques, such as gas chromatography-mass spectrometry (GC-MS), proton transfer reaction-mass spectrometry (PTR-MS), selected ion flow tube-mass spectrometry (SIFT-MS), electronic noses (E-noses) etc., are discussed. The article also addresses the challenges and limitations in VOC-based food authentication, including variability in VOCs profiles, technical limitations, and regulatory considerations. In conclusion, the review underscores the potential of VOCs as indicators in food integrity, predicting that continued technological advancements and interdisciplinary collaboration will enhance food safety, quality, and traceability.

1 | Introduction

Food authentication is a crucial practice that guarantees the quality, safety, and traceability of food products, aiming to detect instances of food fraud, such as adulteration, substitution, and mislabeling. For the sake of gaining more profits, foods may be diluted with cheaper substitutes, mixed with lower-grade ones, or labeled with false information. Turning a blind eye to food fraud may lead to a

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situation where dishonest practices dominate, resulting in a deterioration of the overall health of the food market. The importance of food authentication cannot be overstated, as it benefits a lot. Food authentication safeguards consumer health by ensuring that food products are accurately represented, particularly for allergen declarations and nutritional labeling. It also protects consumers from economic fraud by preventing the sale of lower-quality products misrepresented as premium goods. Additionally, food authentication upholds the integrity of the food supply chain by enhancing transparency and accountability, benefiting both producers and consumers. Moreover, food authentication supports the fair trade of food commodities by authenticating the origin of food products, which is crucial for products with protected geographical indications, ensuring that producers from specific geographical regions known for particular products are not disadvantaged by fraudulent activities.

To ensure the authenticity and accuracy of the results, food authentication relies on a series of analytical and identification methods, including chromatography, spectroscopy, stable isotope analysis, metabolomics, proteomics, enzymatic methods, and DNA-based techniques. However, the rising complexity of food fraud cases necessitates the urgent development of stable, efficient and dependable methods to identify fraudulent alterations.

Volatile organic compounds (VOCs) is an inherent and conspicuous property of food products, which can effectively distinguish them from other varieties or categories. Their unique profiles in different foods are influenced by various factors such as species, geographical origin, cultivation conditions, and processing methods. Based upon this, these VOCs profiles serve as chemical fingerprints, enabling the differentiation of authentic food products from fraudulent ones. They have been successfully utilized in the authentication of various food commodities like dairy products, wine, coffee, honey, olive oil, etc. VOCs can determine the geographical origin of a product, as the environment where the food is grown affects its VOCs profile, particularly beneficial in identifying products with protected geographical indications. VOCs can also detect adulteration by identifying unexpected compounds that should not naturally be present in the food product. Moreover, VOCs can assist in detecting instances of mislabeling, particularly concerning the ingredients and true composition of orange juice. Though VOCs are widely used in food authentication practices, there are few comprehensive articles summarizing their applications and progresses. Current reviews primarily address food quality, safety, and storage management, lacking specific coverage of food authentication (Lin et al. 2023; Tiwari et al. 2020). Some discussions focus on the application of volatile metabolomics for food quality and authentication but lack a comprehensive overview of relevant detection techniques and analysis methods (Lytou et al. 2019).

The aim of this article is to review the advances in the use of VOCs as a pivotal indicator for food authentication. It encompasses a condensation of the role and significance of VOCs in food products, an exploration of advancements in utilizing VOCs as biomarkers for food authenticity, and an overview of the analytical techniques employed in VOCs analysis. The specific objectives of this article are to understand the relevance of VOCs in the context of food authentication, elucidate recent advancements in the use of VOCs as biomarkers in food authentication, provide insights into traditional and emerging analytical techniques for VOCs analysis and discuss potential future directions in VOCs-based food authentication. Additionally, the article emphasizes the importance of interdisciplinary collaboration, such as the integration of machine learning, in enhancing food authentication practices. By achieving these objectives, the article aims to provide a well-rounded understanding of the current state of VOCs in food authentication and to envision their future potential in promoting food safety and integrity.

2 | Overview of Volatile Organic Compounds (VOCs)

2.1 | Basic Properties and Characteristics of VOCs

VOCs are diverse carbon-based chemicals with low boiling points that can contain elements such as hydrogen, oxygen, fluorine, chlorine, bromine, sulfur, or nitrogen in their molecular structure. They encompass a wide range of chemical classes, including aldehydes, ketones, terpenes, alcohols, esters, etc., often existing as isomers with different structures and properties.

VOCs encompass a vast array of everyday items, permeating various sectors and demonstrating remarkable versatility. For example, VOCs play pivotal roles in agriculture, serving as integral components in plant-to-plant communication, attracting pollinators, and acting as deterrents to herbivores, as elucidated by the research (Bouwmeester et al. 2019). In the field of medicine, VOCs are used as biomarkers of oxidative stress, inflammation and carcinogenesis, aiming at monitoring the occurrence of infections and diagnosing diseases (Oxner et al. 2023). They also lead to the formation of secondary organic aerosols, influencing climate and human health. Significantly, VOCs play a crucial role in the sensory experience of food products by contributing to their flavor and aroma profiles. These substances contribute to a unique set of aromas and flavors, thus imparting distinctive smells and tastes to different food items (Figure 1). From fruits and vegetables to dairy, meat, and processed foods, the combination of various VOCs characterizes their unique sensory qualities. Besides, the type, concentration, volatility, and interaction of VOCs with other components influence the perceived odor and flavor. For example, the volatility and solubility of VOCs in wine are significantly affected by the composition of the matrix, which encompasses interactions with polyphenols (Pittari et al. 2021). Thus, in the context of food authentication, the unique VOCs profiles inherent in various food products serve as distinctive chemical fingerprints. These fingerprints can be harnessed to verify crucial attributes such as quality, safety, geographical origin, and more, thereby establishing VOCs as invaluable tools in the quest for ensuring food authenticity.

2.2 | Factors Influencing VOCs Profiles in Foods

VOCs profiles in foods can be influenced by various factors ranging from biological to environmental and processing factors (Figure 2). Understanding these factors allows for more precise

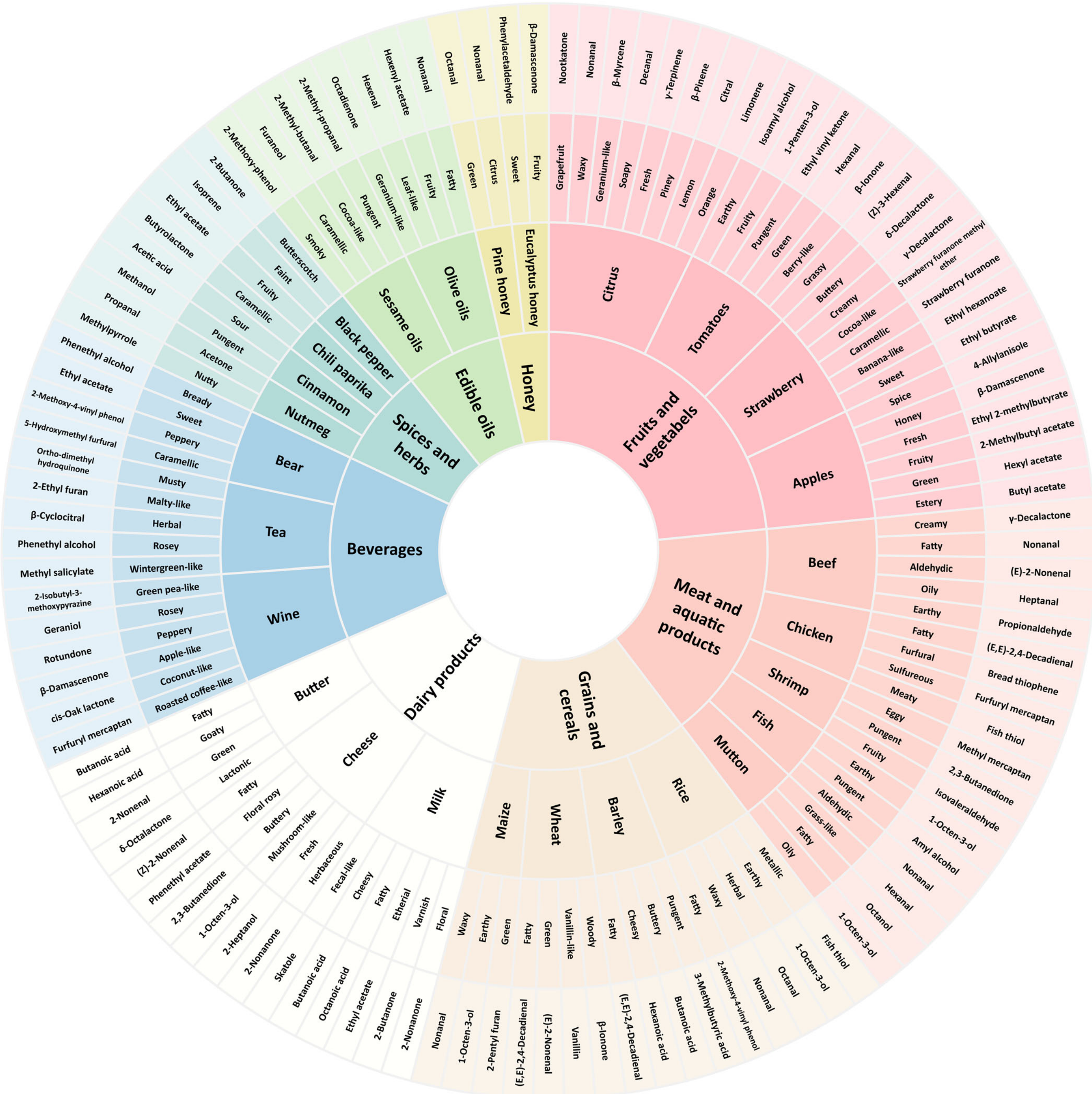

FIGURE 1 | Foods, flavor and VOCs.

and effective use of VOCs in food authentication, providing valuable information about the origin, variety, processing, and storage conditions of a food product.

