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Effects of cooking methods on aroma formation in pork: A comprehensive review

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A B S T R A C T

Pork is widely consumed and appreciated by consumers across the world, and there are various methods of cooking pork. This study aimed to summarize the effects of different heat transfer media on pork flavor and the sources of flavor compounds. The cooking methods are classified based on the heat transfer media used, which include water and steam (e.g. steaming, boiling, and stewing), heat source or hot air (e.g. baking and smoking), oil (e.g. pan-frying, stir-frying, and deep frying), and other cooking technologies. The objective is to provide a reference for researchers studying pork cooking methods and flavor components.

1. Introduction

Pork is an important type of meat for human consumption due to its relatively soft texture, low connective tissue content, and high intramuscular fat levels. Global pork production in 2021 is projected to be 101,481 thousand metric tons, while global pork consumption is expected to be 100,853 thousand metric tons. China, as a major pork consumer, imported 1.76 million tons of pork in 2022, valued at 3.898 billion US dollars, according to data from General Administration of Customs of the P.R. China. https://www.customs.gov.cn/eportal/ui?pageId=302275.

Cooking is an essential step in food preparation, as it can improve the flavor, texture, and appearance of food, and enhance its nutritional value to meet people's diverse taste preferences (Chumngoen, Chen, & Tan, 2016; da Silva et al., 2017; Domínguez, Gómez, Fonseca, & Lorenzo, 2014; Özcan & Bozkurt, 2015; Yuan et al., 2022). Different heat treatment methods can impact the nutritional content and quality of food to varying degrees. Cooking methods can be classified according to the heat transfer media used (Lin, Chen, Liu, & Guo, 2021). For instance, cooking methods that use water and steam, such as steaming, boiling, and stewing, are one category. Cooking methods that involve direct contact with hot air or heat sources, such as baking and smoking, are another. Other cooking methods use oil as a heat transfer medium, such as frying, sautéing, and deep-frying. With the advancement of technology and improvement of living standards, many new processing technologies, such as microwave cooking, low vacuum cooking, and high-pressure processing, are increasingly used in food production.

This paper systematically reviewed the effects of different cooking methods on pork flavor and discussed the sources of flavor compounds that affect pork. This review will help gain more insight into pork flavor chemistry and can provide guidance for improving the flavor of pork and pork processing products. In addition, this review will provide a theoretical basis for the improvement of pork production technologies and quality.

2. Cooking methods and their effects on flavor generation

Raw meat has little or no aroma and only a salty, metallic and bloody taste, while cooked meat has unique and rich aroma with attractive taste. When meat is heated, non-volatile chemicals are converted into volatile ones. The volatile compounds formed during cooking determine the aroma characteristics of meat and contribute the most to its distinctive flavor. During the cooking process, a series of complex chemical reactions occur between the non-volatile components of fatty tissue and lean tissue, such as Maillard reaction and lipid oxidation, producing a large number of reaction products.

2.1. Maillard reaction mechanism

The Maillard reaction is a series of complex chemical reactions that occur when the carbonyl group of a reducing carbohydrate interacts with the amino group of free amino acids, peptides, or proteins (Fu, Zhang, Soladoye, & Aluko, 2020). The Maillard reaction is influenced by various factors, such as the type and concentration of reactants, time, pH

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(Ajandouz, Tchiakpe, Ore, Benajiba, & Puigserver, 2001), temperature (Lan et al., 2010), and water activity (Davidek, Marabi, Mauroux, Bauwens, & Kraehenbuehl, 2018). Different cooking methods result in different processing temperatures for pork. The Maillard reaction is composed of three main stages: early, intermediate, and final (Liu et al., 2020). The reaction starts with the condensation of reducing sugars with free amino acids to produce Amadori or Heyns rearrangement products. In the intermediate stage, hydroxymethylfurfural or dicarbonyl compounds and reducketones are formed at various pH values, leading to a cascade of reactions. In the final stage, a variety of Maillard reaction products, including volatile flavor compounds, brown pigments, or melanoids, are generated (Sohail et al., 2022) (Fig. 1). Due to the intricate process of the Maillard reaction, each reaction and reactant is sensitive to temperature in different ways (Liu et al., 2022).

Heating time and temperature in different processing methods could influence the intensity of Maillard reaction. The Maillard reaction is more intense at higher processing temperatures. Bhaskar et al. studied the Maillard reaction in meat under different cooking treatments, such as braising, autoclaving, sous vide, and oven roasting (Bhaskar, Rene, Ines, & Jorge, 2018). Furosine, an early Maillard reaction indicator, was detected at different temperature–time combinations. Research found that boiling and high-pressure samples showed a significant increase in furosine content. Nε-Carboxymethyl lysine, an advanced glycation end product indicator, also increased with cooking temperature. Samples cooked in the oven showed the highest levels of these indicators, followed by meat cooked with autoclave operations and braising, suggesting that temperature plays a significant role in the development of the Maillard reaction in meat.

To explore the formation of potential Maillard reaction products in stir-fried pork slices, changes in acrylamide and 5-hydroxymethylfurfural (5-HMF) content were analyzed in the samples (Wang et al., 2021). 5-HMF, an important Maillard reaction product, increased significantly, indicating that the Maillard reaction was robust. As heating and reaction time were prolonged, 5-HMF underwent further polymerization or degradation reactions to generate final products, leading to a gradual reduction in its content. Moreover, the pyrazine content also reflected the degree of the Maillard reaction during pork slice processing. Pyrraline is an advanced glycation end product (AGE), and its content increased with prolonged cooking time during stir-frying of meat slices.

The chemical and sensory characteristics of pan-fried pork flavor at 150 °C and 250 °C were studied (Meinert, Andersen, Bredie, Bjergegaard, & Aaslyng, 2007). At higher temperatures, the local dehydration exhibited by the meat accelerates the formation of Maillard-derived flavor compounds. Therefore, the barbecue flavor of pork fried at 250 °C is more intense, and the variety and content of Maillard-derived compounds, such as pyrazines, furans, and aldehydes, increase. However, as the heating temperature increases and the heating time prolongs, the content of harmful substances such as polycyclic aromatic hydrocarbons, heterocyclic aromatic amines, and cholesterol oxidation products in pork also increases (Buła, Przybylski, Jaworska, & Kajak-Siemaszko, 2019; Hung, Lee, Inbaraj, Sridhar, & Chen, 2021; Kim et al., 2022; Polak, Demšar, Zahija, & Polak, 2020; Zhang, Yu, Mei, & Wang, 2013). Therefore, choosing the appropriate frying temperature and time can not only accumulate a stronger barbecue flavor, but also greatly avoid the formation of harmful substances caused by high temperatures (Wang et al., 2021).

2.2. *Lipid oxidation*

Lipid oxidation is a significant biochemical reaction that occurs during the processing or storage of meat products. There are two primary modes of lipid oxidation: (1) direct oxidation of lipids that produce volatile substances; and (2) lipids are first degraded into glycerol, phosphoric acid, and free fatty acids, and then oxidized to form various products. Research has demonstrated that the second mode is the main lipid oxidation pathway in meat products, and direct lipid oxidation without degradation only accounts for a small proportion (Wang, 2009) (Fig. 2). Moderate lipid oxidation can impart excellent flavor to meat products. During processing, many volatile flavor substances in meat are produced by lipid oxidation, such as hexanal and benzaldehyde, which are primarily oxidation products of linoleic acid (Brewer, 2009). Aldehydes containing 6 to 10 carbon atoms have a lower sensory detection threshold and play a significant role in meat aroma. Evaluation of the degree of lipid oxidation is commonly achieved by determining primary and secondary oxidation products. Primary oxidation is typically determined through the measurement of peroxide value and conjugated dienes. Secondary oxidation is typically evaluated by measuring the substrate value of the thiobarbituric acid reaction. Furthermore, the degree of lipid oxidation can be assessed by measuring the amount of volatile compounds using GC–MS. The intensity of lipid oxidation in meat is dependent on the cooking method, temperature, and time (Broncano, Petrón, Parra, & Timón, 2009).

