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Investigation of volatile organic compound (VOC) profile change in foods under different conditions

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Abstract: Volatile organic compounds (VOCs) are widely used in numerous sectors, making the detection of VOCs an important and comprehensive topic of research. Foods naturally release VOCs that have a distinctive and unique characteristic, similar to a fingerprint. The VOC composition released by foods significantly affects both aroma and taste, hence playing a vital influence in customer preferences. Although GC-MS and PTR-MS have historically been the main methods for analyzing VOCs, other techniques such as sensors and e-noses have developed as alternate options for VOC detection in recent times. VOC sensors are being employed in intelligent packaging systems to monitor the shelf life of products and detect indicators of spoiling. From a novel perspective, the analysis of VOCs has provided insight into the cooking process, which is a crucial activity in the food industry. The cooking process is highly customizable, depending on factors such as ingredients, quantity, techniques, and parameters. The complicated composition of VOCs and the chemical processes that occur in food, particularly the Maillard reaction, have been taken into consideration. The objective of this study is to thoroughly examine the creation of VOCs during the process of cooking. The study attempts to understand the specific mechanisms that lead to the production of VOCs, taking into account aspects such as the composition of recipe, cooking methods, and process parameters. Although the outcomes have been variable, and there is a possibility that integrating VOC sensors with advanced image processing and artificial intelligence technologies might facilitate the monitoring and automated termination of the cooking process.

Keywords: Cooking, VOC, sensor, food.

Farklı koşullar altında gıdalardaki uçucu organik bileşik (UOB) profil değişiminin incelenmesi

Özet: Uçucu organik bileşikler (UOB'ler), birçok sektörde yaygın olarak kullanılmakta olup, uçucu organik bileşiklerin tespiti önemli ve kapsamlı bir araştırma konusu haline gelmiştir. Gıda maddeleri, bir parmak izi gibi kendine özgü ve benzersiz bir karakteristiğe sahip UOB'ler doğal olarak salgılar. Gıdalar tarafından salınan UOB bileşimi, hem aroma hem de tat üzerinde önemli bir etkiye sahip olup, bu nedenle müşteri tercihleri üzerinde hayati bir etkiye sahiptir. GC-MS ve PTR-MS tarihsel olarak UOB analizinde ana yöntemler olmasına rağmen, sensörler ve e-burunlar gibi diğer teknikler son zamanlarda UOB tespiti için alternatif seçenekler olarak gelişmiştir. UOB sensörleri, ürünlerin raf ömrünü izlemek ve bozulma belirtilerini tespit etmek için akıllı ambalaj sistemlerinde kullanılmaktadır. Yenilikçi bir perspektiften bakıldığında, UOB'lerin analizi, gıda endüstrisinde kritik bir faaliyet olan pişirme sürecine ilişkin bilgiler sağlamıştır. Pişirme süreci, malzemeler, miktar, teknikler ve parametreler gibi faktörlere bağlı olarak yüksek derecede özelleştirilebilir. UOB'lerin karmaşık bileşimi ve gıdalarda meydana gelen kimyasal süreçler, özellikle Maillard reaksiyonu dikkate alınmıştır. Bu çalışmanın amacı, pişirme süreci sırasında UOB'lerin oluşumunu kapsamlı bir şekilde incelemektir. Çalışma, tarif bileşimi, pişirme yöntemleri ve süreç parametreleri gibi unsurları dikkate alarak UOB'lerin üretimine yol açan spesifik mekanizmaları anlamayı amaçlamaktadır. Sonuçlar değişken olmakla birlikte, UOB sensörlerinin gelişmiş görüntü işleme ve yapay zeka teknolojileriyle entegrasyonunun, pişirme sürecinin izlenmesini ve otomatik olarak sonlandırılmasını kolaylaştırabileceği olasılığı bulunmaktadır.

Anahtar Kelimeler: Pişirme, Uçucu organik bileşikler, sensör, gıda

Review

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1.Introduction

Volatile organic compounds (VOCs) are a class of carbon-based chemical molecules that are known for their tendency to evaporate readily under typical ambient conditions (Cicolella, 2008). Volatile organic molecules are widely found in the atmosphere, soil, and aquatic ecosystems in nature. These chemicals can function as chemical signals and communication instruments for a wide range of species (Tumlinson, 2014). Gaining a thorough comprehension of the importance and impact of VOCs is crucial in tackling many scientific, industrial, and practical difficulties. VOCs are widely used in numerous sectors and their detection is a crucial and thoroughly studied topic (Pozzer et al., 2022). These applications encompass the monitoring of air quality and pollution in the environmental industry, the assessment of inhaled air and the detection of diseases from bodily fluids or breath in the medical industry, the regulation of product quality and safety in the cosmetics industry, and the tracking of changes during processing and the monitoring of shelf life in the food industry (Duan et al., 2023; Zhou et al., 2022c; Rondanelli et al., 2019; Srinivasan et al., 2021; Pozzer et al., 2022). In addition, researchers are currently creating a range of sensors to support investigations in these fields (Khatib & Haick, 2022).

There is increasing awareness about the quality and safety of food in recent years. A method used to identify changes in food is by analyzing VOCs, which are commonly called a fingerprint (Medina et al., 2019). Although instrumental methods like gas chromatography-mass spectrometry (GC-MS) and proton-transfer-reaction mass spectrometry (PTR-MS) have traditionally been the main techniques used for VOC analysis, additional approaches such as different types of sensors have emerged in recent years for VOC detection (Cappellin et al., 2012; Khatib & Haick, 2022). It is essential to have a precise comprehension of VOCs that will be acquired as a result of the intricate nature of the topic. VOC groups can exhibit variations depending on many properties, including molecular weight, polarity, and vapor pressure (Vilar et al., 2022). The analysis of different meals reveals the presence of numerous VOC groups, such as alcohols, aldehydes, ketones, esters, hydrocarbons, acids, and others (Lin et al., 2022). When studying the fruit group, it is noticed that esters are mainly found. However, as the fruit ripens, is harvested, and stored, the presence of esters decreases and alcohols and aldehydes start to form. This ultimately leads to the development of the final aroma of the fruit (Lin et al., 2022; El Hadi et al., 2013). The VOC profile released by foods has a considerable impact on their odor and flavor, and hence plays a crucial role in determining consumer preferences. VOCs can be correlated with distinct scents and flavors. For instance, acetic acid is connected to the intense sourness found in vinegar, 2-Ethyl-6-methyl pyrazine is responsible for the aroma associated with roasted potato, 2-Ethyl-1-hexanol contributes to the refreshing citrus floral scent, and 2-Methyl propanal gives mint its fresh and sweet floral notes (Boscaino et al., 2017).

The complex structure of foods and their freshness are inextricably linked to various processes such as cooking, fermentation and storage. These processes play a vital role in the formation and exchange of VOCs, which determine the taste, odor and aroma of foods. VOCs in foods are a complex chemical structure that is largely shaped by the type of food, its ingredients, and its properties. These unique ingredients can vary depending on many variables, from the type of food to the content and concentration of the ingredients. In meat products, different meat breeds and muscle structure can have significant effects on the taste and aroma profile of meat (Bleicher et al., 2022), while differences in the amount of yeast and fermentation process of the dough cause VOC diversity (Ponzoni et al., 2008). At the same time, the type and variety of vegetables has a significant impact on their flavour. Some vegetables, such as garlic, onion and pepper, have characteristic pungent and strong aromas (Chen et al., 2018). These aromas arise from the unique VOCs that contain.

Cooking methods can dramatically change the chemical composition of foods. Different methods, such as grilling, frying, boiling or steaming, can cause VOCs to form or disappear due to changes in temperature and pressure on the food surface (Zhou et al., 2022b). Food cooking temperature is a critical factor that determines the rate and type of chemical reactions in foods (Starowicz & Zieliński, 2019). Different cooking temperatures can lead to varying results depending on the composition and structure of the food.

Storage time and storage conditions affect VOC changes in foo. Especially in foods with high protein and lipid content, lipid oxidation and protein degradation may lead to the formation of new VOCs as storage time increases (Xu et al., 2017). This contributes to changes in the taste, odor and texture of the food. The microbial load of the food has a significant impact on the VOC profile. Bacteria, yeasts and molds on the surface of food can cause the formation or degradation of VOCs through chemical reactions.