Biological factors play a pivotal role, as different plant or animal breed can have totally distinctive VOCs profiles. For example, the aroma profiles of different varieties of apples or wine grapes can vary significantly due to genetic differences (Rowan et al. 2009). Therefore, wines made from "Cabernet Sauvignon" and "le Pinot" have completely different flavors, and their VOCs profiles also vary. Environmental factors such as geographic location, climate, and soil composition can also greatly influence the VOCs profiles of agricultural products. While citrus trees exhibit adaptability to various soils with adequate drainage, optimal growth is observed in soils predominantly composed of loam or sandy loam (Su et al. 2023). And this is particularly noted in products like wine, where the concept of "terroir" highlights the impact of geographical and climatic conditions on the VOCs present in the wine (Pittari et al. 2021). Moreover, the maturation stage at harvest emerges as a crucial determinant, significantly shaping the VOCs present in a food product. The ripening process can usher in substantial changes to the VOCs profiles of fruits. By evaluating the composition of volatile fractions of Bergamot (*Citrus × bergamia*) at different harvesting stages, researchers found that its VOCs profiles changed, especially the content of β-ocimene, β-mircene, α-terpinene, *trans*-α-bergamotene, α-pinene, and citronellal (Marzocchi et al. 2019). Food processing techniques, ranging

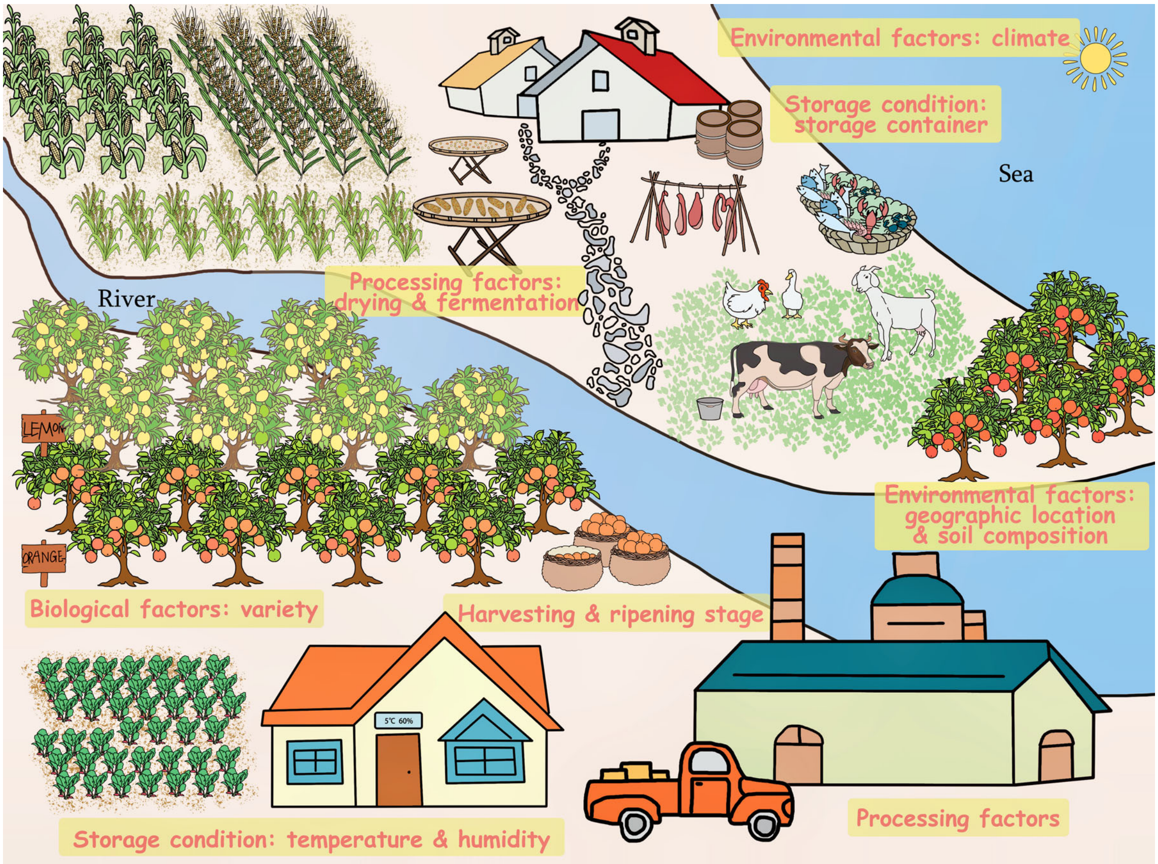

FIGURE 2 | Factors influencing VOCs profiles in foods. Various factors could affect the VOCs profiles in foods. The biological, environmental, harvesting, processing, and storage factors all play crucial roles. (1) Biological Factors: Variety—Different food varieties, such as lemons and oranges, have unique aroma profiles due to genetic factors, influencing VOCs composition. (2) Environmental Factors: Climate—The climate in which crops are grown (temperature, precipitation, etc.) impacts the chemical pathways of VOCs production in plants. (3) Environmental Factors: Geographic Location & Soil Composition—The soil type and location of growth also influence VOCs, as different soils can affect nutrient availability and plant metabolism. (4) Harvesting & Ripening Stage—VOCs are dynamic and change throughout the ripening process. The timing of harvest and ripening stage will affect the final VOCs composition. (5) Processing Factors: Drying & Fermentation— Postharvest processes such as drying and fermentation further alter VOCs profiles in foods, as these methods introduce new chemical reactions. (6) Storage Condition: Temperature & Humidity—The storage conditions, including temperature and humidity, continue to affect VOCs. Controlled storage, such as cold chain transportation, preserves the freshness and VOCs characteristics. (7) Storage Condition: Storage Container—The type of container used for storing food products can impact the VOCs retention and quality of the product. (8) Transportation—The method of transportation, especially cold chain transportation, helps maintain VOCs profiles by preserving food quality during transit, preventing spoilage and degradation.

from heating to fermentation or drying, exert a profound influence on the VOCs profiles of foods. An exemplary instance is the roasting of coffee beans, a process that engenders the formation of hundreds of new VOCs, endowing coffee with its distinctive aroma (Baggenstoss et al. 2008). Furthermore, storage conditions, inclusive of storage container, temperature, humidity, and light exposure, emerge as critical determinants affecting the stability and evaporation of VOCs, consequently altering the VOCs profiles over time. It is known that the aroma of wine comes partly from the flavor of the oak barrels. Besides, recent research underscores the significant impact of controlled atmosphere storage on dragon fruit, particularly in shaping fruit quality with a special emphasis on VOCs profiles (Ho et al. 2021).

In conclusion, the VOCs composition of food is the culmination of a myriad of interacting factors, collectively reflecting the unique characteristics of each specific food product.

2.3 | VOCs in Food Authentication

VOCs are particularly valuable in the context of food authentication due to their unique composition in different food items. By analyzing their presence and concentration, important information can be obtained regarding the origin, variety, quality, ripening stage, and potential adulterations or contaminations of the food product, essentially providing a distinctive "fingerprint" for verification. The use of VOCs as indicators of authenticity has been successfully applied to various food commodities such as wine, coffee, olive oil, and honey, among others. For instance, in the wine industry, VOCs analysis can reveal the wine's geographical origin, grape variety, and even the production year (Gajek et al. 2021). In short, VOCs and their analysis offer a powerful tool for food authentication, contributing to the maintenance of quality standards, prevention of food fraud, and protection of consumers.

The VOCs profile of a food product can provide a measure of its quality and freshness. Certain VOCs might indicate the freshness of a product, while others might suggest spoilage or the onset of rancidity. For example, fresh fish is a perishable food item prone to chemical changes, particularly oxidation and microbiological decay, leading to unpleasant odors, and total volatile basic nitrogen serves as a common marker used to gauge the freshness of unprocessed fish (Martin et al. 2023).