The impact of different cooking temperatures (Meinert et al., 2007), cooking methods (Broncano et al., 2009; Hur, Lee, Moon, & Lee, 2014; Ivic, Tomovic, Jokanovic, Skaljac, & Sojic, 2019; Soladoye et al., 2017; Wang et al., 2016), cooking times (Broncano et al., 2009), and storage times (Soladoye et al., 2017) on the formation of lipid oxidation products in pork were investigated. The results demonstrated that the

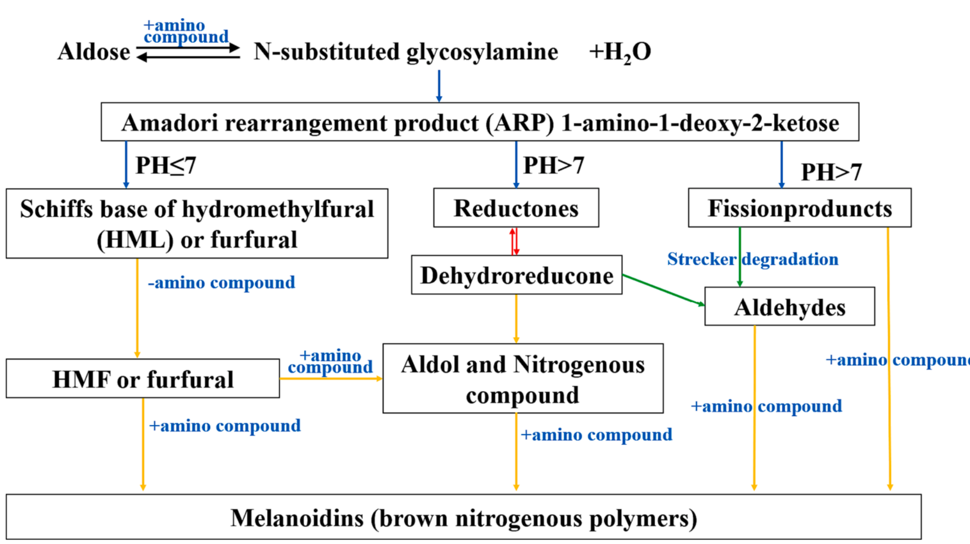

Fig. 1. Schematic diagram of Maillard reaction: Stages and key intermediates. Referred to (Liu et al., 2020).

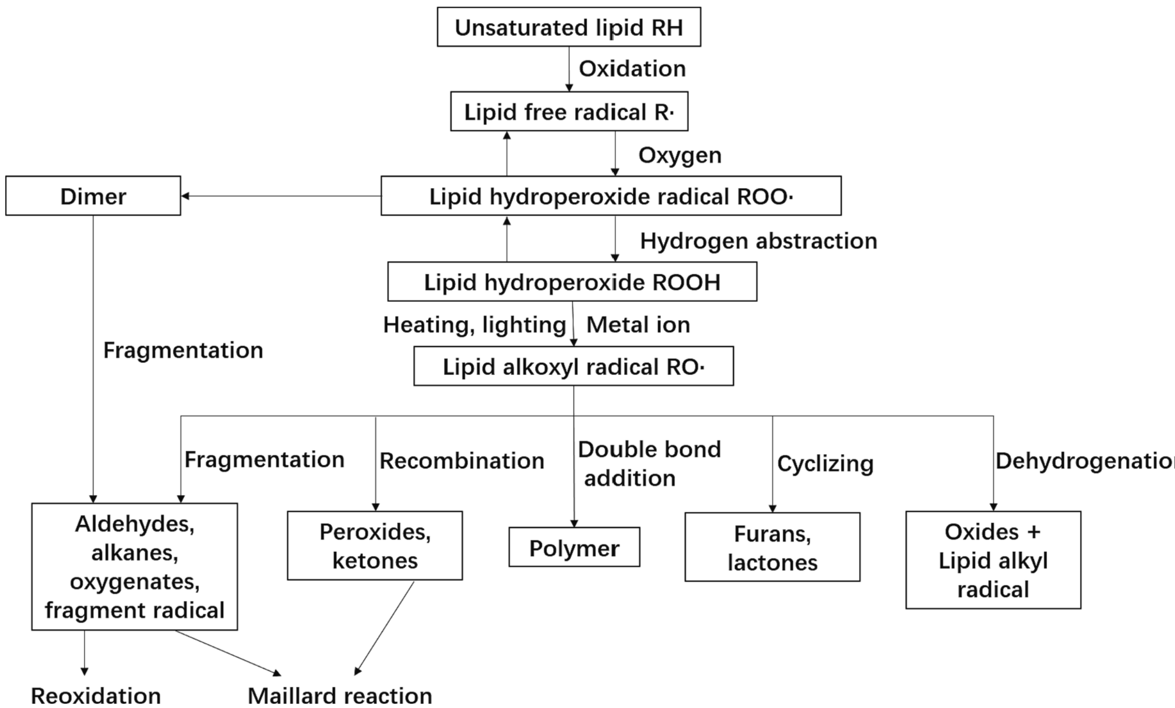

Fig. 2. Complex reactions involved in lipid oxidation and degradation.

peroxide value (POV) and thiobarbituric acid reactive substances (TBARS) values of cooked pork significantly increased, and lipid oxidation in pork increased with an increase in cooking temperature and time. The impact of shorter cooking time and higher temperature on the oxidation process was greater than that of longer cooking time and lower temperature. Roasted and fried meat exhibited the highest oxidation levels (Broncano et al., 2009; Soladoye et al., 2017; Wang, 2009; Wang et al., 2016). However, in a study by (Hur et al., 2014), due to the high heating efficiency, the meat cooked by microwave was heated more evenly than generally occurs in other cooking techniques, resulting in a significantly higher total lipid digestibility of samples cooked by microwave compared to that of meat patties cooked by other methods, The content of free fatty acids was significantly higher than those cooked by frying or boiling meat patties, indicating that the sample with the highest lipid oxidation was the microwave-cooked one. The interaction between microwaves and meat fat was also found to result in the oxidation of polyunsaturated fatty acids. The degree of lipid unsaturation and the content of free fatty acids in pork can also influence the formation of pork flavors (Song et al., 2017).

2.3. *Interaction between lipid and Maillard reaction*

Maillard reaction products can either promote or reduce lipid oxidation (Zamora & Hidalgo, 2011). Moreover, from a non-enzymatic browning perspective, the two pathways share common intermediates and polymerization mechanisms, and the products produced are similar (Zamora & Hidalgo, 2005). The saturated and unsaturated aldehydes generated from lipid oxidation interact with Maillard reaction products to produce heterocyclic sulfur compounds, such as thiazolines, thiazoles, thiapyrans, and thiophenes (Mottram & Elmore, 2002). The resulting products typically have a higher odor threshold than those from the parent reaction, affecting the flavor of food by modifying the formation of other compounds during the Maillard reaction or lipid oxidation, which in turn affects the relative amounts of other flavor compounds in the food aroma spectrum. Thermal processing during frying, cooking, and grilling result in a wide range of volatile product formation due to the interaction of lipid oxidation and the Maillard reaction (Shahidi & Hossain, 2022).