One of the most prominent reactions during cooking is non-enzymatic browning, or Maillard reactions (MR). These reactions involve reducing sugars and amino compounds, releasing many flavor compounds, intermediates, and melanoidins (Shakoor et al., 2022). Understanding MR kinetics can help to create new flavors and optimize production processes. MR consists of complex reactions forming various volatile and nonvolatile molecules and can be classified into three stages: sugar-amine condensation and Amadori rearrangement, sugar dehydration and fragmentation with Strecker degradation, and reactions like aldol condensation, polymerization, and formation of heterocyclic nitrogenous compounds and dark brown products (Amaya-Farfan & Rodriguez-Amaya, 2021).

Several factors affect the propagation of Maillard reactions, including temperature, pH, type of reactant sugar and amino groups, lipid degradation products, water activity, and the availability of metal compounds (Shakoor et al., 2022). Different amino acids with glucose form different aroma compounds, and the chemical composition of sugar directly affects food's aroma, flavor, and color during thermal processing. Protein type also plays a crucial role in forming sensory compounds. Process parameters can release various molecules, with temperature being a crucial promoter. pH value significantly affects Maillard reaction pathways, producing different flavor and odor intermediates. Additionally, technologies like pulsed electric field, microwave, high-pressure processing, and ultrasound influence reaction rate and food properties (Liu et al., 2022).

MR are source of a wide complex of heterocyclic compounds as well as many volatiles such as aldehydes, ketones, esters, acids, alcohols and alkanes. These volatiles can be classified into three main categories. During dehydration of sugar furan derivatives such as 5-hydroxymethylfurfuran (HMF), pyrones, carbonyls and organic acids are formed. The Strecker degradation products such as methional is produced due to amino acid degradation. Further reactions lead formation of a wide variety of volatile compounds: pyrroles, pyridines, pyrazines, thiazoles etc. (Amaya-Farfan, & Rodriguez-Amaya, 2021). The reactions occurring among these volatiles and between other free radicals and lipid oxidation end-products may lead generation of different chemical compounds. Free fatty acids and aldehydes that are produced when lipids are heated may react with a combination of these volatile chemicals and amino acids. The MR produces a diverse range of VOCs. For example, the particular pleasant nutty and roasted aromatic notes of pyrazines have been examined. They have a significant role in the flavor of meals including coffee, chocolate, steak, and rye crisp bread. Furan derivatives give bread, honey, and morning cereals a sweet, caramelized scent. MR may produce desired sensory qualities, they can also have negative impacts on human health or formation of unfavorable colors and smells, which could make a product less appealing. The sensory quality of food products may be significantly impacted by the products of the Maillard reaction (Tamanna & Mahmood, 2015; Starowicz & Zieliński, 2019).

2. Detection of VOCs in Foods

Volatile organic compounds are generally characterized by lightweight molecular structures and low boiling points. In this context, there is a need for rapid, high-solubility measurement methods to analyze VOCs. However, detecting and quantifying VOCs in complex gas matrices can be a process fraught with various challenges. The desired methodology for determining VOCs should possess high sensitivity, selectivity, resolution, and a linear dynamic range (Majchrzak et al., 2018).

GC-MS s currently the most commonly preferred technology for the detection of VOCs. GC-MS is an analytical method that can distinguish and identify different substances in complex mixtures. It utilizes chromatography for the separation of components in the sample and mass spectrometry for sample identification (Gilbert et al., 2013). Due to the complexity of food matrices, complex pre-processing is generally required before analysis. These pre-processing steps can include processes such as distillation, headspace sampling, solvent extraction, adsorption extraction. Sample preparation, designed to separate and pre-concentrate analytes before instrumental analysis, is critical for accurate analysis. Headspace-Solid Phase Microextraction (HS-SPME) is currently one of the most commonly used extraction techniques for VOC analysis in food. It is suitable for use with GC. While GC-MS stands out as a method capable of distinguishing and identifying complex components, the disadvantage lies in the sample preparation and processing time, making it not ideal for meeting the rapid detection requirements for many analytes (Starowicz, 2021). Ion Mobility Spectrometry (GC-IMS) is a rapid separation and detection technology in the gas phase. These devices perform precise measurements and can generate results rapidly. Gas Chromatography-Olfactometry (GC-O) is used to understand the distinct volatile components and their relative contributions to odor characteristics in products. While common detection methods can detect the concentration and types of volatile components, they are often limited in measuring only a small number of VOCs in most food products (Wei, et al., 2023).

Proton Transfer Reaction Mass Spectrometry (PTR-MS) technology is a rapid method that enables real-time measurement of organic volatile compounds. One of the most significant advantages of PTR-MS is the absence of any need for pre-concentration or chemical separation processes before measurement. No sample preparation is required in this context (Majchrzak et al., 2018). In the field of food science and technology, considering the significance of volatile organic compounds, there is a need for simple, fast, and highly sensitive methods for the identification and quantification of these compounds. PTR-MS proves to be a high-sensitivity and accurate method, providing rapid results without the requirement for any sample preparation process. (Ellis & Mayhew, 2013).

Electronic noses are designed to mimic the human olfactory system. Many sensors are sensitive to specific types of odors or vapors. The response patterns of these sensors are analyzed through a computer or software that measures changes on a sample. Electronic noses do not require preprocessing and do not damage raw materials, making them a focal point of attention. However, they may fall short in distinguishing and identifying the generated volatile organic compounds (Dhar et al., 2018).

3. Changes in VOC Profile in Foods

This section will examine the diversity of volatile organic compounds in food, focusing on three specific categories: recipe, cooking techniques, and process parameters.

3.1 Changes in VOC Profile Based on Recipe

One of the most crucial and essential stages in food preparation is recipe determination, which entails the selection of food ingredients. Modifying the recipe involves making modifications such as adding, deleting, or adjusting the quantity of any component. Modifications made to the recipe lead to alterations in the nutritional composition, sensory properties, qualitative traits, and perception of the food and meals (Alozie & Ene-Obong, 2018; Ng et al., 2022). Multiple studies in the literature have consistently shown that recipe adjustments can lead to changes in the generation of VOCs. These variations in VOC profiles resulting from modifications in food recipes are detailed in Table 1 and Table 2.

Table 1 particularly highlights the instances when ingredients are added or enhanced in the recipes. The study conducted by Beltrán Sanahuja et al. (2019) investigated the influence of recipe alterations on the VOC profiles of tomato sofrito, a tomato sauce commonly used as a foundation in many cuisines. Incorporating herbs such as thyme and rosemary into sofrito led to a notable increase in the levels of certain VOC compounds, in comparison to the control. For instance, the inclusion of thyme by itself resulted in the creation of thymol and 2-methyl-5-(1-methylethyl)-phenol, whereas the inclusion of rosemary alone led to the development of molecules including camphene, myrcene, eucalyptol, and camphor. In addition, it was noted that eliminating onions or increasing the garlic proportion in the dish resulted in alterations in VOC profiles when compared to the control.

When attempting to innovate regular or traditional recipes, the inclusion of additional ingredients such as sauces, pastes, and creams has been shown to create VOCs that are different from the original recipe. For example, incorporating onion paste, known for its potent aroma, into bread significantly alters its fragrance profile, leading to the dominance of compounds such as 2-decanone, eugenol, and methyl octyl ketone (Sireyil & Alim, 2022). Similarly, adding fermented cream to bread produces VOCs that improve the scent of the bread. These chemicals include acids, 2-nonanone, 2-undecanone, 2-tridecanone, and δ-dodecalactone (Xu et al., 2022).

When creating functional food, it is typical to incorporate components that provide health benefits (Monteiro et al., 2023). Research has found that VOC evaluations are performed to determine whether functional meals have comparable or distinct taste profiles compared to the control group. Hemp has become popular because of its high protein and low-fat content, as well as its presence of antioxidant components (El Sohly et al., 2017). The hemp-enriched gluten-free bread exhibited a twofold increase in the concentration of aldehydes, ketones, and organic acids compared to typical breads. Additionally, the content of alkenes was three times higher in the hemp-enriched bread (Nissen et al., 2020). In addition, the presence of 2-cyclopentenone-3-hydroxy and (R)-bornane dione was observed exclusively in gluten-free doughs and breads that were enhanced with hemp. As researchers search for new sources of protein, they are also using powdered insects into functional food recipes (de Carvalho et al., 2020). Incorporating cricket powder into gluten-free bread significantly enhances the concentration of pyrazines in the bread, resulting in a pleasant nutty and roasted taste (Wieczorek et al., 2022).