Besides, VOCs can serve as markers for geographic origin and variety. In wine industry, wine's unique aroma, largely derived from its VOCs profile, can reveal its varietal origin and the geographical region where the grapes were grown (Ferreira et al. 2000; Robinson et al. 2014; Zhang et al. 2023). Hence, a specific VOC might serve as the gold criteria for distinguishing between various wines produced by different wineries.

Additionally, VOCs could be used to detect food adulteration and fraud, such as mislabeling of origin or species and adulteration with cheaper substitutes, which is a significant and tricky issue in the food industry. For instance, detecting foreign VOCs can indicate the presence of an adulterant, like premium coffee beans being adulterated with defective ones (Toci and Farah 2014). Similarly, certain VOCs in olive oil can indicate adulteration with lower-grade oils.

Overall, the analysis of VOCs provides valuable information that can contribute to maintaining food authenticity, safety, and quality, thereby protecting consumers and supporting the integrity and sound development of the food industry.

3 | Advancements in VOCs as Indicators in Food Authentication

3.1 | Overview of Food Authentication Methods

Food authentication methods encompass various techniques that aim to ensure the integrity, quality, and safety of food products. Spectroscopic techniques, including infrared spectroscopy (IR), near-infrared spectroscopy (NIR), and nuclear magnetic resonance (NMR) spectroscopy, have a long history of effectively assessing the quality of agricultural products, particularly in the realm of food. By measuring the interaction of light or magnetic fields with the molecular structures of food components, these methods generate a spectral fingerprint for identification and authentication. These methods are sought after for examining food components due to their tendency to necessitate little to no sample preparation, offer swift, nondestructive and real-time analysis, and the capability to conduct multiple tests on a single sample. Chromatographic methods, such as high-performance liquid chromatography (HPLC) and gas chromatography (GC) coupled with mass spectrometry (MS), are powerful tools for separating and identifying individual components in complex food matrices, including VOCs. These technologies exhibit high efficiency in substance separation and analysis, thus are widely used in scientific research. DNA-based methods, such as polymerase chain reaction (PCR) and next-generation sequencing (NGS), enable the identification of species, breeds, or varieties present in a food product, facilitating the detection of adulteration or mislabeling. Isotope ratio analysis examines the ratios of stable isotopes in a food product to reveal information about its geographic origin and authenticity, as environmental factors influence isotope ratios. Sensory analysis involves trained panels or consumers evaluating the taste, aroma, texture, and appearance of a product, providing subjective data that can be correlated with objective measurements to understand consumer preferences and product quality. Though these numerous techniques could be used in food authentication, each possesses unique strengths and weaknesses and may yields more robust and reliable results when used in conjunction with other techniques.

3.2 | Case Studies Demonstrating the Use of VOCs for Food Authentication

3.2.1 | Dairy Products

Previous studies have reported that dairy products, particularly milk, are ranked in the top 10 food categories with the most reported incidences of fraud. This category of foods is often subject to fraud, as they are typically high-value commodities (Biçer et al. 2021; Clarke et al. 2022). Thus, authentication can be important in determining the geographic origin of the product, detecting adulteration, and verifying processing methods, to minimize economically motivated food fraud. And VOCs have been utilized to authenticate a variety of dairy products.

Milk is a complex fluid with diverse phases and particle sizes, containing a broad range of chemical components that primarily mirror the metabolic impact of feeding practices, particularly influenced by the type and storage method of the forage portion in their diet. Factors connected to forage feeding, such as botanical composition, phenological stage during harvest, and storage method (e.g., silage or dried forage), have been noted for their impact on both the VOCs profiles and sensory attributes of dairy products. Therefore, the rearing system of milk can be determined based on the VOCs profiles, as different diets result in distinct contents of fatty acids and distinct levels of VOCs in the milk.

The same goes for cheese. The aroma profile of cheese, mainly constituted by VOCs, is an important aspect of its sensory characteristics and can indicate its authenticity. Advanced techniques like gas chromatography-mass spectrometry (GC-MS) have been employed to identify unique VOCs profiles of various types of cheeses, helping to distinguish between authentic and adulterated products. For instance, high-moisture mozzarella, a fresh pasta filata cheese with origins dating back to 17th-century Italy, can be distinguished based on the presence of 3-methylbutyraldehyde, indicating whether it was produced using traditional acidification techniques (Natrella et al. 2020). And this food authentication technique could prove highly valuable concerning the European Union's PDO labeling for the traditional product, serving to safeguard it against counterfeit imitations. Moreover, employing a range of methods enables the authentication of the geographical origins of cheese, focusing on the concentration of distinct aroma compounds such as butan-2-one, 3-hydroxybutanone, butan-2-ol, octene, and others (Cardin et al. 2022). VOCs analysis can also ascertain the precise origin of milk fan, a fermented milk product resembling cheese, generated in Yunnan Province, China. This determination is facilitated by the unique aroma compounds created by diverse microbial communities specific to each geographical source.

Techniques like GC-MS have also been used in the authentication of butter. Specific VOCs can be used as markers to distinguish between butter made from different sources (e.g., cow, goat, sheep), and to detect adulteration with cheaper vegetable fats (Gemechu et al. 2021). By conducting GC-MS analysis, it is able to identify butter adulterants, including hydrogenated vegetable oil, which may significantly change the fatty acid profile(Aghili et al. 2023).

3.2.2 | Fruits and Vegetables

The use of VOCs for the authentication of fruits and vegetables has proven to be highly effective. Not only can VOCs identify varieties and species, but they can also authenticate the geographical origin and determine freshness and ripening stages (Zhu et al. 2024).

A comprehensive VOCs profile can be used to distinguish between different fruit varieties and geographical origins. For example, Proton Transfer Reaction-Mass Spectrometry (PTR-MS) has been used to differentiate between apple varieties based on their VOCs fingerprints, which are characteristic for each variety (Ciesa et al. 2015). Plus, GC x GC-MS analysis making it possible to discern various apple varieties, like "Fuji," "Gala," "Golden," "Envy," "Ambrosia," etc., as they showed differences in metabolites such as α-farnesene (Barberis et al. 2021). Citrus fruits represent a food commodity that is often targeted for mislabeling. They are often subject to falsification because they can be relatively easily manipulated. The geographical origin of citrus fruits can also be determined through the analysis of VOCs.

The ripening stage and quality of tomatoes have also been studied using VOCs. A PTR-MS study showed that it is possible to identify the ripening stage of tomatoes based on their VOCs emissions, which vary as the tomato matures (Farneti et al. 2012). Specific VOCs have been identified as biomarkers to determine the ripening stage and quality of melons, including ethyl hexadecanoate, ethyl hexanoate, α-terpineol, and others (Majithia et al. 2021). Additionally, the authenticity and freshness of melons can be verified through their VOCs profiles.

3.2.3 | Meat and Aquatic Products

VOCs play an integral role in authenticating meat and aquatic products. These biomarkers can be employed for identifying the species, verifying the geographic origin, and determining the freshness of these food products.

Research shows that specific VOCs can be used to differentiate between various types and breeds of meats. Utilizing headspace-gas chromatography-ion mobility spectrometry (HS-GC-IMS) analysis enables swift, high-throughput, highly sensitive, and species-specific identification of six meat types, namely cattle, sheep, pigs, rabbits, rats, chickens, and carp (Li et al. 2022). This contributes to advancements in food safety, facilitating the detection of issues like meat fraud and adulteration. Similarly, the freshness of fish can be determined by VOCs analysis. An investigation employing DHS-GC-TOFMS identified particular VOCs, such as 2,3-butanedione, acetic acid, 2-butanol, ethyl acetate, and an additional set of 10 compounds, as potential indicators of fish spoilage (Moser et al. 2023). Moreover, GC-MS has been applied to differentiate between various shrimp species and ascertain the geographical source of both shrimp and its derived products by analyzing distinctions within their VOCs profiles (Ji et al. 2023).

3.2.4 | Beverages

The application of VOCs in beverage authentication has emerged as an essential method in assuring quality and preventing food fraud. It allows for the differentiation between types, brands, geographical origins, and even the detection of adulteration.

VOCs have been extensively used in food authentication of alcoholic beverages. Research shows that VOCs could be used to identify the varietal, vintage, and geographical origin of wines. For instance, headspace solid-phase microextraction coupled to gas-chromatography with mass spectrometry detection (HS-SPME/GC-MS) has been applied to differentiate wines from different regions and varieties based on their VOCs profiles, specifically terpenes, benzene-derivatives, ketones and fermentation-derivatives (esters and alcohols) (Zhang et al. 2023). It could help to discern adulteration of grapes of different vintages, plantations and varieties. VOCs analysis has also been used to distinguish between different types of beers. In a study using PTR-MS, beers from different fermentation methods could be differentiated based on their unique VOCs fingerprints (Richter et al. 2018).