Six methods were used to treat beef patties to compare the effects of different cooking methods on the lipid and protein components of hamburgers (Rodriguez-Estrada, Penazzi, Caboni, Bertacco, & Lercker, 1997). The results showed that the peroxide value of raw samples was significantly higher than that of cooked hamburgers; however, the p-anisidine value of raw meat was significantly lower than that of cooked hamburgers. For cooked samples, heat treatment reduces the amount of peroxides that are converted to secondary oxidation products, resulting in an increase in the p-anisidine value. The total oxidation (TOTOX) values for roasted and barbecued hamburgers were significantly higher than those for raw meat and other cooked samples, while the combination of microwave and roasting had the lowest TOTOX value. In this case, some of the secondary products may combine with other molecules, such as Maillard reaction products, and produce a series of compounds. Although some studies have found that aromatic volatiles derived from lipids dominate in pork samples fried at 150 °C, while those derived from Maillard reactions dominate at 250 °C(Meinert et al., 2007), there are currently no reports on the effects of different cooking methods on lipid-Maillard interactions in pork.

3. Effects of cooking methods on the formation of volatile compounds

3.1. *Impact of steaming, boiling and stewing on pork*

Steaming is a cooking process that uses steam as a heat-transfer medium. During steaming, the juices inside and outside the raw materials are not volatilized as much as in other heating methods, thus retaining the umami substances in the dishes and reducing aroma loss. Boiling involves heating raw materials in a pot with an appropriate amount of soup or water and condiments, allowing them to mature in the pot. Boiling is the most versatile and functional technique for cooking with water as the heat-transfer medium. Stewing is similar to boiling, where raw materials are added to soups and condiments. The difference is that stewing involves boiling with a high flame initially, followed by a low flame for prolonged cooking. Stewing maximizes nutrient preservation without producing harmful substances from excessive heating. Covering the pot during stewing reduces oxygen exposure, thereby retaining antioxidants.

The effect of different steaming times on the flavor of pork belly fat was studied (Bi et al., 2022). Using gas chromatography-ion mobility spectrometry (GC-IMS), a total of 36 compounds were identified, including 14 aldehydes and 11 ketones. The results showed that the concentrations of volatile compounds in the 30 and 180-minute samples were similar, but different from those in the uncooked samples. After steaming, the contents of octanal, heptanal, ethyl hexanoate, hexanal-m, 2-methylbutanal-m, 2-methylbutanal-d, 3-methylbutanal-d, ethyl acetate-m, ethyl acetate-d, and 2, 3-butanedione increased significantly. These compounds are the main volatile flavor compounds in the steamed samples (relative odor activity value, ROAV $\geq$ 1). Hexanal-d and 1-heptanol were the key volatile compounds in the samples after steaming. After steaming for 180 min, the contents of 3-hydroxy-2-butanone and ethyl formate continued to increase and became the main volatile flavor compounds of the samples. The content of 3-hydroxy-2-butanone and ethyl formate continued to rise after cooking for 180 min, becoming the primary volatile flavor compounds.

Different pork varieties (Han, Zhang, Fauconnier, & Mi, 2020), extraction methods (Wang et al., 2016), and stewing methods (Han et al., 2021) were used to stew pork, resulting in the detection of 61, 94, and 60 compounds, respectively, with the highest content being aldehyde compounds. Ketones and esters were not detected in samples from the high-temperature stewing method, but in another study (Han, Zhang, & Fauconnier, 2021), the amount of alcohols and ketones in pork samples gradually increased with the addition of seasoning. Odor activity value (OAV) calculation revealed that although the types of odor-active compounds were the same in different pork stewing methods, their OAV values differed significantly. Among them, hexanal, nonanal, and 1-octene-3-ol were considered the main contributors to the flavor of stewed pork. Different core temperatures in pork during boiling also affect the flavor and quality of pork (Chae & Kim, 2010).

The influence of seasoning on the volatile components and sensory characteristics of stewed pork was studied by gradually adding salt, spices, soy sauce, sugar, and cooking wine to the seasoning formula (Han, Zhang, & Fauconnier, 2021). The contents of volatile compounds were highest in pork stewed in water and salt, and the types and proportions of aldehydes and heterocyclic and sulfur-containing compounds increased significantly, among which (Z)-hept-2-enal, 2-butyloct-2-enal, and tetradecanal were only detected in samples stewed in water and salt. This indicated that spices, soy sauce, sugar, and cooking wine had certain inhibitory effects on the production of some aldehydes in stewed pork, but the principle of inhibition is unknown. The OAV values obtained using different processing methods are shown in Table 1.

By comparing different stewing durations (Chang, Wang, Chen, Zhang, & Sun, 2021), stewing conditions (Wang, Song, Zhang, Tang, & Yu, 2016), and pork stews (Xu et al., 2011; Zhao et al., 2017), 48, 78, 104, and 42 compounds, respectively, were detected, among which hydrocarbon and aldehyde compounds were the most abundant. Acid compound content was highest in (Chang et al., 2021) and (Zhao et al., 2017), while aldehyde compound content was highest in (Yongxia Xu et al., 2011). Thirty, 47, 27, and 19 key flavor compounds were identified by GC-O, among which aldehydes were the most common. Commonly smelled compounds include hexanal (green, cut-grass), (E)-2-heptenal (fatty), (E,E)-2,4-decadienal (fatty), and 1-octen-3-ol (mushroom). In the pork soup stock (Takakura, Osanai, Masuzawa, Wakabayashi, & Nishimura, 2014), 15 compounds had flavor dilution (FD) $\geq$ 64. Through aroma recombination, addition, and omission experiments, acetol, octanoic acid, δ-decalactone, and decanoic acid were identified as the main active compounds affecting the aroma of pork stock. The volatile flavor compounds in pork soup are shown in Table 2.

3.2. Impact of roasting and smoking on pork flavor and texture

Roasting is a cooking method that involves placing processed materials inside an oven and heating them with heat radiation produced by an open flame or a dark flame. After roasting, the raw materials have a crispy surface and a charred flavor. Smoking is a primary processing technology for smoked products. The use of wood chips, brown sugar, and other materials produced by incomplete combustion of smoke is a processing method that alters the flavor of raw materials and enhances product quality.

Different roasting techniques and the core temperature of pork during cooking can impact the flavor and texture of pork (Bejerholm & Aaslyng, 2004). The effects of different curing solutions on volatile compounds in roasted pork neck meat have been investigated (Biller, Boselli, Obiedziński, Karpiński, & Waszkiewicz-Robak, 2016). The results revealed that curing the meat before roasting could not only significantly alter the concentration and distribution of volatile compounds, but also reduce chemical differences between surface and internal layers. In total, 94 compounds were identified in roasted pork neck meat, and only 53 compounds were found in all surface samples. All of these 53 volatile compounds were significant by factor analysis and explained the differences among the surface samples related to the marinating process. The internal part had significantly higher contents of aldehydes and alcohols than the surface sample, while the surface sample had higher contents of ketones, carboxylic acids, esters, furan and pyran derivatives, pyrazine, pyrrol and pyridine derivatives, benzene derivatives, and other compounds than the internal part. By controlling the roasting temperature, it was found that among the 21 volatile compounds (Chen, Liu, & Chen, 2002), the total amount of volatile substances in pork jerky roasted at 200 °C was higher than that in pork jerky roasted at 150 °C. Under both conditions, the relative content of 1-octen-3-ol and methyl-eugenol was the highest, and the content difference was significant (at 200 °C, the content was 2108.6 μg/kg and 1321.4 μg/kg, respectively, and 192.2 μg/kg and 169.1 μg/kg at 150 °C). Due to the extremely high temperature during the roasting process, it is possible that lipid oxidation compounds have reacted or combined with other molecules, leading to a reduction in the content of oxidation compounds, such as hexanal (Broncano et al., 2009).