In a study conducted by Gaglio et al. (2021), bread was supplemented with 10% powdered buffalo worm larvae and mealworm larvae. The addition of insect powder mostly resulted in an increase in VOCs in the form of carbonyl compounds, notably dodecanal, 2,4-dodecadienal, and 2-octenal-2-butyl. Another alternative to animal-based proteins is algae and algae powders are valuable in the functional food market (Mellor et al., 2022). Incorporating *Spirulina* spp. powder into bread recipes results in an increase in the concentration of medium organic acids in the VOC profile (Casciano et al., 2021). In addition, the presence of certain bioactive compounds such as thymol, borneol, and nicotinic acid has been noted. The use of food industry waste is an essential matter. In the research done by Yao et al. (2021), the inclusion of apricot kernel skin in white bread was employed to enhance the value of waste and make use of its valuable nutritional composition. The inclusion of apricot kernel skin led to the creation of numerous aromatic compounds, contributing fruity, sweet, caramel-like, and nutty aromas to the bread. The chemicals present are maltol, 2-ethyl-1-hexanol, phenylacetaldehyde, benzaldehyde, styrene, ethyl hexanoate, 2-acetylfuran, 3-methylbutanal, butyl acetate, propyl butyrate, 3-methylthionyl propyl aldehyde, 6-methyl-5-heptene-2-ketone, ethyl acetate, and furfural.

Table 1. Studies examining the VOC profiles resulting from recipe modifications through the enrichment of foods.
Tablo 1. Yemek tariflerinin, yiyeceklerin zenginleştirilmesi yoluyla yapılan değişikler sonucunda ortaya çıkan UOB profillerini inceleyen çalışmalar.

Food	Variables		Dominant VOCs	Methodology	Reference
Gluten-Free bread	Addition of cricket powder	Control	Crumb: Alcohols, ketones, aldehydes Crust: Aldehydes, pyrazines, alcohols	GC×GC-ToFMS	Wieczorek et al., 2022
		Cricket powder added	Crumb: Ketones, aldehydes, alcohols Crust: Aldehydes, pyrazines, alcohols		
Chesnut cream added muffin	Addition of sorbate	Control	Vanillin, 2-furanmethanol, furfural, nonanal, 2-pentyl furan	SPME-GC/MS	Boscaino et al., 2017
		Sorbate added	Vanillin, 2-furanmethanol, furfural, 2-pentyl furan, nonanal		
Bread (naan)	Addition of onion paste	Control	5-methylfuranal, 2-ethyl-5-methylpyrazine, butyl octyl lactone	SPME-GC/MS	Sireyil & Alim, 2022
		Onion paste added	2-decanone, eugenol, methyl octyl ketone, heptanone, undecane, geraniol		
Whole Sourdough Bread	Addition of cooked purple potato flour and Citrus albedo	Control	Acetic acid, hexanal, ethyl acetate, 2-pentyl furan, isopentyl alcohol	SPME-GC/MS	Taglieri et al., 2021
		8% cooked purple potato flour enriched	Acetic acid, furfural, 2-methylbutanal, isovaleraldehyde (syn. 3-methylbutanal), hexanal		
		8% cooked purple potato flour and 0.75% Citrus albedo enriched	Acetic acid, furfural, hexanal, isovaleraldehyde (syn. 3-methylbutanal), 2-methylbutanal		
"Ciabatta" Bread	Addition of powdered insects	Control	Hexanal, phenylethyl alcohol, 3-metil-1-butanolo, nonanal, 4-methyl-1-pentanal	SPME-GC/MS	Gaglio et al., 2021
		10% powdered buffalo worm larvae enriched	Hexanal, phenylethyl alcohol, 3-metil-1-butanolo, exanoic acid, nonanal		
		10% powdered mealworm larvae enriched	Hexanal, phenylethyl alcohol, exanoic acid, 4-methyl-1-pentanal, nonanal		
Bread	Addition of fermented cream	Control	3-methyl-1-butanol, hexanal, phenylethyl alcohol, 3-hydroxy-2-butanone, nonanal	SPME-GC/MS	Xu et al., 2022
		8% fermented cream enriched	3-methyl-1-butanol, phenylethyl alcohol, hexanal, benzaldehyde, nonanal		
Tomato Sofrito	Addition of herbs	Control	Di-2-propenyldisulfide, 3,4-dihydro-3-vinyl-1,2-dithii, 2-methyl-2-pentenal, methyl-2-propenyldisulfide, di-2-propenyltrisulfide	SPME-GC/MS	Beltrán Sanahuja et al., 2019
		0.0016% thyme enriched	Borneol L, 2-methyl-5-(1-methylethyl)-phenol, dipropyldisulfide, trans,trans-2,4-decadienal, trans-2-decenal		
		0.0016% rosemary enriched	Eucalyptol, camphor, dipropyldisulfide, trans, trans-2,4-decadienal, alpha-terpineol		

GCxGC-ToF-MS: Gas chromatography time of flight mass spectrometry, SPME-GC/MS: Solid phase microextraction/gas chromatography-mass spectrometry.

The previously mentioned experiments have examined the perceptible sensory effects detected when any modification is introduced to a certain recipe. Nevertheless, literature research suggests that VOCs are very responsive to alterations in food and recipe adjustments, to the extent that they can fluctuate even when various types or variants of the same component are used. Table 2 examines the alterations in VOC profiles that occur when several types of the same component are utilized.

Table 2. Studies examining the VOC profiles resulting from recipe modifications through using of different varieties of the same ingredient.

Tablo 2. Farklı çeşitlerde aynı malzemenin kullanılmasıyla yapılan tarif değişikliklerinin sonucunda ortaya çıkan UOB profillerini inceleyen çalışmalar.

Food	Variables		Dominant VOCs	Methodology	Reference
Wholemeal sourdough bread	Sourdough culture	Yeast activity and homofermentative / heterofermentative LAB	Ethanol, 3-methyl-1-butanol, phenylethanol, 2-methyl-1-propanol, acetaldehyde and 2,3-butanedione	GC-MS and PTR-MS	Warburton et al., 2022
		Obligate heterofermentative LAB	Acetic acid and acetate esters		
		Yeast activity	Aldehydes and lactones		
Bread dough	Grain type of flour	KAMUT® khorasan grain	1-hexanol, 2-butyl-2-octenal, 2-(1-methlypropyl)-phenol, 3-methly-benzoic acid	SPME-GC/MS and E-nose	Saa et al., 2019
		Durum wheat grain	2,5-dimethyl furan, ethylbenzene, 3-ethyl-2-methyl-1,3-hexadiene		
Bread	Sourdough culture	LAB/Yeast in 1.5 ratio	Ethanol, acetic acid, 3-Methyl-1-butanol, hexanal	SPME-GC/MS	De Luca et al., 2021
		LAB/Yeast in 3.3 ratio	Acetic acid, hexanal, ethanol, 3-methylbutanal		
		Yeast beer	Acetic acid, ethanol, 3-methylbutanal, hexanal		
Pizza	Sourdough culture	*L. curvatus*	5-methylfurfural, phenylethanal, furfuraldehyde	SPME-GC/MS	Francesca et al., 2019
		L. graminis	2-acetylfuran, phenylethanal, ethyl decanoate		
		L. plantarum	1- pentanol, pentanoic acid, furfuraldehyde, hexanal		
		Mixture of facultative heterofermentative species	Hexanal, octanoic acid, 2-phenylfuran, eptanoic acid		
		L. rossiae	3-methyl-1-butanol, phenylethyacetate, ethyl octanoate		
		L. sanfranciscensis	3-methyl-1-butanol, 1-hexanol, ethyl benzoate, acetic acid		
		L. brevis	Benzyl acetate, acetophenon, acetoin, 2-phenyl ethanol		
		Mixture of obligate heterofermentative species	Ethyl octanoate, acetoin, acetic acid, ethyl lactate		
		all six strains together	2-acetylfuran, 4-(2-butyl) phenol, trans-2-octenal, nonanal		
Bread	Flour type	Durum wheat	Acetic acid, isobutyl alcohol, diethyl ether	PTR-ToF-MS	Makhoul et al., 2015
		Bread wheat type «00»	Acetic acid, isobutyl alcohol, diethyl ether		
		Bread wheat type «0»	Acetic acid, isobutyl alcohol, diethyl ether		
		Manitoba flour	Acetic acid, isobutyl alcohol, propanol		
	Yeast type	Lesaffe	Acetic acid, isobutyl alcohol, diethyl ether		
		Pakmaya	Acetic acid, isobutyl alcohol, diethyl ether		
Bread	Sourdough culture	Fresh *Pediococcus pentosaceus* SP2	Ethanol, γ-Butyrolactone, ısoamyl alcohol, benzaldehyde, ethyl acetate	SPME-GC/MS	Plessas et al., 2020
		Freeze-Dried *Pediococcus pentosaceus* SP2	Ethanol, γ-Butyrolactone, benzaldehyde, 2-Phenylethanol, ethyl acetate		
		Immobilized *Pediococcus pentosaceus* SP2	Ethanol, γ-Butyrolactone, isoamyl alcohol, 2-Phenylethanol, ethyl acetate		
		Control / *Saccharomyces cerevisiae*	Ethanol, γ-Butyrolactone, 2-Phenylethanol, Isoamyl alcohol, ethyl acetate		
Bread	Genotypes of Sicilian durum wheat	Senatore Cappelli, Bidì, Saragolla	Toluen, ethyl tetradecanoate, phenol, 3-Methyl-1-butanol	SPME-GC/MS	Ruisi et al., 2021
		Vertola, Simeto, Tripolino	Toluen, phenol, benzaldehyde, 2-Ethylhexanol		
		Iride, Creso, Aziziah	Toluen, 3-Methyl-1-butanol, methyl decanoate, 1-Octanol		
		Realforte rosso, Scorsonera, Perciasacchi	Hexanoic acid, benzyl alcohol, octanoic acid, ethyldodecanoate		
		Timilia, Russello, Biancuccia	Decanoic acid, hexanoic acid, 2-Octen-1-ol, nonanal		