Through VOCs analysis, it could help to discriminate non-alcoholic beverages as well. The quality and geographical origin of coffee beans can be determined. An electronic nose was employed to differentiate coffee beans from distinct origins by analyzing their characteristic VOCs, including compounds like 1-(4-nitrophenyl)-3-phenylamino-propenone and carboxylic acids, alongside positive attributes, as well as compounds like 2-methyl-furan and 2,5-dimethyl-pyridine, denoting negative qualities (Barea-Ramos et al. 2022). Additionally, VOCs have been used to authenticate tea type and origin. Research involving GC-MS found that specific VOCs could be used as indicators to differentiate between various tea types. In addition, food fraud incidents frequently occur in juices, including the adulteration of fruits from different varieties and production areas. Through HS-SPME-GC-MS analysis, it allowed the discrimination of the juice samples from different apple varieties, including "Starkrimson," "Gala," "Jonagold" and "Fuji," according to the GC and sensory datasets (Guo et al. 2020). Lemon Juice is a category where Food Labeling Scandal frequently occurs, including insufficient content, inconsistent varieties, extra additions, etc. Research has shown that an electronic nose using metal oxide semiconductor sensors and chemometric techniques is highly efficient for the quick, noninvasive categorization of authentic and fraudulent lemon juice, achieving over 95% accuracy in identifying adulterated samples (Mohammadian et al. 2023).

3.2.5 | Grains and Cereals

VOCs profiles have shown promising applications in the authentication of grains and cereals, in terms of species differentiation, geographic origin determination, and quality assessment.

VOCs in rice have been used for variety identification. Additionally, VOCs can be utilized to differentiate the storage conditions and duration of rice. This is because, over time, there was a decrease in the concentrations of 2-acetyl-1-pyrroline, while the contents of n-hexanal and 2-pentylfuran increased (Wongpornchai 2004). VOCs have also been used to assess the quality of wheat, particularly in detecting infestations. Electronic noses have been utilized to identify VOCs profiles associated with fungal infestations in stored wheat (Mota et al. 2021). Moreover, research employing proton-transfer-reaction quadrupole ion time-of-flight mass spectrometry (PTR-QiTOF-MS) and HS-SPME-GC-MS, along with multivariate analysis, showcased the potential to ascertain the geographical source of maize by examining its VOCs profiles (Ekpa et al. 2021). Malting barley's germination process and malt quality can be monitored using VOCs as well. Specific VOCs have been linked with germination and malting times, allowing for the optimization of the malting process (Calvi et al. 2022).

3.2.6 | Edible Oils

Edible oils are extensively consumed and used in worldwide, owing to their nutritional advantages, enjoyable taste, and practical attributes. However, the adulteration of edible oils stands as a significant concern in the realm of food fraud (Dou et al. 2024). Oils of inferior quality or from alternative sources may be blended into premium oils, which are then sold at equivalent or lower prices than the authentic products, particularly in olive oil. The most prevalent violations involve the promotion of virgin olive oil as extra virgin olive oil or the marketing of blends containing other vegetable oils (such as sunflower, corn, palm, rapeseed, etc.) as olive oil (Casadei et al. 2021). Besides, mislabeling or spoiled oil concerns are also common in the market. While the fatty acid profile was traditionally used to authenticate olive oil, VOCs serve as emerging and reliable indicators. Sesquiterpene hydrocarbons (SH) have been identified as effective geographical markers for virgin olive oil. The SH fingerprint, along with chemometrics, enables the discrimination between EU and non-EU oils, ensuring a high level of accuracy in verifying the country of origin. In fact, a series of fatty acid oxidation products, including hexanal, octanal, nonanal, decanal, (*E*,*E*)-2,4-decadienal and etc., can also serve as reliable VOCs indicators for the food authentication of olive oil (Cecchi et al. 2021). Other than olive oil, in the realm of vegetable oils, food fraud issues are also quite common. For example, sesame oil, with pricey sensory and high nutritional properties, is often adulterated through the inclusion of less expensive oils, including seed oils like sunflower, soybean, corn, and canola oils. Using electronic nose and GC-MS analysis, pure sesame oil can be easily distinguished from sunflower, canola, soybean, and corn oils, as well as blends with varying ratios of these oils (Aghili et al. 2023). GC-MS data provides conclusive chemical evidence, revealing differences in the volatile emissions between authentic sesame oil samples and those adulterated; while electronic nose offers a simple, fast, accurate, and effective method for detecting adulteration.

3.2.7 | Honey

According to the Canadian Food Inspection Agency in its annual report in 2023, food fraud worldwide is on the rise and was found most often in expensive cooking oil and honey. As a natural substance with numerous health benefits, especially monofloral honey, it commands a high price, making it susceptible to food fraud. In particular, honey is frequently susceptible to adulteration and mislabeling regarding its source (Martinez-Castillo et al. 2020). The primary issues pertaining to the authenticity of honey have centered around its geographical and botanical origins. Through the utilization of HS-GC-MS, it becomes possible to accurately identify the botanical origins of honey, encompassing rosemary, orange blossom, albaida, thousand flower, and others, which may effectively assist in preventing honey fraud (Castell et al. 2023). Admittedly, the evaluation of chemical indicators, including VOCs, may be affected by beekeeping techniques, environmental conditions and climate changes, which may result in an unreliable determination of its floral or geographical origin (Madesis et al. 2014). Besides, the inclusion of unallowed substances during the production and processing, like syrups or sugars, is also a significant concern. However, there are fewer methods and cases using VOCs as indicators in this regard.

3.2.8 | Spices and Herbs

In addition to the above categories, food fraud issues are also common in sectors like spices and herbs. Spices and herbs are essential for great food, providing distinctive flavors and potential health benefits. Due to their high value, restricted availability, and the intricacies involved in their production and sourcing, spices and herbs are vulnerable to food fraud. Food fraud cases often involve blending expensive spices with nonaromatic plant materials, using dyes to impart specific color to the spices, and incorporating fillers or other substances into the spices. For example, Saffron (*Crocus sativus*), a highly valued spice of economic significance, may be adulterated with diverse substitutes, including *Carthamus tinctorius*, *Chrysanthemum morifolium*, *Zea mays*, *Nelumbo nucifera*, safflower, gardenia, meat fibers and so on (Negi et al. 2021). Yet, with the help of VOCs, it becomes possible to discern the inferior ones from the spices and herbs. For instance, based on the color and aroma, the most important organoleptic characteristic of saffron, researchers developed an integrated system combining computer vision and electronic nose, which could help to differentiate the authentic and adulterated saffron samples with high accuracy (Kiani et al. 2017). They also found that aroma characteristic variables were more effective than color variables, demonstrating the advantages of using VOCs as indicators for food authentication. Similarly, Zacometti et al. constructed a quick, nontargeted method for authentication of black pepper by HS-GC-IMS, able to classify samples with complex origins as authentic, exogenously-adulterated or endogenously-adulterated with an overall accuracy of 90% and 96% (Zacometti et al. 2024). It can be noted that the integration of VOCs detection and analysis methods with machine learning is a trend in the food authentication of spices and herbs.

4 | Advances in Analytical Techniques for VOCs Analysis

4.1 | Overview of Traditional Analytical Techniques for VOCs Analysis

In the field of perfumery, perfumers hold a supreme position, endowed with unique olfactory talents that enable them to discern the aromas of nearly a thousand perfumes without the aid of instruments. Furthermore, they possess the ability to accurately identify over fifty compounds present in these fragrances. The expertise of perfumers is linked to the reorganization of crucial olfactory and memory-related brain regions, elucidating their extraordinary capacity to envision scents and craft fragrances. The perfumer not only has the ability to identify the components of fragrances but also to assess their texture, depth, and longevity. They can recognize various features of fragrances, such as distillation origin, vintage, and geographical source, providing a profound understanding for perfume formulation. In an era without instrumental support, the olfactory skills of perfumers became the sole tool for deciphering the complexity of fragrances, offering invaluable professional contributions to the ancient production and application of fragrances.

However, the human olfactory system requires extensive time for training and is challenging to precisely qualify and quantify volatile substances. Hence, various detection instruments have been developed to address this issue. The determination and analysis of VOCs in food samples require sensitive and reliable analytical techniques. Over the years, various traditional analytical methods have been extensively employed due to their proven efficiency and reliability.

GC-MS is one of the most frequently used techniques for the analysis of VOCs. It allows for the separation, identification, and quantification of VOCs, providing detailed information about the composition of the sample (Alves and Franco 2003). SPME is not an analysis technique per se; SPME is a sample preparation technique that is commonly used in conjunction with GC-MS for VOCs analysis. It offers the advantages of simplicity, sensitivity, and the ability to concentrate trace levels of VOCs (Pawliszyn 1997). The advent of GC-MS has exerted a profound impact on the study of VOCs, affording a highly precise analytical capability for the efficient separation and identification of VOCs samples. Additionally, GC-MS demonstrates exceptional sensitivity, enabling the detection of trace amounts of VOCs within samples. Consequently, this technology facilitates the identification of a broader spectrum of VOCs in samples, enabling the exploration of substances that fall below the threshold of human olfactory perception. The emergence of GC-MS stands as a pivotal advancement, providing researchers with a sophisticated tool to delve into the intricate realm of VOCs research.