The impact of different smoking methods on the sensory properties, free amino acids, and volatile compounds of bacon has been investigated (Guo, Wang, Chen, Yu, & Xu, 2021). Only 13 volatile compounds were detected in unsmoked bacon, whereas 59 volatile compounds were identified in smoked bacon. Among them, no phenolic compounds were found in the unsmoked bacon, and only one ketone and two hydrocarbon compounds were detected, with a content of less than 6 μg/kg. Conversely, the detected contents in bacon after smoking were 94.44 μg/kg and 1214.37 μg/kg. The volatile compounds in bacon are influenced by the smoking process, wood type, seasoning, and other factors, and the total amount and relative content of volatile compounds in bacon smoked in various ways also differ.

3.3. Impact of pan-frying, stir-frying and deep frying on pork

Pan-frying involves heating a small amount of oil in a pan, placing the food in it, and cooking it until it is fully cooked and slightly golden brown or even slightly mushy on the surface. The amount of oil should not be immersed in the raw materials. Deep-frying is similar to pan-frying, but involves heating at a high temperature, and the amount of oil used is generally several times more than the raw material. Stir-frying is one of the most widely used cooking methods, mainly using oil as the main thermal conductivity. The raw materials are heated over medium–high heat in a short time, and turned at any time to cook. Stir-frying is generally a quick process, with the ingredients evenly heated to reach an edible state, that delivers a superior quality and flavor and helps to maintain the nutritional components of the raw materials (Bai et al., 2021).

Table 1
Odor-active compounds (OAVs ≥ 1) identified in stewed pork using different processing methods.

Compounds	[a]Odor threshold (μg·kg−1)	fresh pork[1]	stewed pork with water[1]	stewed pork with water and salt[1]	Traditional stewed pork[2]	High-temperature stewed pork[2]	Duroc × (Landrace × Yorkshire) pig[3]	Sanmenxia pig[3]	Tibetan pig[3]
Pentanal	9	3.1 ± 0.4	6.0 ± 0.8	8.3 ± 0.1	13.5 ± 1.2	11.1 ± 0.7	4.6	1.3	16.1
Hexanal	4	0.9 ± 0.3	158.3 ± 3.3	158.5 ± 3.7	426.7 ± 7.2	353.0 ± 2.8	524.2	225.7	301.9
Heptanal	3	18.9 ± 1.1	40.9 ± 5.3	53.4 ± 0.7	55.8 ± 7.1	62.4 ± 0.4	41.7	19.0	32.2
Octanal	0.578	121.0 ± 15.5	260.0 ± 14.8	329.9 ± 35.8	380.8 ± 9.1	883.9 ± 31.7	142.2	N.D.	150.5
(Z)-Hept-2-enal	13.5	N.D.	0.4 ± 0.01	2.9 ± 0.7	/	/	/	/	/
Nonanal	1	219.8 ± 13.3	844.4 ± 94.8	1475.5 ± 124.6	987.7 ± 24.5	2339.4 ± 31.1	333.8	255.7	454.6
(E)-2-Octenal	3	8.2 ± 0.4	25.3 ± 0.4	14.1 ± 2.5	/	/	15.7	7.1	7.7
Decanal	2	2.6 ± 0.3	4.5 ± 0.9	4.0 ± 0.3	/	/	N.D.	5.5	N.D.
Benzaldehyde	7	/	/	/	8.7 ± 0.5	12.2 ± 0.4	3.3	1.4	7.1
Benzeneacetaldehyde	4	0.6 ± 0.03	1.0 ± 0.2	1.5 ± 0.4	/	/	/	/	/
(E)-2-Nonenal	1	39.2 ± 5.0	59.5 ± 13.3	79.5 ± 5.2	63.1 ± 12.9	77.9 ± 7.2	16.6	8.7	13.9
(E)-2-Decenal	0.4	9.8 ± 0.7	18.6 ± 3.6	15.4 ± 3.4	/	/	N.D.	34.0	N.D.
(E,E)-2,4-Nonadienal	0.16	30.1 ± 3.0	67.7 ± 3.2	64.0 ± 2.5	/	/	55.7	25.7	N.D.
Dodecanal	2	/	/	/	/	/	2.2	1.5	N.D.
2-Undecenal	0.78	3.3 ± 0.3	3.5 ± 0.9	3.1 ± 0.4	/	/	9.3	N.D.	N.D.
(E,E)-2,4-Decadienal	0.07	104.3 ± 14.7	143.3 ± 7.6	113.4 ± 13.1	/	/	153.4	83.1	N.D.
1,8-Cineole	1	1.7 ± 0.8	9.6 ± 0.8	15.2 ± 1.8	158.5 ± 2.6	160.4 ± 2.2	/	/	/
1-Octen-3-ol	2	0.7 ± 0.2	65.0 ± 2.2	68.5 ± 1.5	268.2 ± 8.9	256.7 ± 6.5	194.3	114.5	56.9
Ethyl hexanoate	1	/	/	/	/	/	N.D.	7.8	N.D.
Styrene	65	/	/	/	/	/	3.8	N.D.	1.4
2-Ethylfuran	2.3	/	/	/	/	/	17.3	18.5	22.7
Linalool	6	/	/	/	8.8 ± 1.0	8.6 ± 0.5	/	/	/
1-Octanol	110	/	/	/	0.6 ± 0.0	1.8 ± 0.1	/	/	/
(E)-2-Octen-1-ol	3,50	0.8 ± 0.1	1.5 ± 0.2	1.2 ± 0.2	22.4 ± 1.4	28.6 ± 2.0	10.9	8.1	4.5
2,3-Butanedione	4.37	2.9 ± 0.5	5.4 ± 0.4	5.3 ± 0.7	/	/	/	/	/
Hydroxyacetone	10	N.D.	2.1 ± 0.4	5.8 ± 1.5	/	/	/	/	/
2,3-Octanedione	12	25.3 ± 1.7	48.2 ± 2.2	93.5 ± 15.4	/	/	/	/	/
D-Limonene	10	N.D.	1.3 ± 0.2	2.2 ± 0.1	14.4 ± 1.5	32.9 ± 0.7	/	/	/
β-Phellandrene	8	/	/	/	10.2 ± 0.8	13.5 ± 0.5	/	/	/
Naphthalene	60	/	/	/	0.6 ± 0.1	1.8 ± 0.0	/	/	/
Ethyl acetate	5	N.D.	9.3 ± 0.8	14.0 ± 0.8	/	/	/	/	/
Estragole	6	/	/	/	18.8 ± 1.5	22.0 ± 0.5	/	/	/
Anethole	15	0.2 ± 0.03	1.1 ± 0.04	1.1 ± 0.1	71.2 ± 2.1	55.9 ± 0.8	N.D.	N.D.	1.0
Eugenol	7.1	/	/	/	61.4 ± 2.0	21.7 ± 0.8	/	/	/
2-Pentylfuran	6	N.D.	178.6 ± 18.1	162.6 ± 29.7	36.9 ± 2.0	55.8 ± 0.2	40.7	27.1	22.1
Methanethiol	1.05	0.9 ± 0.3	45.2 ± 3.5	80.1 ± 18.1	/	/	/	/	/
Dimethyl disulphide	1.1	/	/	/	/	/	76.8	116.5	141.3
Dimethyl trisulfide	0.01	N.D.	136.7 ± 9.1	N.D.	/	/	/	/	/
2-Acetylpyrazine	62	/	/	/	/	/	1.4	1.4	1.5
2-Acetylthiazole	10	/	/	/	/	/	3.3	6.8	7.0
Benzothiazole	80	/	/	/	/	/	1.4	1.2	1.3
Total		594.6 ± 58.6	2136.6 ± 186.9	2773.0 ± 263.3	2608.3 ± 71.3	4399.6 ± 29.6	1662.6	970.6	1243.7

Note: N.D. = not detected. "/", no data found.
[a] Orthonasal odor thresholds are all in water (μg/kg) except for the specified liquids (μg/kg) or air (μg/m3) copied from Gemert, L. J. V. Odour Thresholds: Compilations of Flavor Threshold Values in Air, Water and Other Media, Second enlarged and revised edition; Oliemans Punter & Partners BV: Utrecht, the Netherlands, 2011.
[1−3] The Nos. in the brackets are the references Nos. listed in the supplementary file 1.