E-nose: Electronic nose, GC-MS: Gas chromatography–mass spectrometry, GC-TOF-MS: Gas chromatography-time-of-flight-mass spectrometry, HS-GC-IMS: Headspace gas chromatography-ıon mobility spectrometry, PTR-MS: Proton transfer reaction–mass spectrometry, PTR-ToF-MS: Proton transfer reaction time-of-flight mass spectrometer, SPME-GC/MS: Solid phase microextraction/gas chromatography-mass spectrometry.

Table 2. Studies examining the VOC profiles resulting from recipe modifications through using of different varieties of the same ingredient (continue).

Tablo 2. Farklı çeşitlerde aynı malzemenin kullanılmasıyla yapılan tarif değişikliklerinin sonucunda ortaya çıkan UOB profillerini inceleyen çalışmalar (devamı).

Food	Variables		Dominant VOCs	Methodology	Reference
Bread	Flour type and Sourdough culture	Semolina based flour-Mixed flour sourdough	Phenylethyl alcohol, ethanol, furfural, 2-furancarboxaldehyde, 5-methyl	SPME-GC/MS	Molfetta et. al., 2021
		Semolina based flour-Traditional wheat flour sourdough	Phenylethyl alcohol, ethanol, furfural, 2-nonenal		
		Semolina based flour with no sourdogh- control	Phenylethyl alcohol, ethanol, furfural, octanoic acid		
		Mixed flour (durum wheat semolina, barley, oat, rye, and buckwheat)- Mixed flour sourdough	Phenylethyl alcohol, furfural, benzyl alcohol, 2-furancarboxaldehyde, 5-methyl		
		Mixed flour (durum wheat semolina, barley, oat, rye, and buckwheat)- Traditional wheat flour sourdough	Phenylethyl alcohol, furfural, benzyl alcohol, octanoic acid, ethyl ester		
		Mixed flour (durum wheat semolina, barley, oat, rye, and buckwheat) with no sourdough - control	Phenylethyl alcohol, furfural, benzyl alcohol, octanoic acid, ethyl ester		
Wheat Bread	Sourdough type	Lentil sourdough	Ethanol, 1-hexanol, furfural, 3-methyl-1-butanol, hexanal	GC–MS	Perri et al., 2021
		Sprouted lentil sourdough	Ethanol, 1-hexanol, furfural, benzylalcohol, hexanal		
		Control- no sourdough	Ethanol, 3-methyl-1-butanol, hexanal, furfural, nonanal		
Bread	Sourdough type	Sourdough with *L. Lactis*	2-octen-1-ol, 2,4-nondienal, phenylethyl alcohol, benzaldehyde, acetoin	GC–MS	Wu et al., 2022
		Sourdough with *L. Lactis* and corn oil	Ethyle lactate, 1-hexanol, acetoin, hexanoic acid, 2-nonenal		
		Regular - control	Indole, 2-methoxy-4-vinylphenol, 3-methyl-1-butanol, 1-hexanol		
Bread	Type of LAB in fermentation	*Saccharomyces cerevisiae* - control	Ethanol, isopentanol, 2-heptanone, ethyl acetate, 2-pentanone, hexanal	HS-GC–IMS	Hu et al., 2022
		S. cerevisiae and *Lactiplantibacillus plantarum*	Ethanol, ısopentanol, ethyl 2-hydroxypropanoate, ethyl acetate, 2-heptanone, 2-pentanone		
		S. cerevisiae and *L. delbrueckii*	Ethanol, ısopentanol, 2-heptanone, 2-butanone, 2-pentanone		
		S. cerevisiae, L. plantarum, and *L. delbrueckii*	Ethanol, isopentanol, 2-heptanone, 2-pentanone, 2-butanone,		
Bread	Flour type	52% wheat flour	Acetic acid, hexanal, ethyl acetate, 2-pentyl furan	SPME-GC/MS	Sanmartin et al., 2020
		47% wheat flour and 5% flaxseed cake flour	Ethyl acetate, isobutyl alcohol, 2-butanone, hexanal		
		44,5% wheat flour and 7,5% flaxseed cake flour	Ethyl acetate, 2-butanone, isobutyl alcohol, hexanal		
		42% wheat flour and 10% flaxseed cake flour	2-butanone, ethyl acetate, furfural, dihydro-2-methyl-3(2H)-furanone		
Bread	Sourdough type	Traditional sourdough	Ethanol, γ-butyrolactone, 2-phenylethanol, furfural, benzaldehyde	SPME-GC/MS	Kazakos et al., 2022
		Sourdough with *Lacticaseibacillus paracasei* SP5	Ethanol, γ-butyrolactone, butyl acetate, benzaldehyde, 2-phenylethanol		
Cooked Chicken	Strain of chicken	Leghorn- slow growing	Ethanal, 1,2-butadiene, 1,4-hexadiene, butanal, hexanal	PTR-ToF-MS	Mancinelli et al., 2021
		Hubbard- medium growing	Ethanal, 1,2-butadiene, 1,4-hexadiene, butanal, butene		
		Naked Neck- medium growing	Ethanal, 1,2-butadiene, 1,4-hexadiene, butanal, butene		
		Ross 308- fast growing	Ethanal, 1,2-butadiene, 1,4-hexadiene, butanal, butene		

E-nose: Electronic nose, GC-MS: Gas chromatography–mass spectrometry, GC-TOF-MS: Gas chromatography-time-of-flight-mass spectrometry, HS-GC-IMS: Headspace gas chromatography-ıon mobility spectrometry, PTR-MS: Proton transfer reaction–mass spectrometry, PTR-ToF-MS: Proton transfer reaction time-of-flight mass spectrometer, SPME-GC/MS: Solid phase microextraction/gas chromatography-mass spectrometry.

Table 2. Studies examining the VOC profiles resulting from recipe modifications through using of different varieties of the same ingredient (continue).

Tablo 2. Farklı çeşitlerde aynı malzemenin kullanılmasıyla yapılan tarif değişikliklerinin sonucunda ortaya çıkan UOB profillerini inceleyen çalışmalar (devamı).