Fourier transform infrared spectroscopy (FTIR) provides qualitative and quantitative analysis of VOCs based on their infrared absorption characteristics. In FTIR analysis, samples are exposed to infrared radiation, and molecular vibrations induce the absorption of infrared light. Each molecule exhibits unique vibrational frequencies, allowing the identification of compounds in the FTIR spectrum through the analysis of absorption peaks. It is a non-destructive method and is particularly suitable for functional group analysis and the study of molecular structures (Othman 2022). FTIR has been extensively researched and applied in the field of food authentication. For instance, it can be utilized to discern the adulteration of citrus essential oil samples with coconut essential oil, facilitate halal certification for ham products, and identify potential adulteration of pomegranate juice with grape juice (Riswanto et al. 2023; Vardin et al. 2008; Xu et al. 2012). The versatility of FTIR in detecting subtle compositional variations underscores its significance in ensuring the authenticity and quality control of food products. These applications demonstrate the efficacy of FTIR as a traditional valuable tool in the realm of food authentication.

Although liquid chromatography-mass spectrometry (LC-MS) is not commonly used for VOCs due to their volatility, it is occasionally employed for certain applications, especially when dealing with more polar volatile compounds that might not be amenable to GC-MS (Fiehn 2016).

The traditional detection methods listed above have their advantages and limitations, but they, especially GC-MS, provide a solid foundation for the analysis of VOCs in food samples, and new detection methods are emerging (Figure 3). We have compiled a selection of detection methods and the corresponding food items reported in existing research, with the aim of providing a clearer comparison of the various methods (Table 1).

4.2 | Recent Advancements in VOCs Analysis Techniques

4.2.1 | Gas Chromatography-Mass Spectrometry (GC-MS)

GC-MS has been at the forefront of VOCs analysis for several decades and continues to be a mainstay in food authentication due to its robustness, sensitivity, and wide applicability. In recent years, advancements in GC-MS technology and methods have further increased its potential in the field of food authentication.

The introduction of high-resolution GC-MS has dramatically improved the separation and identification of VOCs, especially for complex mixtures where multiple compounds might coelute on traditional GC columns. This high-resolution technique allows for the discrimination of VOCs based on minute differences in their mass spectra (Rubiolo et al. 2010). Two-

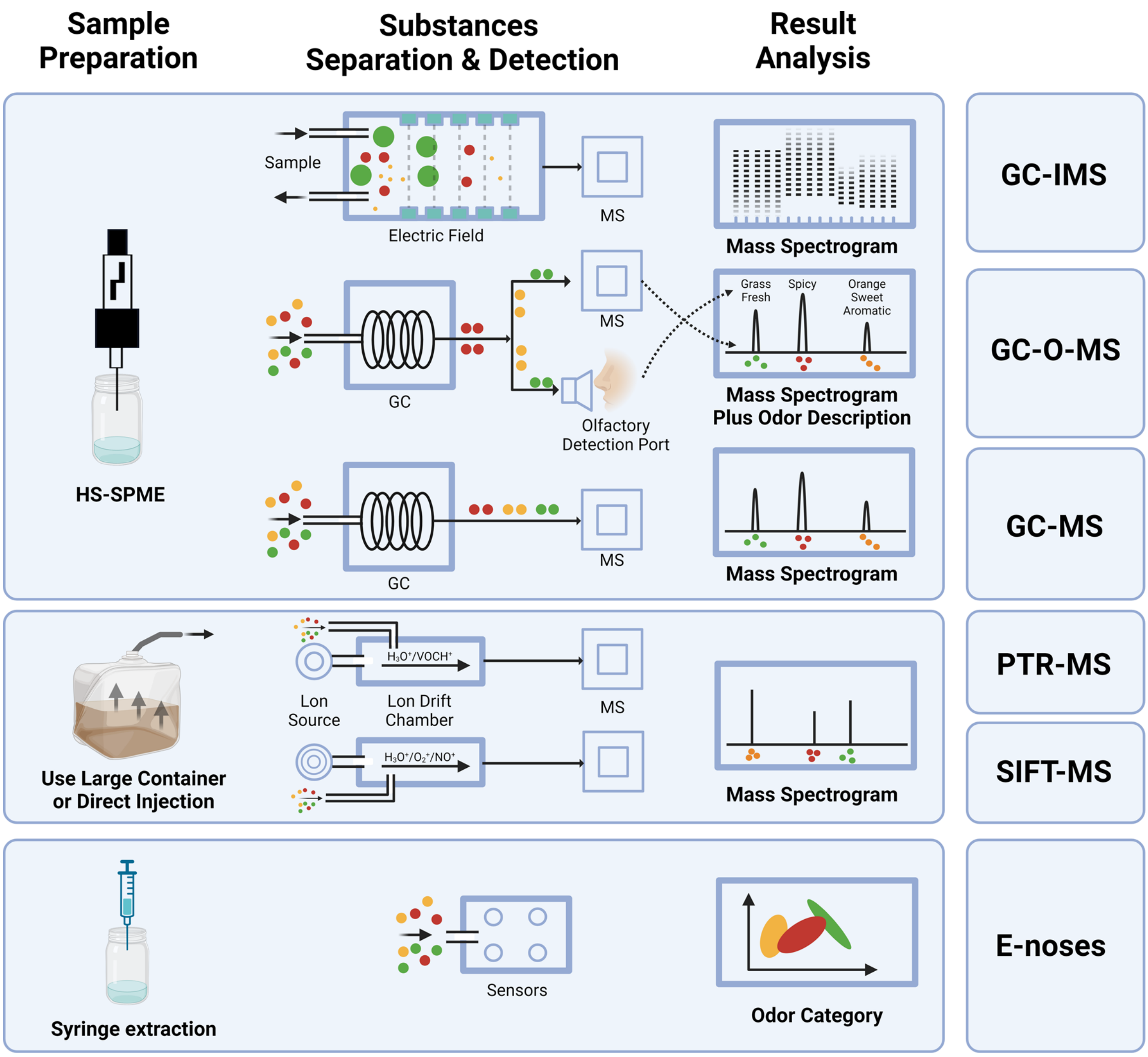

FIGURE 3 | The mechanisms of food authentication techniques.

dimensional GC-MS (GC x GC-MS) offers an additional level of separation compared to conventional GC-MS by using two orthogonal GC columns, significantly increasing the peak capacity and resolving power. It has been successfully applied in food authentication, particularly in cases where the VOCs profiles are extremely complex, such as in coffee or wine. Headspace sampling, combined with GC-MS, is a powerful tool for VOCs analysis as it allows for direct sampling of the volatile fraction without the need for sample extraction. This results in reduced sample preparation time and eliminates potential extraction bias.

At present, HS-SPME-GC-MS is the most commonly used and practical method. HS is a method of sample injection, that is, the sample is often placed in the headspace bottle. The thermodynamic equilibrium of the gas-liquid (gas-solid) two phases is reached by heating, and then the top gas is extracted (Soria et al. 2015). SPME is a technique in which fused quartz fibers coated with a fixed phase are used for adsorption and enrichment, and then desorption and injection when extracting gas samples. This technique can make the detection results of volatile substances with low content and low volatility more accurate. GC is a separation technique used to separate chemical components in sample mixtures and to detect their existence and content. MS is an analytical technique for measuring the mass-charge ratio of charged particles. It can be used to determine molecular weight and elemental composition, and to clarify the chemical structure of molecules (Zoccali et al. 2019). The combination of gas chromatography and mass spectrometry leads to the three-dimensional presentation of data, that is, material identification, chromatographic peak height and chromatographic peak retention time. In the field of food authentication, GC-MS has been employed across various food categories such as vegetables, fruits, meat, aquatic products, grains, cereals, beverages, dairy products, edible oils, spices and herbs, among others. It has successfully identified several characteristic volatile compounds specific to each category. GC-MS has emerged as the preferred method for researchers seeking characteristic biomarkers. These characteristic biomarkers are primarily employed for the adulteration detection of commodities and the traceability authentication of their origins, such as identifying the adulteration of inexpensive fruit juice in pomegranate juice (Nuncio-Jáuregui et al. 2014). Additionally, they are utilized to differentiate wines from various vineyards to ensure the authenticity of the grape wine (Riswanto et al. 2023). In recent years, there has been a growing

TABLE 1 | Common techniques in food authentication.