Table 2
Volatile flavor compounds identified in pork soups.

No.	Compounds	Odor description[a]	RIs[b]		References[c]
			Polar	Non Polar	
Aldehydes					
1	Hexanal	Green, cut-grass	1082	794	4,5,6,7
2	(E)-2-heptenal	Fatty	1329	960	4,5,6,7
3	(E)-2-octenal	Nutty, fatty	1435	1066	4,5
4	Benzaldehyde	Almond-like, roasty	1514	963	4,5,8
5	(E)-2-decenal	Waxy, fatty, meaty	1631	1261	4,5,6
6	(E)-2-undecanal	Fruity	1736	/	4
7	(E,E)-2,4-decadienal	Fatty	1819	1319	4,5,6,7
8	(E,E)-2,4-nonadienal	Fatty	1695	1218	5,6,7
9	Octanal	Fatty	1291	1013	5,7
10	Vanillin	Vanilla	2460	/	8
11	Nonanal	Fatty, oily	1397	1104	5,6,7,8
12	2-Undecenal	Fatty	1747	1381	5,7
13	Decanal	Sweet	1501	1207	5,7
14	Pentanal	Green	927	687	5,6
15	(E)-2-hexenal	Green, fatty	/	835	6,7
16	Heptanal	Sweet melon, fatty	1184	886	5,6,7
17	Phenylacetaldehyde	Rose	/	1049	6
18	(E)-2-nonenal	Cucumber	1542	1150	6,7
19	(E)-cinnamaldehyde	Spicy	2053	1273	5
20	Benzeneacetaldehyde	Rosy	/	1051	5
21	(E,E)-2,4-heptadienal	Chicken soup	1486	1024	7
Sulfur compounds					
22	3-(Methylthio)propanal	Cooked potato	1437	912	4,6
23	Dimethyl sulfone	Sulfurous burnt	1889	921	4
24	Dimethyl disulfide	Onions, Rotten	1075	739	5
25	Methyl ethyl disulfide	Onions	1149	828	5
26	Diethyl disulfide	Garlic	1218	925	5
27	Dimethyl trisulfide	Meaty, cooked cabbage, sulfur	1389	984	5,6
28	Diethyl trisulfide	Garlic	1518	1142	5
29	Methanthiol	Sulfur, gasoline	/	455	6
30	2-Methyl-3-furanthiol	Cooked meat	/	875	6
31	2-Furfurylthiol (Furfuryl mercaptan)	Sesame, meat, cheesy	/	916	6
32	2-Mercaptothiophene	Sesame	/	986	6
33	2-Thiophenecarboxaldehyde	Sulfur, nutty	/	1005	5,6
34	4-Methyl-5-thiazoleethanol	Sesame	2289	1299	4,6
35	3-(Methylthio)propionaldehyde	Cooked potato	1461	912	5
Ketones					
36	2-Heptanone	Coconut, woody	1170	/	4
37	3-Hydroxy-2-butanone	Fatty, yogurt	1270	705	4,6
38	1-Hydroxypropan-2-one (1-Hydroxy-2-propanone)	Pungent	1286	673	4
39	2-Butanone	Green	901	/	5
40	2-Pentanone	Sweet	978	/	5
41	1-Penten-3-one	Pungent, rotten	1017	745	5
42	Acetophenone	Floral, sweet	1661	/	5
43	Acetol	Mushroom-like, green	1197	/	8
44	2-Pentadecanone	Sweet	1913	/	8
45	2,3-Pentanedione	Butter	1060	/	5
46	6-Methyl-5-hepten-2-one	Fruity	1342	/	5
Alcohols					
47	1-Pentanol	Fusel oil, peanut	1255	775	4,5
48	1-Octen-3-ol	Mushroom	1454	982	4,5,6,7
49	2-Furanmethanol	Caramel, bread	1644	861	4
50	2-Butanol	Alcoholic	1029	/	5
51	2-Pentanol	Sweet, alcoholic	1124	/	5
52	3,5-Octadien-2-ol	Green	/	1021	5
53	Phenylethyl alcohol	Rose	/	1115	5
54	1-Octanol	Fatty, oxidized oil-like	1552	1076	5,7,8
55	1-Heptanol	Floral	1457	980	6
56	(E)-2-nonen-1-ol	Fatty, sweet	/	1175	7
Acids					
57	Propanoic acid	Pungent acidic	1513	/	4
58	Butanoic acid	Pungent acidic	1610	/	4
59	Hexanoic acid	Sour, fatty	1827	992	4
60	Octanoic acid	Fatty, waxy	2035	1175	4,8
61	Nonanoic acid	Waxy	2140	/	4,8
62	Decanoic acid	Sour, fatty	2249	/	4,8
63	Tetradecanoic acid	Fatty, soapy	2662	/	4
64	Acetic acid	Sour, sweat	1343	/	8
65	3-Methylbutanoic acid	Animal, cheese-like	1576	/	8
66	Dodecanoic acid	Camphor	2392	/	8
Esters					
67	δ-Decanolactone	Sweet, creamy	2181	1487	4,8

(continued on next page)

Table 2 (*continued*)

No.	Compounds	Odor description[a]	RIs[b]		References[c]
			Polar	Non Polar	
68	Ethyl acetate	Fruity	886	/	5
69	Butanoic acid butyl ester	Fruity	1222	/	5
70	γ-Undecalactone	Peach	1298	/	5
71	γ-decalactone	Peach	/	1430	6
72	Methyl palmitate	Sweet	2130	/	8
Heterocyclic compounds					
73	2-Acetylpyrrole	Musty	1953	/	4
74	2-Acetylthiazole	Sesame, roasted, rice	1657	1023	5,6
75	Benzothiazole	Caramel	1974	1224	5
76	2-Acetyl-1-pyrroline	Nutty, roasted	/	950	6
77	2-Ethyl-3-methylpyrazine	Roasted	/	1023	6
78	5-(Hydroxymethyl) furfural	Musty	2431	/	8
79	4-Hydroxy-2,5-dimethyl-3(2H)-furanone	Sweet, caramel	2011	1055	4,6
Aromatics					
80	p-Cresol	Herbal, animal	2078	1075	4
81	Naphthalene	camphoric	1733	1185	5
Furans					
82	Furfural	Roasted	1469	/	5
83	2-Pentylfuran	Fruity, green	1238	1002	5,7
Thiophenes					
84	2-Methylthiophene	Onion	1091	/	5
Hydrocarbons					
85	Toluene	Fruity, sweet	1039	759	5
Others					
86	Pyridine	Burnt	1195	737	5
87	D-Limonene	Sweet	1192	1035	5
88	2,4-Bis(1,1-dimethylethyl)-phenol	Woody	/	1407	6

[a] Odor descriptions were referred to the references of Nos. writing in this table.
[b] Retention indices (RIs) relative to the n-alkanes in the polar (DB-wax) and non-polar (DB-5) columns documented in the NIST 14 database. "/", no data found.
[c] The Nos. in the brackets are the references Nos. listed in the supplementary file 1.