Food	Variables		Dominant VOCs	Methodology	Reference
Braised pork	Meat type and lean meat and fat fractions	Jinan (JN)	Lean meat: Fenchyl alcohol, octanoic acid ethyl ester, phenol, linalool Fat: Linalool, camphene, 3-carene, β-phellandrene	GC-MS and E-nose	Da et al., 2021
		Chengdu (CD)	Lean meat: 3-darene, 3-methyl phenol, butanoic acid, acetic anhydrate Fat: α-phellandrene, 2-pinene, 4-methyl phenol, α-terpineol		
		Xiamen (XM)	Lean meat: Nonanoic acid, propanoic acid, 1-(4-methoxyphenyl)-2-propanone, trans-2-undecenal Fat: 1-(4-methoxyphenyl)-2-propanone, 2-methyl 1-propanol, benzeneethanol		
		Hangzhou (HZ)	Lean meat: 1-(2- furanly) ethanone, butyrolactone, 1,4-dichlorobenzene, 2-furanmethanol Fat: 2-furanmethanol, ısoamyl alcohol, 2,5-dimethyl-pyrazine, trimethyl-pyrazine		
		Shijiangzhuang (SJZ)	Lean meat: Trimethyl-pyrazine, 1,4-dichlorobenzene, 2-furanmethanol, butyrolactone Fat: 2-furanmethanol, 4-methyl-1-(1-methylethyl)-3-cyclohexen-1-ol, benzeneethanol, 1-pentanol		
		Beijing (BJ)	Lean meat: 6-nonenal, 2-octenal, phellandrene, 3,7-dimethly 1,3,6 octatriene Fat: 3,7-dimethyl-1,3,6-octatriene, 1-hexanol, benzaldehyde, β-myrcene		
		Shanghai (SH)	Lean meat: Camphene, anethole, 1,4-dichlorobenzene, linalool Fat: 1,4-dichlorobenzene, anethole, benzaldehyde, 4-methoxy-benzaldehyde		
		Meizhou (MZ)	Lean meat: α-copaene, 4-methoxy-bezaldehyde, limonene, anethole Fat: 1-hexanol, 1-pentanol, 4methoxy-benzaldehyde, 2-methoxy-4-(2-propenyl)-phenol		
		Changsha (CS)	Lean meat: Isoamyl alcohol, DL-limonene, α-pinene, 2,6-dimethyl-pyrazine Fat: Isoamyl alcohol, anethole, 5-methyl-2-furancarboxaldehyde,		
		Guangzhou (GZ)	Lean meat: 2,6-decadienal, trans-2-undecenal, phenylethyl alcohol, 1,8-cineole, Fat: Benzeneethanol, linalool, 2-furanmethanol, 2,5-dimethyl-pyrazine		
		Wuxi (WX)	Lean meat: Butyrolactone, 2,6-dimethyl-pyrazine, methyl-pyrazine, 1,8-cineole Fat: 3-phenyl-2-propenal, 2,5-dimethyl-pyrazine, trimethyl-pyrazine, 1,8-cineole		
		Shenyang (SY)	Lean meat: Acetic acid, 5-methylfurfural, butyrolactone, hexanoic acid ethyl ester Fat: 5-methyl-2-furancarboxaldehyde, 1,4-dichlorobenzene, camphene, 3-carene		
Chinese blanched chicken	Distinct parts of chicken	Skin	Ethanol, 1-hexanol, pentane, methyl propionate	GC-TOF-MS	Xu et al., 2020
		Thigh	Ethanol, octane, 1-hexanol, 1-pentanol		
		Head	Ethanol, 1-butanol, 3-methyl-, 1-hexanol, propanoic acid, pentyl ester		
		Breast	1-Hexanol, 2-octanol, 1-pentanol, 1-butanol, 3-methyl-		
		Butt	Ethanol, 1-hexanol, pentane, 1-pentanol		

E-nose: Electronic nose, GC-MS: Gas chromatography–mass spectrometry, GC-TOF-MS: Gas chromatography-time-of-flight-mass spectrometry, HS-GC-IMS: Headspace gas chromatography-ıon mobility spectrometry, PTR-MS: Proton transfer reaction–mass spectrometry, PTR-ToF-MS: Proton transfer reaction time-of-flight mass spectrometer, SPME-GC/MS: Solid phase microextraction/gas chromatography-mass spectrometry.

After reviewing the literature, it has been noted that research on bakery goods primarily focuses on the variety of flour and sourdough types. Sourdough is a traditional type of starter that has been used for a long time to make baked items rise. It contains a variety of microorganisms, including yeasts, lactic acid bacteria (LAB), and acetic acid bacteria (AAB) (Arora et al., 2021; De Vuyst et al., 2023). The study done by De Luca et al. (2021) investigated the volatile organic compounds produced during bread manufacturing using various combinations of yeast and LAB bacteria. Breads with a LAB/Yeast ratio of 1.5 had the greatest quantities of alcohols and alkanes, whereas bread prepared with beer yeast had the highest concentrations of aldehydes. A separate investigation utilized a sourdough that consisted of six distinct *Lactobacillus* species to ferment pizza dough (Francesca et al., 2019). Pizzas that included optional heterofermentative *Lactobacillus* species in the sourdough exhibited elevated concentrations of furfuraldehyde, benzaldehyde, 2-ethylhexanol, and phenyl ethanal. Conversely, the presence of obligatory heterofermentative *Lactobacillus* species resulted in the identification of benzyl acetate, acetic acid, and 3-methyl-1 butanol in the pizzas. The choice of flour and the specific grain used to produce the flour can affect the VOC composition of dough and dough-based meals. This has been demonstrated in studies conducted by Makhoul et al. (2015), Saa et al. (2019), Ruisi et al. (2021), and Molfetta et al. (2021). The study executed by Sanmartin et al. (2020) involved the preparation of bread recipes utilizing wheat and flaxseed cake flours. The VOC profile analysis of the study showed that the presence of acetic acid, which is most abundant in bread baked with sourdough and wheat flour, decreased when flaxseed flour was added. Nevertheless, the concentration of 2-butanone, isobutyl alcohol, and furan compounds exhibited a rise with the addition of flaxseed flour. The study conducted by Ruisi et al. (2021) observed alterations in the VOC profiles and primary constituents of the end bread product when 15 distinct durum wheat genotypes were employed in the breadmaking process. This suggests that VOC profiles are responsive to differences in flour and grain types. There are studies available that investigate the combined impact of different types of flour and differences in sourdough culture. The study conducted by Molfetta et al. (2021) examined the synergistic impact of different types of flour and changes in sourdough culture. Flours made from semolina and a mixture of durum wheat semolina, barley, oat, rye, and buckwheat were utilized. Additionally, sourdough cultures made from conventional wheat flour and a mixture of flours were employed. Analysis of VOCs in breads made with various combinations revealed that the inclusion of sourdough had a smaller impact on the VOC profiles of bread compared to the specific type of flour utilized.

Research on meat products has shown that differing species can lead to changes in the types and quantities of VOCs present (Xu et al., 2020; Mancinelli et al., 2021; Da et al., 2021). The study reported by Xu et al. (2020) examined the influence of boiling five distinct chicken parts on the resulting VOC profile. The findings indicated that the volatile chemicals and their amounts in Chinese blanched chicken differ depending on the chicken parts used, resulting in alterations in the aroma and sensory characteristics of the product. The analysis indicated chicken breast meat as the most favored portion. The study conducted by Da et al. (2021) found that the VOC profiles of braised pig meals might differ depending on the location where the pork was obtained. These differences can be detected by sensory qualities. All research highlights that even the smallest alterations in recipes and components have a significant effect on the VOC profile.

The researches given in Table 1 and Table 2 have consistently shown that even little changes made to food recipes can result in significant or minor changes to the final VOC composition of the product.

3.2 Changes in VOC Profile Based on Cooking Methods

Most VOCs in meat are generated through the Maillard reaction, lipid oxidation, and thiamine degradation, with the cooking method significantly influencing their formation. Aldehydes from lipid degradation are particularly sensitive to cooking methods, contributing to the meat's characteristic flavor (Song et al., 2011). Different cooking methods result in various VOCs in chicken breast, including esters, aldehydes, and alcohols. Ethyl acetate and methyl octanoate are key esters for chicken flavor. Yu et al. (2021) studied the effects of boiling, frying, and roasting on VOCs in Piao chicken breast. They found that boiling produced higher peak concentrations of nonanal, octanal, heptanal, hexanal, and valeraldehyde compared to frying and roasting. The levels of 1-octen-3-ol and n-hexanol were similar in boiling and frying but higher in roasting. Roasting also resulted in significantly higher levels of methylthiopropionaldehyde, benzaldehyde, acetone, 2-butanone, γ-butyrolactone, and 2-ethylfuran compared to boiling and frying.