Methods	Broad category	Specific category	Key indicators	Effects	References
GC-MS	Vegetables and fruits	Garlic	1,2-Dimethoxybenzene, 1-(2-methyl-1-cyclopenten-1-yl)-ethanone, mequinol, 2-methoxyphenol, 3,4-dimethylthiophene, (*E*)-1-allyl-2-(prop-1-en-1-yl) disulfane	Distinguishing the geographical origin of garlics	Mi et al. (2021)
	Meat and aquatic products	Donkey	Heptanal, 1-octen-3-ol, ethyl acetate, 1-hexanol, nonanoic acid, nonanal, 2-octanone, 2-butanone, hexanal, phenylethyl alcohol, 2-heptanone, 2-nonanone, tridecane	Distinguishing between donkey, beef and mutton	Man et al. (2023)
	Grains and cereals	Wheat	(*E*,*E*)-2,4-decadienal, (*E*)-2-nonenal, 1-pentanol, 2-pentylfuran, 1-Hexanol, Nonanal, (*E*)-2-hexenal, vanillin, dihydroactinidiolide, β-ionone	Differentiating wheat from different geographical origins	De Flaviis et al. (2021)
	Beverage	Grape wine	Piperitone, 3-mercapto-2-methylpropanol, 2-hexenol, 3-hexenol, 1,4-cineole, 1,8-cineole, limonene, (*R*)-linalool, α-Terpineol, hotrienol	Distinguishing geographical origin	Riswanto et al. (2023)
	Dairy products	Cheese	Hexanoic acid propyl ester, butan-2-ol and the hydrocarbons undecane	Distinguishing between different origins and varieties	Bozoudi et al. (2018)
	Edible oils	Olive oil	Sesquiterpene hydrocarbon fingerprint	Geographical authentication of virgin olive oil	Quintanilla-Casas et al. (2022)
	Spices and herbs	*Piper nigrum* L.	Piperine, cholest-4-en-3-one and benzoic acid	Identification of papaya adulteration	Gul et al. (2018)
	Honey		Lilac aldehyde D, dill ether, 2-methylbutanal, heptane, benzaldehyde, α,4-dimethyl-3-cyclohexene-1-acetaldehyde and herboxide	Distinguishing between citrus honeys of different geographical origin	Karabagias and Nayik (2023)
HPLC-MS & UPLC-MS	Vegetables and fruits	*Toona sinensis*	Concentration of rutinoside, quercetin-3-*O*-β-*D*-glucoside, quercetin-3-*O*-α-*L*-rhamnoside, and kaempferol-3-*O*-α-*L*-rhamnoside	Toon quality authentication	Sun et al. (2016)
	Grains and cereals	Wheat	Concentration of protocatechuic acid	Distinguishing the organic and conventional wheat	Weesepoel et al. (2016)
	Edible oils	Extra virgin olive oils	HPLC-UV fingerprint	Identification of adulteration in extra virgin olive oil	Carranco et al. (2018)
	Spices and herbs	Paprika	Combined UPLC and MS data	Identification of adulteration in paprika	Cetó et al. (2020)
Electronic nose	Vegetables and fruits	Grape	Sensor response value	Geographical origin and agronomic practices	Longobardi et al. (2019)

(Continues)

TABLE 1 | (Continued)

Methods	Broad category	Specific category	Key indicators	Effects	References
	Meat and aquatic products	Mutton	A predictive model for the pork content in minced mutton	Identification of pork adulteration in minced mutton	Tian et al. (2013)
	Meat and aquatic products	Chicken	Evaluation of volatile fatty acids	Differentiating the quality of meat	RAUDIENÉ et al. (2018)
	Spices and herbs	Licorice	Sensor detection results	Differentiating the geographic origin of licorice roots	Russo et al. (2014)
PTR-MS	Beverage	Coffee	A wide range of chemical classes (nitrogen and sulfur heterocycles, furans, pyrans, phenols, carbonylic compounds, esters and carboxylic acids)	Distinguishing between regular coffee and organic coffee	Özdestan et al. (2013)
	Meat and aquatic products	Lamb	Volatile fingerprints	Classification of lamb origins	Erasmus et al. (2017)
	Dairy products	Cheese	Volatile fingerprints	Differentiating cheeses from various origins	Galle et al. (2011)
FTIR spectroscopy	Vegetables and fruits	Citrus	FTIR values and data processing model	Identification of coconut oil adulteration in citrus essential oil	Riswanto et al. (2023)
	Beverage	Pomegranate juice	Spectra with in the 1780–1685 cm^{-1} region	Authentication of pomegranate juice concentrate (PJC) and its adulteration with grape juice concentrate (GJC)	Vardin et al. (2008)
SIFT-MS	Vegetables and fruits	Garlic	Volatile sulfur compounds	Distinguishing between different varieties	Özcan-Sinir and Barringer (2020)
	Edible oils	Olive oil	1-Octanol, 1-penten-3-one, 2-phenylethanol, dodecane, anisole, ethyl nonanoate, isobutanoic acid, ocimene, phenol, toluene	Identifying whether there is adulteration in extra-virgin Argan Oil (EVAO)	Ozcan-Sinir (2020)
GC-IMS	Grains and cereals	Quinoa	n-Hexanol, 3-methyl-1-butanol, (*E*)-2-hexenal, butyrolactone, 1,8-cineole, alpha-phellandrene, 2-propanone, 2-hexanone	Authenticating quinoa flour for adulteration with wheat and rice Flour	Yang et al. (2022)
	Edible oils	Camellia seed oil	Aldehydes, ketones, heterocycles, alcohols, esters and acids	Distinguishing different varieties and processing stages of camellia seed oil	Fang et al. (2022)
NIR spectroscopy	Grains and cereals	Rice	Combined with the PLS-DA approach	Discriminating authentic and adulterated samples	Le Nguyen Doan et al. (2021)
	Beverage	Coffee	Composition and concentration of tocopherol; spectra with highest absorption in 400-700 nm	Detection of corn adulteration in coffee	Winkler-Moser et al. (2015)

trend towards integrating GC-MS analytical outcomes with machine learning. This integration aims to achieve superior predictive performance, potentially representing a future mainstream approach in research (Kessler et al. 2015).

To enhance detection precision and broaden applicability, researchers continue to refine traditional GC-MS methods. These advancements consolidate the position of GC-MS in the identification of VOCs in the realm of food analysis, furnishing higher quality data to bolster the capabilities of food authentication.

4.2.2 | Electronic Noses (E-Noses) and Electronic Tongues (E-Tongues)

E-noses and e-tongues represent significant advancements in the field of food authentication. They mimic human olfactory and taste systems, detecting and differentiating flavors and odors.

Recent progress in sensor technologies has led to the development of e-noses capable of detecting specific VOCs. E-noses employ various types of sensors like metal oxide semiconductors, conducting polymers, and quartz crystal microbalances. These instruments can generate an "odor print" or profile for different food items and are highly valuable for the detection of food adulteration or spoilage. The core of the electronic nose software is cluster analysis, that is, through PCA principal component analysis, LDA linear correlation analysis and other analysis methods to find out the common ground of the data within the group and the differences between the groups, so that the groups can be well distinguished to judge whether there are differences between the samples (Peris and Escuder-Gilabert 2009). While e-noses cannot precisely quantify volatile substances, when combined with chemometrics, they can differentiate grapes and honey sourced from various geographical origins. Furthermore, electronic noses can be applied in halal authentication to detect adulteration of pork in beef and mutton (Huang and Gu 2022). In terms of qualitative comparisons, e-noses represent a swift and convenient experimental method. In the future, continuous innovation and development in technologies such as nanotechnology and micro-electromechanical systems (MEMS) processes will further enhance the recognition capabilities and accuracy of electronic noses. Additionally, e-noses will integrate with other technologies, forming more powerful detection and analysis systems. For instance, combining e-noses with spectroscopy and mass spectrometry can achieve more precise analysis of gas composition and substance detection (Romano et al. 2016).

E-tongues work on similar principles as e-noses but are focused on liquid samples. They can analyze different parameters such as bitterness, sweetness, and sourness, which are relevant for beverage authentication. Notably, recent advancements include the development of biosensor-based e-tongues that can provide highly specific and sensitive detection of taste profiles (Escuder-Gilabert and Peris 2010). These sensor-based techniques offer several advantages, including rapid analysis, non-destructiveness, and the potential for real-time monitoring. While the e-tongues does not emphasize aromatic components, researchers often combine it with e-noses during sample detection to obtain multidimensional experimental data, thereby enhancing the reliability of identification results.

4.2.3 | Proton Transfer Reaction-Mass Spectrometry (PTR-MS)

PTR-MS has emerged as a powerful analytical tool in the field of food science, particularly in the detection of VOCs. This technique offers several benefits, including high sensitivity, real-time analysis, and the ability to measure VOCs without the need for sample preparation. The working principle of PTR-MS is through the proton transfer reaction between the reaction ion H_3O^+ and the measured substance VOCs, the VOCs is converted into (VOCs) H^+, so as to realize the ionization of VOCs and subsequent mass spectrometry detection (Yuan et al. 2017).