The effects of frying on aroma components in pork were compared and analyzed using different pork products (Timón, Carrapiso, Jurado, & van de Lagemaat, 2004) and cooking methods (Yang et al., 2017). The volatile components in fried bacon and fried pork loin were similar, but fried bacon had many pyrazine, pyridine, and other nitrogen-like compounds that were almost absent in fried pork loin. Although the composition of the compounds in the fried bacon sample was higher than that in the fried pork loin sample, the concentrations of most compounds in the bacon sample were much lower. This can be attributed to the inhibition of lipid oxidation in the presence of nitrite. Aldehydes such as pentanal, hexanal, heptanal, and nonanal were the most abundant compounds in fried pork. They were abundant in uncured products, whereas cured products contained lower levels. It was found in (Yang et al., 2017) that the types and concentrations of aromatic active compounds in samples prepared using different cooking methods differed significantly. In addition to aldehydes and alcohols, pyrazines were also detected in deep oil-frying samples with a high content. The 2,5-dimethylpyrazine and 6-methyl-2-ethylpyrazine contents were 59 μg/kg and 56.659 μg/kg, respectively. However, the aldehyde content in the electric oven cooking sample was 2.6 times that in the deep-oil frying sample, which may be due to the pork loin being heated for a long time. Different frying temperatures can also affect the aroma components of pork. Compared to 150 °C, pan-frying at 250 °C generally increases the intensity of the flavor and odor of fried meat and burnt caramel, whereas the intensity of boiled meat, piggy, and sour flavors and odors decreases (Meinert et al., 2007). Pyrazine compounds were only formed at 250 °C. Moreover, different types of frying fats also have an impact on the volatile compounds in fried pork (Ramírez, Estévez, Morcuende, & Cava, 2004).

To investigate the changes in basic components, aroma components, and potentially harmful substances in the stir-frying process of meat slices, the volatile components in edible oil, vinegar, raw meat, and cooked samples were analyzed separately (Wang et al., 2021). Stir-frying increased the variety of volatile compounds in pork slices and produced 2-methylpropanal and heptanal, which were not detected in raw meat. Pyrazine compounds were primarily formed during the prolonged processing time of meat slices, and their content increased with longer stir-frying time. Table 3 provides a list of compounds that were detected multiple times in various pork cooking methods. To visually indicate the possible clustering relationships between different processing methods, sample material groups, and sensory attributes, a Venn diagram (Fig. 3) was performed using TBtools based on Table 3. Fig. 3 indicated that only three common volatile compounds produced by different cooking methods, namely hexanal, heptanal, and 3-hydroxy-2-butanone. Hexanal and heptanal were considered universal contributors to meat flavour (Cui et al., 2023). 3-Hydroxy-2-butanone was also one of the key volatile compounds in pork belly fat (Bi et al., 2022). All of these three compounds played an important role in the flavor of pork. Out of a total of 208 compounds, 22 were only detected in smoked pork, indicating that these 22 compounds may be characteristic compounds of smoked pork. Similarly, 24 compounds were only detected in stewed and boiled pork, and they played a crucial role in stewed and boiled pork.

3.4. Effects of other cooking methods on pork flavor

Sous vide cooking is a vacuum-sealed method of cooking with precise temperature control that provides a wide range of doneness and texture options. Cooking in heat-stabilized vacuum pouches not only improves shelf life but also taste and nutrition (Baldwin, 2012; Pathare & Roskilly, 2016; Rotola-Pukkila, Pihlajaviita, Kaimainen, & Hopia, 2015). Using traditional and sous vide cooking methods under various conditions, differences in quality, flavor, and other aspects of braised meat were compared. Among all volatile compounds, aldehydes played a significant role in all samples, especially tetradecanal, benzaldehyde and hexadecanal. Octen-3-ol, phenylethyl alcohol, 2-octen-1-ol (E), and 1-octanol are the main flavor substances in braised meat. 2,3-octanedione and 2-cyclopentanone are the main ketones detected in braised meat (Jiang et al., 2022). By comparing different sealing treatments and sous vide cooking of pork loin patties, it was found that additional sealing

Table 3
Volatile compounds in pork processed by various cooking methods.