Bi et al. (2021) used GC-IMS to analyze VOCs in Gushi chicken breast after stewing and air frying. They found that aldehydes and volatile alcohols varied significantly with cooking methods. (E)-2-octenal was a key aldehyde in stewed chicken, making up about 4.71% of the total VOCs. Stewing also increased the content of 1-octen-3-ol, n-hexanol, and trans-2-hexen-1-ol compared to air frying. Air-fried chicken had unique VOCs like benzene acetaldehyde and 3-(methylthio) propionaldehyde. Zhou et al. (2022a) studied VOCs in Fuliji roast chicken during frying and stewing. Frying increased hexanal, nonanal, octanal, heptanal, 2-heptanone, 3-octanol, 1-octen-3-ol, 1-pentanol, and ethyl acetate, linked to lipid oxidation. Stewing increased benzaldehyde, nonanal, octanal, isovaleral, methylheptenone, and other compounds, indicating lipid oxidation of aldehydes and ketones.

Studies have examined VOC profiles in deep frying and air frying methods. High-temperature frying imparts unique flavors due to crust formation, lipid oxidation, and the Maillard reaction (Bou et al., 2012). Air frying significantly reduces fat content (Shaker, 2015), altering the VOC profile. Cao et al. (2020) found that air-fried chicken nuggets have fewer VOCs compared to deep-fried ones. Deep frying increases aldehyde content due to immersion in oil, with (E,E)-2,4-decadienal being the most abundant aldehyde in both methods, resulting from linoleic acid oxidation.

The literature shows that fish cooked using various methods predominantly have aldehydes and ketones as VOCs. Chen et al. (2021) reported that VOCs in tilapia muscles significantly decreased after microwaving, roasting, steaming, and boiling, especially aldehydes. 1-octen-3-ol was minimally affected. Ketones, from the oxidation of polyunsaturated fatty acids or amino acid degradation, increased after cooking, with the highest increase seen after roasting. Jin et al. (2023) studied Coregonus peled meat cooked by boiling, steaming, roasting, frying, and sous vide. Aldehydes were the most dominant VOCs, particularly hexanal, which was higher in the steaming and sous vide groups. Sous vide had the highest total aldehyde content, indicating increased unpleasant odors. Frying resulted in a more pleasant odor, with ketones being the second most dominant VOC, especially higher in the frying process.

Yang et al. (2023) studied the effects of steaming (100°C), boiling (100°C), frying (160°C), and high-pressure steaming (121°C) on crayfish (*Procambarus clarkii).* Different heat treatments significantly affected VOC content. Ketones, high in raw crayfish, disappeared after boiling, frying, and high-pressure steaming. Aldehydes, especially benzaldehyde and nonanal, were predominant in all methods, with the highest content in fried crayfish. Boiled crayfish had the highest hydrocarbon content, while steamed crayfish had more oxygen-containing compounds.

The impact of different cooking methods on VOC formation in cooked vegetables has been studied. Sweet potatoes, the third most important crop globally, are typically prepared by steaming, boiling, or baking (Vollmer et al., 2022). These methods alter their chemical components (Franková et al., 2022). Zhang et al. (2023) investigated the effects of baking, boiling, and steaming on the taste, aroma, and chemical composition of sweet potatoes. Predominant VOCs were aldehydes and terpenes, including hexanal, (E)-2-heptenal, benzaldehyde, benzeneacetaldehyde, (E)-2-nonenal, decanal, and sesquiterpenes. Few furans were detected in steamed and boiled samples, while furfural, 2-furanmethanol, and 2-acetylfuran were predominantly found in baked samples.

A study examined the impact of different cooking methods on the VOCs of garlic, focusing on sulfur compounds, which degrade at high temperatures (Kuettner et al., 2002). Bi et al. (2023) used GC-IMS to analyze garlic VOCs after steaming, frying, boiling, and roasting. Significant differences in sulfur compounds were observed. Fried garlic had the highest sulfur and thioether content, while steamed garlic had the lowest. Aldehydes were the major VOCs after sulfur compounds. Roasted garlic had significantly higher levels of hexanal, pentanal, heptanal, and caprylaldehyde compared to other methods.

Table 3. Studies examining the VOC profiles resulting from cooking methods.
Tablo 3. Pişirme yöntemine bağlı olarak farklı UOB'lerin oluşumunu inceleyen çalışmalar.

Food	Cooking Method	Dominant VOCs	Methodology	Reference
Chinese Piao Chicken	Boiling	Nonanal, Octanal, Heptanal, Hexanal, Valeraldehyde	GC-MS, UPLC-Q-Exactive-MS, GC-IMS	Yu et al., 2021
	Frying	n-Hexanol, n-Pentanol dimer, 2-Heptanone		
	Roasting	Phenylacetaldehyde, Furfural, Etanol, γ- Butirolakton		
Chicken Breast	Stewing	2-ethyl-1-hexanol, (E)-2-octenal, ethyl acetate, 1-octen-3-ol, n-hexanol,	GC-IMS	Bi et al., 2021
	Air Frying	Benzene acetaldehyde, 3-methylthiopropionaldehyde, (E)-2-octenal		
Fulji Chicken	Frying	Hexanal, nonanal, octanal,1-octen-3-ol, ethyl acetate	GC-IMS	Zhou et al., 2022a
	Stewing	Benzaldehyde, nonanal, octanal, methylheptenone, ethyl acetate		
Chicken Nuggets	Air Frying	(E,E)-2,4-decadienal, 2-Undecenal, (Z)-2-Decenal, Nonanal, D-Limonene	HS-SPME-GC-MS	Cao et al., 2020
	Deep Frying	(E,E)-2,4-decadienal, 2,4-Decadienal, 2-Undecenal, (Z)-2-Decenal, β-Caryophyllene		
Tilapia	Microwaving	Methyl-cyclohexane, 5-Methyl-2-heptene	E-nose, HS-SPME-GC-MS, HS-GC-IMS	Chen et al., 2021
	Roasting	Methyl-cyclohexane, *Trans*-2-ethyl-2-hexen-1-ol, Subtotal, 5-Amino-pentanol, Cis-1,3-dimethyl-cyclohexane		
	Steaming	Hexane, 2,4,4-Trimethyl-1-pentene		
	Boiling	(E)-2-Octen-1-ol, Methyl-cyclohexane, 2,3,3-Trimethyl-1,4-pentadiene, 1,2-Dimethyl-cyclohexane, 1,4-Dimethyl-cyclohexane		
Coregonus Peled	Frying	Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone, Acetone	E-nose, GC-IMS	Jin et al., 2023
	Roasting	Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone, Acetone		
	Steaming	Octanal, Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone		
	Microwaving	Octanal, Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone		
	Sous-Vide	Octanal, Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone		
	Air Frying	Octanal, Heptanal, Hexanal, 1-Penten-3-ol, 2-Butanone		
Crayfish	Steaming	Benzaldehyde, Nonanal	HS-SPME-GC-MS	Yang et al., 2023
	Boiling	Benzaldehyde, Nonanal, 2,4-Dekadienal		
	Frying	Benzaldehyde, Nonanal, 2,4-Dekadienal, 1-Octen-3-ol		
	High Pressure Steam	Benzaldehyde, Nonanal		
Sweet Potato	Baking	Hexanal, (E)-2-heptenal, benzaldehyde, (E)-2-nonenal, decanal sesquiterpenes	SPME-GC-MS	Zhang et al., 2023
	Boiling	Hexanal, (E)-2-heptenal, benzaldehyde, (E)-2-nonenal, decanal sesquiterpenes		
	Steaming	Hexanal, (E)-2-heptenal, benzaldehyde, (E)-2-nonenal, decanal sesquiterpenes		
Garlic	Boiling	Diallyl disulfide, 1-Propenyl propyl Disulfide, Allyl methyl disulfide, Cis-bis-(1-Propenyl) Disulfide, Prop-1-ene-3,3′ -thiobis	GC-IMS	Bi et al., 2023
	Frying	Methyl2-methyl-3- furyl disulfide, 1-Propenyl propyl disulfide, Methyl propyl trisulfide, Diallyl disulfide, (E)-hept-2-enal		
	Steaming	Ethyl phenylacetate, 1-Propenyl propyl disulfide, Cis-bis-(1-Propenyl) disulfide, Diallyl isulfide, Prop-1-ene-3,3′ -thiobis		
	Roasting	Ethyl phenylacetate, 1-Propenyl propyl disulfide, Diallyl disulfide, Allyl methyl disulfide, Prop-1-ene-3,3′ -thiobis		

E-nose: Electronic nose, GC-MS: Gas chromatography–mass spectrometry, GC-IMS: Gas chromatography-ion mobility spectrometry, HS-SPME-GC-MS: Headspace-solid phase microextraction/gas chromatography-mass spectrometry, SPME-GC/MS: Solid phase microextraction/gas chromatography-mass spectrometry, UPLC-Q-Exactive-MS: Ultraperformance liquid chromatography plus Q-Exactive tandem mass spectrometry.