PTR-MS is real-time, and it allows for continuous, real-time monitoring of VOCs, providing immediate data for analysis. This makes it an invaluable tool for applications that require quick decision-making, such as process monitoring and quality control in food production. PTR-MS has high sensitivity. It can detect VOCs at very low concentrations, often at parts per billion (ppb) levels, making it suitable for detecting subtle changes in food samples that could indicate authenticity issues. Unlike some other analytical techniques, PTR-MS does not require any sample preparation, allowing for non-destructive analysis. This is particularly advantageous in preserving the integrity of the sample, especially valuable in food authentication where traceability is key.

Recent studies have successfully used PTR-MS for food authentication. For instance, it has been applied to differentiate geographical origin and cultivar of olive oils (Ruiz-Samblás et al. 2012), differentiate pig rearing methods in pork (Oliveira et al. 2015), and delineate the geographical origins of dried distillers grains with soluble (Tres et al. 2014).

Despite the high initial investment and operational costs, the advantages of PTR-MS in providing real-time, sensitive, and non-destructive analysis of VOCs are increasingly being recognized in the field of food authentication.

4.2.4 | Selected Ion Flow Tube-Mass Spectrometry (SIFT-MS)

Selected Ion flow tube-mass spectrometry (SIFT-MS) has emerged as a promising technique for the detection and quantification of VOCs in food authentication. This technique offers advantages such as real-time analysis, high sensitivity, and the capability to identify and quantify multiple VOCs simultaneously without the need for calibration. SIFT-MS makes use of the different characteristics of the charge number, shape and mass of ions in the gas phase, and then separates and detects the gas phase ions through the ion flow tube (Smith et al. 2023).

SIFT-MS enables quantitative analysis. One of the main advantages of SIFT-MS is its ability to provide direct, absolute quantification of VOCs without the need for calibration standards. This can greatly speed up analysis time and reduce costs associated with calibration gas standards. SIFT-MS is synchronized and it allows for the simultaneous analysis of multiple VOCs, which is critical in food authentication where a multitude of markers may need to be assessed to confirm the authenticity of a product (Kim et al. 2013). SIFT-MS has high sensitivity and selectivity. SIFT-MS can detect and quantify VOCs at very low concentrations, often in the parts per billion or even parts per trillion range. It is also highly selective, which can be critical in the identification of specific markers for food authentication. Additionally, both SIFT-MS and PTR-MS have convenient sampling methods. Both of them do not need sample pretreatment, and gaseous samples can be injected directly without damage. These detection methods are good choices for some items with high value.

SIFT-MS has been successfully applied to the certification of adulteration in olive oil and has clearly identified some markers (Ozcan-Sinir 2020). In addition, it is also used to distinguish different varieties of garlic by comparing the contents of different sulfur-containing volatile compounds (Özcan-Sinir and Barringer 2020). Although there is limited research on SIFT-MS in the realm of food authentication, it holds significant applicability in the non-destructive testing of premium food items and the rapid detection within warehouse logistics.

4.2.5 | Other Emerging Techniques

Apart from the conventional and established techniques for VOCs analysis, several emerging methodologies show promise in the domain of food authentication. Some of these include GC-IMS, gas chromatography olfactometry (GC-O).

GC-IMS is the abbreviation of the instrument coupled with gas chromatography and ion transfer spectrometry. It is a commonly used gas analysis technique, which can be used to analyze VOCs in samples quickly and sensitively. The analytical principle of GC-IMS is based on the separation of VOCs in the gas chromatographic column and the ionization and movement of VOCs in the ion transfer spectrum (Yang et al. 2023). The result image of GC-IMS mass spectrometry is relatively special. The horizontal and vertical coordinates represent the VOCs and the sample, respectively, and the middle point represents the content of the substance. This kind of image can directly reflect the difference of VOCs in different samples (Wang et al. 2020). GC-IMS can be employed for identifying adulteration of wheat and rice in quinoa flour (Yang et al. 2022). Additionally, it serves as a method for determining the organic certification of olive oil (Jurado-Campos et al. 2021).

GC-O is often used in conjunction with MS, namely GC-O-MS. This is an analytical technique that combines smell with instrumental detection. The detection of the sample is one more step than that of GC-MS, that is, the sniffer sits at the outlet of the odor meter, records the smell in the gas effluent, qualitatively describes the aroma information and the intensity of the aroma, and obtains the chemical composition and odor characteristic information of the sample. The commonly used GC-O detection methods are a time-intensity method, intensity method, dilution method and detection frequency method. Because the human nose is usually more sensitive than any physical detector, GC-O has a strong detection capability in odor analysis, making it a great potential for food certification (Song and Liu 2018). GC-O, as a relatively novel analytical instrument, currently lacks direct examples specifically applied in food authentication. However, by amalgamating human olfaction with instrumentation, it possesses the capability to qualitatively describe each separated volatile compound. This integration holds potential to serve as a supplementary tool for food authentication. Moreover, the operation of GC-O-MS requires skilled personnel with specialized training, potentially creating a new category of employment opportunities for the society.

These emerging technologies currently have limited applications in food authentication. With continued efforts from researchers, potential matches with specific types of food may be identified. As machine learning research progresses, there is a possibility of finding better entry points for VOCs detection data in food authentication, thereby enhancing the speed, accuracy, and cost-effectiveness of food identification. Furthermore, there are numerous food authentication methods that do not stem from the perspective of VOCs, which will not be elaborated upon here.

4.3 | Advantages and Disadvantages of Different Technologies

Several techniques have been employed for the detection and quantification of VOCs in food authentication, each with its own advantages and drawbacks. Here, we provide a comparison of some of these key methods (Figure 4).

GC-MS is one of the most commonly used techniques for VOCs analysis. It provides detailed information on the molecular structure of compounds, allowing for precise identification and quantification (Wang et al. 2018). However, it requires the extraction and concentration of VOCs, and the procedure can be time-consuming and may introduce analytical errors.

E-noses are sensor-based systems that mimic the human olfactory system. They are less expensive and simpler to use than traditional analytical techniques. While they cannot provide detailed structural information about the compounds, they are capable of rapidly distinguishing between complex mixtures based on their overall scent "signature" (Gardner and Bartlett 1999). This makes them useful for rapid, on-site testing, but less suited for detailed analysis.

PTR-MS and SIFT-MS are powerful tools for the direct, absolute quantification of VOCs without the need for calibration standards. They offer real-time analysis and can identify and quantify multiple VOCs simultaneously. However, these techniques require specialized equipment and expertise, which can be costly.

GC-IMS and GC-O enable the final data to be presented in three dimensions, allowing testers to more intuitively compare the differences in the type and content of VOCs between samples, or to better describe VOCs (Gou et al. 2023).

Each of these techniques has its own place in the realm of food authentication, and the choice of method depends largely on

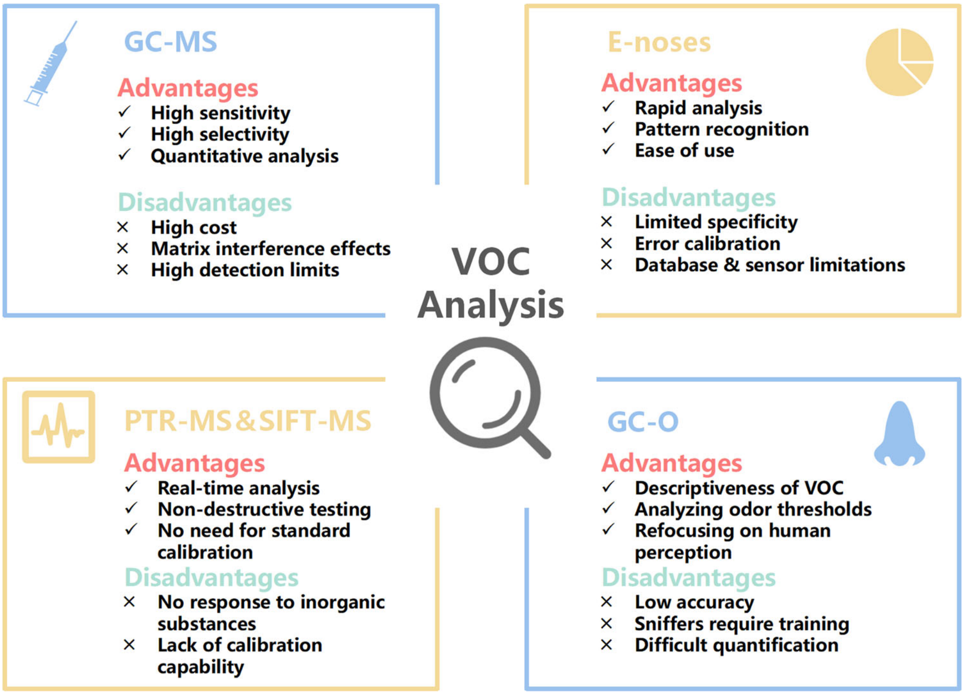

FIGURE 4 | Advantages and Disadvantages of Food Authentication Techniques.

the specific requirements of the analysis, including factors like the complexity of the sample, the level of detail required, the available resources, and the need for onsite versus laboratory analysis.