No.	Compounds	RIs[a]		Odor description[b]	Processing method[c]
		Polar	Non Polar		
Aldehydes					
1	Hexanal	1098	789	green, cut-grass, rancid, fatty, fruity, acorn	stewed[1,2,4,5,6], boiled[3,9], smoked[15,16,17,19,20], roasted[22,23,24], fried[10,12,14], stir-fried[11], deep fried[13]
2	(E)-2-heptenal	1316	970	fatty	Stewed[4,7,5,6], boiled[9], smoked[16,17], roasted[22], freid[14]
3	(E)-2-octenal	1416	1065	nutty, fatty	Stewed[1,4,7,5,6], boiled[3], smoked[16,18], roasted[21,22], freid[14]
4	Benzaldehyde	1530	939	almond-like, roasty	Stewed[1,2,8,5,6], boiled[3,9], smoked[15,16,17,19,20], roasted[22,23,24], fried[10,12,14], deep fried[13]
5	(E)-2-decenal	1600	1247	waxy, fatty, meaty	Stewed[1,4,5,6], boiled[3,9], roasted[22,23]
6	(E)-2-undecanal	1731	/	fruity	Stewed[4,7]
7	(E,E)-2,4-decadienal	1781	1306	fatty, fried, waxy	Stewed[1,4,7,5,6], boiled[3,9], smoked[16], roasted[22,23]
8	(E,Z)-2,4-decadienal	/	1327	fat, fried	Smoked[16], roasted[22], freid[14]
9	(E,E)-2,4-nonadienal	1695	1204	fatty, geranium, pungent	Stewed[1,6], boiled[3], smoked[16], roasted[22]
10	Octanal	1291	1013	fatty, green, fresh, meat, stew-like, rancid, fruity, rancid, sewage, roasted	Stewed[1,2,4,7,5], boiled[3,9], smoked[15,18,19,20], roasted[22,23], freid[14]
11	Nonanal	1388	1090	fatty, oily, rancid, sweet, green	Stewed[1,2,4,7,8,5,6], boiled[3,9], smoked[15,16,19,20], roasted[22,24], fried[10,12,14], deep fried[13]
12	2-Undecenal	1747	1159	fatty, sweet	Stewed[1,5], boiled[3], fried[10], smoked[15,16]
13	Decanal	1501	1207	sweet, penetrating, floral, citrus, waxy	Stewed[1,7,5], boiled[3,9], smoked[16,20], roasted[23], fried[10,12,14]
14	Pentanal	1002	693	green, nutty, toasted, fruity, pungent, acrid	Stewed[1,2,5,6], boiled[3,9], smoked[15,16,17,20], roasted[22,23], fried[10,12,14]
15	(E)-2-hexenal	1206	856	green, fatty	Stewed[7,6], boiled[9], smoked[16], roasted[22]
16	Heptanal	1192	881	fatty, oily, toasted, fruity, sewage, cured ham-like	Stewed[1,2,4,7,5,6], boiled[3,9], smoked[15,16,19,20], roasted[22,23], fried[10,12,14], stir-fried[11]
17	Phenylacetaldehyde	1648	1031	rose	Stewed[6], roasted[22]
18	(E)-2-nonenal	1542	1157	cucumber, peanut, almond, fatty	Stewed[1,2,7,5,6], boiled[3,9], smoked[18]
19	Benzeneacetaldehyde	/	1051	rosy, honey	Stewed[1,5], boiled[9], smoked[16], roasted[23], fried[10,14]
20	(E,E)-2,4-heptadienal	1486	1007	chicken soup	Stewed[7], boiled[3], smoked[16], roasted[22], fried[10]
21	Propanal	776	/	almond-like, green, broth, spicy	Stewed[1], fried[12]
22	2-Methylpropanal	/	552	toasted, fruity, pungent, alcoholic, nutty	Smoked[15], fried[10], stir-fried[11]
23	2-Methylbutanal	903	662	rancid, almond-like, toasted, fruity	Smoked[15,17,19,20], roasted[23], fried[10,12,14], stir-fried[11]
24	3-Methylbutanal	906	654	acorn, nutty, almond, toasted, cheesy, salty, fruity, pungent, malty	Smoked[15,16,19,20], roasted[22,23], fried[10,12,14], stir-fried[11]
25	2-Hexenal	/	855	fruity, olive oil-like	Smoked[15,16], fried[10,14]
26	2-Heptenal	1310	/	green, fatty, fried food-like, fruity, almond	Fried[10,12]
27	2-Octenal	1416	1062	leaves, pungent, fatty, rancid, tropical fruit-like, fruity	Smoked[15], fried[10,12]
28	2-Nonenal	/	1163	fatty, waxy	Smoked[15,16], fried[10,14]
29	2,4-Decadienal	/	1325	fatty, rancid	Roasted[24], fried[10]
30	Butanal	850	593	smoky, fish, amylic, aldehyde	Stewed[1], smoked[17], fried[10,12]
31	2,4-Nonadienal	/	1218	/	Stewed[7], fried[10]
32	2-Decenal	/	1266	/	Smoked[15,16], fried[10]
33	Dodecanal	1706	1412	herbaceous, fatty	Boiled[3], smoked[20], roasted[23], freid[14]
34	Tetradecanal	1918	1609	roasted, fried	Stewed[1,7,6], boiled[3], smoked[16], roasted[22,23]
35	Pentadecanal	2025	1713	/	Stewed[1], boiled[3,9], smoked[16], roasted[22]
36	Hexadecanal	2133	1791	/	Stewed[1,6], boiled[3,9], smoked[16,21], roasted[22,23]
37	Octadecanal	2380	1998	/	Stewed[6], boiled[9], smoked[16], roasted[24]
38	Undecanal	1598	1305	floral, green, mild	Smoked[20], roasted[23]
39	(E)-2-Pentenal	/	746	/	Stewed[7], roasted[22]
40	4-(1-Methylethyl)benzaldehyde	/	1200	/	Stewed[5], roasted[22]
41	(E)-9-Octadecenal	/	1991	/	Stewed[1], roasted[22,24]
42	tridecanal	1812	1525	fatty, sweet	Boiled[3], roasted[23]
43	(Z)-4-Decenal	1534	1202	/	Stewed[1], boiled[3]
44	2-butyl-2-octenal	/	1372	cured ham, meaty	Stewed[1], boiled[3]
45	2-Methyl-2-butenal	1103	738	/	Stewed[7,6]
Sulfur compounds					
46	3-(Methylthio)propanal	1424	906	cooked potato	Stewed[5,6], smoked[15,16]
47	Dimethyl disulfide	1073	737	onions, rotten, burnt	Stewed[1,5,6], boiled[3], smoked[15], fried[10,12,14]
48	Dimethyl trisulfide	1389	972	meaty, cooked cabbage, sulfur, rotten egg	Stewed[1,5], boiled[9], smoked[15], roasted[23], fried[10,12]
49	Methanethiol	/	<500	sulfur, gasoline, rotten eggs, meat or fish, cheesy	Stewed[1], smoked[15]
50	2-Thiophenecarboxaldehyde	1679	1008	sulfur, nutty	Stewed[1,5,6]
51	4-Methyl-5-thiazoleethanol	2275	1266	sesame	Stewed[5,6]
52	(Z)-13-Octadecenal	2343	1965	/	Boiled[9], smoked[16]
Ketones				/	
53	2-Heptanone	/	892	coconut, woody, spicy, toasted	Stewed[1,6], smoked[15,16,20], roasted[22,23], fried[10,14]
54	3-Hydroxy-2-butanone (acetoin)	1290	718	fatty, yogurt	Stewed[4,5], smoked[16], roasted[22], fried[10,14], stir-fried[11]
55	1-Hydroxypropan-2-one (1-Hydroxy-2-propanone)	1303	668	pungent, sweet	Stewed[1,4,5], smoked[16]

(continued on next page)

Table 3 (*continued*)