3.3 Changes in VOC Profile Based on Process Parameters

The most frequently preferred method in food processing is heat treatment, which creates an attractive flavor profile for foods (Aaslyng & Meinert, 2017). During the cooking process of foods, processes related to heat treatment, such as the Maillard reaction, oxidation and degradation of lipids, and caramelization, significantly affect the formation of VOCs, and these reactions are largely affected by process parameters such as application time and temperature (Palermo et al., 2014).

Studies in the literature have investigated the impacts of various time and temperature combinations concerning process parameters. In the study conducted by T. Zhou et al. (2022b) simulated meat systems containing linoleic acid were established, and heating processes were carried out under different conditions. To compare the effects of various heating parameters on flavor, heating processes of 30 or 60 minutes were conducted at 50, 70, and 90 °C. Aldehydes were found to be predominant, rapidly increasing in the early stages of heating but decreasing in aldehyde content after 60 minutes. Ketones and alcohols were reported as the most dominant VOCs, especially with an increase in temperature, the quantity of 1-octen-3-ol increased. The impact of high-temperature heating on the VOC profile appears to be more influenced by temperature rather than time, suggesting that polymerization triggered by high temperature plays a more significant role.

Heating pork at different time and temperature combinations affects the amount of VOCs. While an increase in temperature generally has a positive impact on VOCs, an increase in time typically exhibits a negative effect. In the study conducted by Del Pulgar et al. (2013) pork cheeks were cooked using the sous vide cooking technique at 60 and 80 °C for 5 and 12 hours. The VOCs exhibited the highest levels in samples cooked at 80°C for 5 hours and the lowest levels in samples cooked at 80°C for 12 hours. VOCs influenced by lipid oxidation are affected by both time and temperature conditions, and in the advanced stages of the lipid oxidation process, VOCs predominantly form, such as heptanal, octanal, 2-octanone, and nonanal. In another study, the impact of cooking with superheated steam on VOCs was examined depending on temperature and time conditions (Wang et al., 2019). Various reactions during cooking led to the formation of sulfur compounds and heterocyclic compounds. Particularly at high temperatures, such as 160 and 180 °C for a duration of 20 minutes, nitrogen-containing heterocyclic compounds became dominant. In samples cooked with superheated steam, an observed decrease in the VOC profile of the samples was noted as the cooking duration extended. Up to a cooking time of 20 minutes, a reduction in the amount of volatile compounds within the samples was indicated. Similarly, in the study conducted by Bi et al. (2022) it was observed that the VOCs decreased with increasing duration. Pork samples were subjected to steam treatment for 30 and 180 minutes. Aldehyde contents were dominant in both cooking durations, especially hexanal and heptanal contents were significantly increased, but they were observed to be relatively lower at 180 minutes compared to 30 minutes.

In the study conducted by Ge et al. (2020) investigating the effect of hot air drying temperature on VOCs, the difference between the parameters of 60, 70 and 80 °C has been examined. This study has demonstrated a significant increase in the content of 2-acetylfuran and 2-ethylfuran with the rise in temperature (60-80 °C). In comparison to other VOCs, most aldehydes exhibited the lowest content in samples dried at 80 °C under the same moisture content. Furthermore, it has been found that the change in VOCs is closely associated with temperature, and the majority of VOCs decrease with the increase in drying temperature (60-80 °C) at the same moisture content. However, high drying temperature has supported the formation of ethyl octanoate, methyl octanoate, benzaldehyde, furfural, acetal, 5-methylfurfural, and 2-acetylfuran due to Maillard reaction and Strecker degradation. These VOCs have shown the highest content at 80 °C.

In a study conducted by Cheng et al. (2022), the effects of sous vide braising at different temperature and duration conditions on chicken meat were investigated. Process parameters included 75 °C for 2 hours and 3 hours, and 65 °C for 3 hours and 4 hours. Despite examining these variations, the study concluded that the differences had a minimal impact on the VOCs. The primary volatile components identified in the sous vide braised chicken samples were 1-pentanol, heptanal, octanal, n-nonanal and pentanal.

In the study by Natrella et al. (2022), stretching mozzarella cheese at 70 °C resulted in approximately five times more total VOCs than stretching at 90 °C. Specifically, ketones and alcohols were eight and four times more abundant, respectively, at 70 °C. This difference is due to reduced microbial activity at lower temperatures, allowing more VOCs to develop during cooling. In contrast, the higher temperature at 90 °C suppressed microbial activity, leading to lower VOC levels.

Although extensive research has examined the effects of temperature and duration on food processing, other parameters also play a role. Truong et al. (2022) investigated the impact of thermal, physical, and enzymatic processing methods on the VOCs in asparagus juice. They found that both thermal and enzymatic methods increased ester levels but decreased concentrations of alcohols and aldehydes, such as 2-hexanal and heptanal. In another study on fruit juice, the effects of different pasteurization techniques were examined. Rodríguez et al. (2021) compared the effects of ohmic heating and conventional heating on carrot juice. They observed that conventional heating (80°C–7 minutes) led to higher levels of sesquiterpenes and lower levels of monoterpenes. In contrast, the VOC profile of ohmic heating-treated carrot juice was similar to the control but with reduced levels of sabinene and α-bergamotene. In a study conducted by Ferreira et al. (2019), whey-based beverages treated with ohmic heating exhibited a more complex and diverse VOC profile compared to those processed using conventional heating methods. OH treatment, especially under conditions such as 1000 Hz-25 V and higher voltages, significantly contributed to the formation of esters, alcohols, carboxylic acids, and furan derivatives. The results indicated that thermal and chemical processes like the Maillard reaction and caramelization influenced the development of these compounds. Notably, furfural, 5-hydroxymethylfurfural, and dihydroxyacetone were detected in all samples subjected to ohmic heating. Additionally, aromatic compounds such as terpenes and furan derivatives were more prominent at higher voltages, suggesting that ohmic heating enhances the formation and preservation of VOCs.

In another study, the effects of ultrasonic power across various parameters were examined. Bao et al. (2022) investigated the effects of different ultrasonic power levels (0, 200, 300, and 400 W at 20 kHz) on VOCs in dry-cured yak meat. Alcohol content significantly increased in treated groups, although no significant differences were noted among the 200 W, 300 W, and 400 W levels. Aldehyde content rose with higher power due to lipid oxidation, while hydrocarbon content decreased at 400 W. Additionally, higher ultrasonic power increased ketone levels, linked to amino acid degradation and fatty acid oxidation.

In the study conducted by Benozzi et al. (2015), process parameters were examined by utilizing different starter cultures to assess their impact on the formation of VOCs during fermentation. Utilizing the PTR-ToF-MS technique for real-time monitoring, the research revealed significant variations in the aroma profiles depending on the specific starter cultures employed. Key VOCs, such as acetaldehyde, methanethiol, butanoic acid, 2-butanone, diacetyl, acetoin, heptanoic acid, and benzaldehyde, demonstrated culture-dependent fluctuations in concentration.

In a study conducted by Wang et al. (2021), the effects of different slaughter methods on VOC formation in sea bass (*Lateolabrax japonicus*) were investigated. The slaughter method was found to influence the formation of volatile compounds in sea bass for various reasons. Methods that caused more stress on the fish led to increased lipid oxidation, raising the levels of volatile compounds such as aldehydes. Additionally, the slaughter method affected the sea bass's ketone and alcohol content, with some methods increasing ketone levels while others raised alcohol levels. The formation of esters also varied depending on the method used.