5 | Challenges, Opportunities, and Future Directions

5.1 | Challenges and Limitations in VOCs-Based Food Authentication

While the use of VOCs as biomarkers for food authentication has shown significant potential, several challenges and limitations still need to be addressed.

The first is the variability of the distribution of VOCs. VOCs profiles can be influenced by numerous factors, including genetic differences, geographical origin, agricultural practices, and post-harvest handling and processing methods. This variability can lead to discrepancies and inaccuracies in the identification and quantification of VOCs, impacting the reliability of authentication results (Cordero et al. 2015). The second is sample collection and storage. The methods used to collect and store samples can significantly affect VOCs profiles. The lack of standardized collection, storage, and handling procedures can introduce errors and inconsistencies in VOCs analysis, reducing the accuracy and reliability of the results (Lancioni et al. 2022). The third is technical limitations. Some analytical techniques used for VOCs analysis, such as GC-MS and PTR-MS, require complex, expensive equipment and specialized expertise. Furthermore, these techniques may not be able to detect all VOCs, particularly those present in low concentrations. The fourth is data analysis and interpretation. The analysis and interpretation of data from VOCs analysis can be challenging due to the complexity and diversity of VOCs profiles. Advanced statistical and machine learning methods can help address this issue, but they require sophisticated computational resources and expertise (Goodacre et al. 2004). The fifth are regulatory and legal considerations. There are also regulatory and legal challenges associated with the use of VOCs for food authentication. Current regulations may not cover all aspects of VOCs analysis, and there may be legal implications related to the accuracy and reliability of VOCs-based authentication methods (Ismail and Nielsen 2017).

5.2 | Potential Future Directions and Opportunities in VOCs-Based Food Authentication

The field of VOCs analysis for food authentication has the potential for significant growth and development, propelled by technological advancements, evolving consumer demands, and the efforts of researchers.

The establishment of standardized procedures is crucial for advancing research in the field. Specifically, the development of protocols for sample collection, storage, and handling is imperative to minimize variability and enhance the reproducibility of VOCs profiles. It is essential that these standardized procedures comprehensively address influential factors affecting VOCs profiles, including but not limited to temperature, sample types, and storage duration (Cassotta et al. 2024; Steffen and Pawliszyn 1996). The implementation of such standardized methodologies will contribute to the reliability and comparability of data across studies. Furthermore, once standardization is established, researchers will be able to quickly select pre-processing methods based on sample types, significantly shortening the experimental cycle. This also promotes the enhancement of the scientific knowledge system in the realm of VOCs analysis.

The continued evolution of analytical techniques will likely further improve the sensitivity, selectivity, and speed of VOCs analysis. Developments in sensor technology, such as the use of nanomaterials, could enable real-time, on-site VOCs analysis (Röck et al. 2008). Additionally, the integration of VOCs analysis with other analytical techniques, such as metabolomics and proteomics, could provide a more comprehensive and accurate assessment of food authenticity (Cevallos-Cevallos et al. 2009).

The integration of artificial intelligence (AI) and machine learning (ML) into the analysis of VOCs represents a potential paradigm shift in the field. These advanced techniques have the capability to revolutionize VOCs analysis by effectively handling intricate datasets, discerning subtle patterns, and achieving highly accurate predictions of food authenticity (Borràs et al. 2015). Employing advanced statistical methods and machine learning algorithms further enhances the analysis and interpretation of complex VOCs data. Through the identification of intricate patterns and relationships within the data, these methods contribute significantly to augmenting the predictive accuracy of models designed for VOCs-based authentication. This amalgamation of cutting-edge technologies and analytical methodologies holds great promise for advancing the precision and reliability of VOCs analysis, thereby shaping the landscape of research in the authentication of food products (Goodacre et al. 2004).

The creation of collaborative databases encompassing VOCs profiles across various food products and geographical origins stands as a key facilitator for global-scale food authentication efforts. Such shared repositories could significantly streamline the authentication process by providing comprehensive datasets for comparative analysis. The success of this endeavor hinges on active collaboration among researchers, industry professionals, and regulatory bodies. Establishing a unified platform where experts can contribute and access VOCs profiles will not only enhance the efficiency and accuracy of food authentication but also foster a collaborative environment that encourages the exchange of knowledge and methodologies. This collective approach is imperative for addressing the complexities of VOCs analysis and ensuring the robustness and reliability of global-scale food authentication initiatives.

Shifts in regulatory requirements and heightened consumer demand for food traceability have the potential to propel the adoption of VOCs-based methods for food authentication (Tan et al. 2024). The convergence of these factors underscores the necessity for regulatory bodies to offer explicit guidance and support in advancing the development of standardized procedures and quality assurance measures. By providing comprehensive guidelines, regulatory bodies contribute to the establishment of a robust foundation for the implementation of these methods, thereby addressing the evolving landscape of food safety and traceability in response to both regulatory changes and consumer preferences.

6 | Conclusion

This review comprehensively examines the remarkable strides made in utilizing VOCs as pivotal biomarkers in food authentication. VOCs, inherent in diverse food items, serve as essential indicators of authenticity, possessing distinctive profiles influenced by food type, geographical origin, and processing, facilitating the identification of counterfeit or adulterated foods. Substantial advancements across various food categories, including dairy, fruits, vegetables, meat, seafood, beverages, and grains, underscore the versatility and effectiveness of VOCs in food authentication.

Furthermore, it is important to highlight the expanding applications of VOCs in food authentication, ranging from verifying the authenticity of the origin and quality of various food products to detecting potential adulteration. This broad spectrum of applications underscores the potential of VOCs to revolutionize the field.

The review highlights traditional and emerging analytical techniques such as GC-MS, PTR-MS, SIFT-MS, e-noses, e-tongues, GC-IMS, and GC-O, improving the accuracy, sensitivity, and speed of VOCs-based authentication. Despite these advancements, challenges persist regarding VOCs profile variability, sample handling, method standardization, data interpretation, and regulatory aspects, prompting active exploration of strategies to address these issues.

It is essential to note that ongoing research and innovation in this field, coupled with interdisciplinary collaboration, are paramount for overcoming current limitations and exploring new horizons. The integration of advanced analytical techniques with artificial intelligence and machine learning could potentially revolutionize food authentication, making it more reliable, efficient, and accessible. Interdisciplinary collaboration and regulatory guidance play vital roles in furthering VOCs-based food authentication, with its ongoing development promising significant contributions to food safety, quality, and authenticity. This progress will inevitably yield crucial tools for safeguarding food supply integrity, ensuring consumer protection, and combating food fraud.

The field of food authentication stands on the brink of transformation, with VOCs emerging as potent biomarkers to ensure food integrity. This approach has shown promise in diverse applications, from authenticating the origin and quality of a range of food products to detecting potential adulteration. As we refine the technologies and methodologies associated with VOCs analysis, we can expect an even greater impact on food safety, quality, and traceability.

However, this technological progress must move in tandem with the development of robust standards and regulatory frameworks. It is imperative that regulatory bodies, in conjunction with scientists and food industry stakeholders, work towards clear, enforceable standards that guide the implementation of VOCs analysis in practical settings. This collaborative effort is vital for achieving the full potential of VOCs as biomarkers for food authentication.

Moreover, considering the global nature of food supply chains, it is crucial to foster international cooperation in standardizing VOCs-based food authentication methods. This not only enhances the effectiveness of these techniques but also fosters mutual trust between countries, consumers, and food industries.

In conclusion, the prospects of VOCs as biomarkers for food authentication are indeed promising. It is a dynamic and rapidly evolving field that holds significant potential for ensuring the safety and integrity of global food systems. As we look to the future, we can anticipate that advancements in this field will continue to play a crucial role in combating food fraud and maintaining consumer trust.

Author Contributions

Han Yang: data curation, formal analysis, investigation, methodology, project administration, supervision, writing – original draft, writing – review and editing. **Manxi Wu:** formal analysis, investigation, methodology, software, visualization, writing – original draft, writing – review and editing. **Xinyu Shen:** software, supervision, validation. **Yichen Lai:** software, supervision, validation. **Dengliang Wang:** funding acquisition, project administration, resources. **Chao Ma:** funding acquisition, resources. **Xianming Ye:** funding acquisition, methodology, resources. **Cui Sun:** resources, software. **Jinping Cao:** resources, supervision, validation. **Chongde Sun:** methodology, project administration, resources. **Yu Zhang:** methodology, project administration, resources. **Yue Wang:** methodology, project administration, resources, supervision, validation.

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Ethics Statement

This study does not involve studies on human embryos or fetuses (including human embryonic stem cells), recombinant DNA technology, empirical studies or medical trials with human subjects, acquisition or use of human cells and tissues, or animal experiments or medical research on animals. All research activities comply strictly with international ethical guidelines and national laws and regulations, ensuring no involvement in ethically sensitive areas.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the article or from the corresponding author upon reasonable request.

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