4.Variability of VOC Profiles Throughout The Process

It is well known that the perception of taste and aroma in the final food product is strongly linked to the VOCs emitted from the food (Aghili et al., 2023). As mentioned earlier, VOC constituents are quite sensitive and can vary according on the recipe, cooking technique, and process conditions. From a wide viewpoint, it seems obvious that there is a diverse VOC profile not just in the end product but also throughout the whole process.

The baking process, particularly for baked goods, is essential for ensuring the ultimate quality and the taste of the finished product. During the process of producing bread, it has been noted that there is a changing profile of VOCs at different phases of fermentation and baking. The study conducted by Gancarz et al. (2021) evaluated the VOC constituents during the process of bread fermentation and baking at intervals of 15 minutes each. The concentration of alcohols raised throughout the process of fermentation, but declined during the process of baking. The concentration of hydrocarbons rose, while the levels of esters reduced during the baking process. The quantity of pyridazines remained constant until the 30th minute of baking, at which point it experienced a rapid increase. A recent research by Pico et al. (2020) examined the baking process of gluten-free bread by analyzing the VOCs emitted from five different bread samples. The investigation was done using PTR-MS and lasted for 40 minutes. During the process of baking bread, the Maillard reaction and caramelization processes cause a shift in the VOC profile. Furan derivatives were the prevailing compounds at the 20th minute of baking, but pyrazine derivatives took over during the 30-35 minute period. The observed profile change exhibited dynamism throughout the whole baking process.

Grilling is a prominent cooking technique employed for a variety of meats (Ježek et al., 2020). The theory was developed by considering the variability of VOC profiles and their correlation with the cooking state. The objective was to ascertain the amount of cooking in grilled chicken through the use of VOC chemicals and computer vision techniques (Fedorov et al., 2021). This study employed an electronic nose equipped with 8 distinct sensors to observe the chicken grilling process for a duration of 40 minutes. During the cooking process, alcohols, carbon monoxide (CO), and methane (CH_4) were the most prevalent substances, although their levels gradually decreased. The study showed that VOCs, when combined with computer vision techniques, may be used to classify cooking degrees as undercooked, well-cooked, and overcooked according to their resistance pattern.

Drying is a technique employed to eliminate moisture from food, hence enhancing its microbiological safety (Solchansanj et al., 2020). It is applicable to several food products categories, including meat and fruits. The study conducted by Kiani et al. (2018) examined the VOC profiles of mint leaves that were dried using hot air for a duration of 300 minutes. This investigation utilized an electronic nose (e-nose) that was equipped with 11 metal oxide semiconductor (MOS) sensors. During the drying process, the MOS sensors detected high levels of CO, ethanol, alcohols, methane, and hydrogen, and a noticeable reduction was noted. An analysis was conducted to examine the variations in aroma between fresh and dried mint leaves. Additionally, modeling techniques were employed to identify the ideal duration for drying the leaves. A different study was focused on clarifying the distinction in smell between grapes that are freshly harvested and those that have been dried in the sun. This was achieved by evaluating the VOC constituents (Javed et al., 2021). Aldehydes, alcohols, terpenes, and ketones were the primary components found in fresh grapes. However, these VOC groups diminished throughout the process of sun-drying, and instead, the formation of acids, furans, and pyrazines was detected. Consistent with these findings, fresh grapes had fruity and flowery fragrances, but dried grapes exhibited roasted and fatty fragrances. When it comes to grapes, it has been noted that the alteration in the VOC profile throughout the first and final stages of the drying process has a major effect on their taste.

The use of fermentation technology has been prevalent in the food business since it can not only preserve foods but also improve their taste characteristics and boost their nutritional content (Swain et al., 2014). Yogurt, cheeses, and acidified dairy products are derived from the lactic acid fermentation of milk, and they make up a substantial part of the dairy group (Widyastuti & Febrisiantosa, 2014). Soukoulis et al. (2010) examined the process of lactic acid fermentation in milk using Proton-transfer-reaction time-of-flight mass spectrometry (PTR-TOF-MS) for a duration of 300 minutes. The study found that lactic acid fermentation led to an increase in acetaldehyde, diacetyl, acetoin, and 2,3-pentanedione, whereas 2-propanone, 2-butanone, 2-pentanone, and 2-heptanone declined. Another notable kind of fermentation is ethanol fermentation, which serves as the foundation for the manufacturing of alcoholic drinks such as beer and wine (Wachełko et al., 2021). The study conducted by Richter and colleagues (2018) utilized PTR-ToF-MS for tracking the process of beer fermentation over a period of 80 hours. Upon examination of CO_2 and ethanol, it was seen that CO_2 initially increased during the initial 24-hour period of fermentation, but then declined. In contrast, ethanol had a consistent upward trend, reaching its peak value after 60 hours. The PTR-MS examination emphasized the importance of evaluating the groups that showed apparent and meaningful variations, highlighting the importance of monitoring the mass-to-charge ratio 145.121 (ethyl hexanoate) and 173.153 (isoamyl isovalerate or ethyl octanoate) groups during the beer production process.

Research has demonstrated that many food preparation techniques, including baking, grilling, drying, and fermentation, have been thoroughly investigated. It has been discovered that the resultant VOCs are closely linked to the quality of the food.

5. Future Perspectives

Volatile organic compounds (VOCs) are crucial in the food industry due to their significant role in flavor, aroma, and freshness. Specific VOCs are released by foods either gradually over time or as a result of any processing they undergo. This makes VOCs increasingly important in areas such as food quality, freshness, storage processes, and process control (Lin et al., 2024; Wang & Chen, 2024). It is observed that VOC sensors are widely used, and even electronic noses have been developed. There are numerous studies and models validated through the use of e-noses, which are based on VOC emissions from foods. There is a wide range of studies utilizing e-noses, such as quality classification in olive oil, detection of pesticide residues in soybeans, monitoring fermentation duration in wine, origin determination in cheese, and freshness tracking in chicken breasts (Conrado et al., 2021; Lin et al., 2022; Zhang et al., 2021; Lee-Rangel et al., 2022; Zheng et al., 2023).

Additionally, VOC sensors play a crucial role in intelligent food packaging. The main purpose of employing VOC sensors in intelligent packaging, as demonstrated by comprehensive research, is to oversee the longevity of the food item and precisely detect the release of certain VOC chemicals throughout its degradation. Furthermore, it is crucial to issue alerts to customers if they exceed a predetermined threshold amount. The deterioration of meat, poultry, and fish products is strongly linked to the rise in the generation of nitrogenous chemicals (Matindoust et al., 2021). Efforts in sensor development have therefore been concentrated on these specific chemicals. In their study, Yin et al. (2023) employed CO_2, O_2, and C_2H_4 sensors to observe the exchange of gases in storage spaces affected by microbial growth during the spoiling of apples.

VOC sensors are commonly employed for monitoring the expiration date of certain food products. These studies inquire into the feasibility of monitoring the cooking process, a crucial procedure in the food sector, and even examine the potential for automatically terminating the cooking at a certain stage. The topic of cooking is described as exceedingly versatile due to the utilization of diverse techniques and the fluctuation in both amount and ingredient modifications, resulting in significant variations in VOC profiles. The investigations conducted by Gancarz et al. (2021) and Pico et al. (2020) successfully monitored the VOCs produced during the process of bread baking. Moreover, a study conducted by Fedorov et al. (2021) employed VOC monitoring to determine the optimal cooking degree for a whole chicken. The integration of VOC sensors with image processing, artificial intelligence (AI), and camera systems offers great promise to completely transform the automation of cooking termination and the identification of process endpoints.

6. Conclusion

The complex nature of the cooking field emerges from its numerous variables and the temperature-dependent chemical reactions that take place in the meal. The intricate structure of the food also impacts the volatile organic compound characteristics they release. Modifying the ingredients or inserting a new ingredient into food has an effect on VOCs. The use of different cooking procedures, such as baking, boiling, or grilling, to the same food leads to different VOC profiles. This is because each cooking process causes distinct chemical changes in the food owing to its fundamental nature. Modifications in temperature and time variables within a singular cooking technique applied to identical food result in noticeable alterations in VOCs, namely those linked to temperature. Though the subject is complex, research on the evolution of cooking methods has great potential. The identification of indicator VOCs demonstrates the potential for automated cooking termination, similar to the reasoning used in intelligent packaging. This might provide customers more convenience. There is a possibility for collaboration with advanced technologies in this matter.

7. Conflicts of interest

The authors declare no conflict of interest.

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