No.	Compounds	RIs[a]		Odor description[b]	Processing method[c]
		Polar	Non Polar		
56	2-Butanone	908	597	green, buttery	Stewed[1,5], smoked[15,17,19,20], fried[12,14]
57	2-Pentanone	978	687	sweet	Stewed[5], boiled[9], smoked[17,20], roasted[23], fried[10]
58	Acetophenone	1661	1069	floral, sweet	Stewed[1,5], boiled[9], smoked[17,19,20]
59	2-Pentadecanone	2008	1688	sweet	Stewed[4,7,8,6], boiled[9], smoked[16], roasted[22]
60	2,3-Pentanedione	1060	722	butter	Stewed[1,5], fried[10,12]
61	6-Methyl-5-hepten-2-one	1342	990	fruity	Stewed[5], smoked[17,20], fried[10]
62	2,3-Butanedione	/	593	sweet, vanilla/caramel-like	Stewed[1], smoked[17,20], fried[10,14]
63	2-Octanone	1297	/	fruity, green, floral, fresh	Stewed[1], stir-fried[11]
64	1-Octen-3-one	1315	/	rust-like, dust, mushroom	Smoked[15,18]
65	2-Nonanone	/	1087	floral, fruity	Boiled[9], roasted[22,23], fried[10,14]
66	Cyclohexanone	1289	844	sweet, wine-like	Boiled[9], smoked[17], fried[10]
67	2-Methyl-2-cyclopenten-1-one (2-Methyl-2-cyclopentenone)	/	909	/	Smoked[19], fried[10]
68	2,3-Octanedione	1333	983	mushroom, fungi, green, woody	Stewed[1,6], smoked[15], roasted[23], fried[10,14]
69	2-Decanone	/	1193	heavy, sweet	Roasted[23], fried[10]
70	2-Undecanone	/	1294	fruity, fatty	Boiled[9], fried[10,14]
71	Acetone (propan-2-one)	810	503	fruity	Smoked[19], stir-fried[11], fried[12,14]
72	2-Heptadecanone	/	1910	/	Boiled[9], smoked[16], fried[14]
73	2,3-Dimethyl-2-cyclopenten-1-one	/	1027	/	Smoked[15,16,19]
74	3-Methyl-2-cyclopenten-1-one	1498	976	sweet, fruity	Stewed[6], boiled[9], smoked[16,18,19]
75	3-Methyl-1,2-cyclopentanedione	/	/	/	Smoked[16,19]
76	3-Ethyl-2-cyclopenten-1-one	1677	1065	caramel-like	Smoked[16,18]
77	3,5-Octadien-2-one	1564	1098	/	Boiled[3], roasted[22]
Alcohols					
78	1-Pentanol	1250	761	fusel oil, peanut, strong, balsamic, mildly sweet	Stewed[1,5,6], boiled[3,9], smoked[15,16,17,19], roasted[22,23], fried[6,14], stir-fried[11]
79	1-Octen-3-ol	1451	960	mushroom, earthy, dust rust-like	Stewed[1,2,4,7,5,6], boiled[3,9], smoked[15,16,19], roasted[23,24], fried[10,14]
80	2-Furanmethanol	1635	864	caramel, bread	Stewed[6], boiled[3,9], smoked[15,16,20], roasted[22], stir-fried[11]
81	2-Butanol	1029	606	alcoholic	Stewed[5], fried[10]
82	3,5-Octadien-2-ol	/	1021	green	Stewed[5], roasted[22]
83	Phenylethyl alcohol	1883	1112	rose	Stewed[1,5,6], smoked[15]
84	1-Octanol	1553	1072	fatty, oxidized oil-like	Stewed[1,2,7,8,5,6], boiled[3], smoked[15,19], roasted[23], fried[10,14]
85	1-Heptanol	1457	970	floral	Stewed[1,5,6], boiled[9], smoked[15], roasted[23], fried[10]
86	Ethanol	937	453	alcohol, sweet	Stewed[5], smoked[17,19], stir-fried[11], fried[12]
87	1-Nonanol	1564	1173	fatty, green	Stewed[1,5]
88	Benzyl alcohol	1848	1045	/	Stewed[6], boiled[9]
89	2-Methyl-2-propanol	/	1016	/	Stewed[5], fried[10]
90	1-Butanol	1155	/	medicinal, fruity	Stewed[1,6], boiled[9], fried[10]
91	1-Penten-3-ol	1172	675	pungent, butter	Stewed[1,6], smoked[15,20], roasted[22,23], fried[10]
92	3-Methyl-3-buten-1-ol	1254	733	/	Stewed[6], boiled[9], fried[10]
93	3-Methyl-2-buten-1-ol	1325	767	/	Stewed[6], boiled[9], fried[10]
94	1-Hexanol	1358	869	fruity, green	Stewed[1,6], boiled[3], smoked[15,19], roasted[22,23], fried[10,14]
95	2-Ethylhexanol	1493	1028	minty	Stewed[1], boiled[9], roasted[23], fried[14]
96	2,3-Butanediol	1568	778	/	Stewed[1,6], stir-fried[11]
97	Isopropyl alcohol	916	707	/	Smoked[17], fried[12]
98	3-Methyl-1-butanol (Isoamyl alcohol)	/	726	/	Smoked[15,19], roasted[22]
99	1,8-Cineole	1204	/	mint, sweet	Stewed[1,2]
100	4-Terpinenol	/	1177	/	Stewed[1], roasted[24]
101	(E)-2-Octenol	1610	1079	soap, plastic	Stewed[1,2,5], boiled[3]
102	2-Ethyl-1-hexanol	1493	1030	/	Stewed[5,6]
Acids					
103	Propanoic acid	1539	/	pungent acidic, sweat	Stewed[6], stir-fried[11], fried[14]
104	Butanoic acid	1635	824	pungent acidic, rancid, cheesy	Stewed[6], smoked[16]
105	Hexanoic acid	1857	1036	sour, fatty, cheesy, sweat	Stewed[4,6], fried[14]
106	Octanoic acid	2049	1179	fatty, waxy	Stewed[4,8,6], fried[14]
107	Nonanoic acid	2153	1275	waxy	Stewed[4,8,6], roasted[23], fried[14]
108	Decanoic acid	2255	1376	sour, fatty	Stewed[4,8,6], fried[14]
109	Tetradecanoic acid	/	1769	fatty, soapy	Stewed[5,6], boiled[9], smoked[16]
110	Acetic acid	1431	660	sour, sweat	Stewed[1,8,6], smoked[19,20], stir-fried[11], fried[14]
111	3-Methylbutanoic acid (Isovaleric acid)	/	864	animal, cheese-like, Foot-like, acid, spoiled ham	Stewed[8], smoked[17]
112	Dodecanoic acid	2474	1574	camphor	Stewed[4,8,6]
113	Pentanoic acid	1732	893	meaty, roasted, spoiled ham	Stewed[1,6]
114	Hexadecanoic acid	/	1952	waxy	Stewed[7,6], boiled[9], smoked[16,21]
115	Octadecanoic acid	/	2148		Stewed[7,6], boiled[9]
Esters					
116	Ethyl acetate	886	569	fruity	Stewed[1,5], smoked[17,19], stir-fried[11]
117	Methyl palmitate	2196	1923	sweet	Stewed[8,6]
118	Butyl acetate	1089	/	fruity	Stir-fried[11], stewed[6]
119	Hexanoic acid ethyl ester	1231	997	/	Stewed[5], smoked[16]

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Table 3 (*continued*)

No.	Compounds	RIs[a] Polar	RIs[a] Non Polar	Odor description[b]	Processing method[c]
120	Butyrolactone	/	911	/	Stewed[1], smoked[16], roasted[23]
121	γ-Dodecalactone	/	1683	peach-like	Smoked[16], roasted[22]
122	γ-Butyrolactone	1610	908	/	Stewed[4,6], smoked[17]
123	Ethyl propionate	957	696	/	Stewed[5], smoked[17]
124	4-Hexanolide	1693	1063	/	Stewed[1,6]
	Heterocyclic compounds				
125	2-Acetylpyrrole	/	1061	musty	Smoked[17], roasted[23]
126	2-Acetylthiazole	1650	1040	sesame, roasted, rice	Stewed[5,6], boiled[3,9], smoked[16], roasted[22,23]
127	Benzothiazole	1961	1224	caramel, cheese	Stewed[1,5,6], boiled[3,9], smoked[20], roasted[22]
128	Furfural (2-Furfural)	1469	818	roasted	Stewed[1,5,6], boiled[9], smoked[16,17,19,20], roasted[22], fried[10], stir-fried[11]
129	2-Pentylfuran	1234	993	fruity, green, butter	Stewed[1,2,4,7,5,6], boiled[3,9], smoked[15,16,19,20], roasted[22,23,24], fried[10,12,14], deep fried[13]
130	2-Ethylfurane	952	712	sweet, rubber, pungent	Boiled[3], smoked[20], roasted[22]
131	3-Methylthiophene	1185	773	/	Stewed[1], boiled[3]
132	Methylpyrazine	/	827	/	Smoked[16], roasted[23], fried[10]
133	2,5-Dimethylpyrazine	1316	915	/	Smoked[16], roasted[22,23], fried[10,14], stir-fried[11], deep fried[13]
134	2-Ethyl-3,5-dimethylpyrazine	1441	1079	/	Fried[10,12,14]
135	2-Acetylfuran	1483	913	sweet, roast	Smoked[18], fried[10]
136	2-Furanmethanethiol	/	913	/	Smoked[18], fried[10]
137	Pyridine	1178	742	burnt	Stewed[1,5,6], boiled[9,6], smoked[19,20], fried[10,14]
138	Pyrrole	/	751	/	Smoked[20], fried[10], stir-fried[11]
139	2,3,5-trimethylpyrazine (trimethylpyrazine)	1405	1006	roasty, earthy	Smoked[16,18], stir-fried[11], fried[12], deep fried[13]
140	2-Methylfuran	817	/	/	Smoked[20], fried[12]
141	Dibenzofuran	2284	1505	/	Stewed[5], smoked[16]
142	5-Methylfurfural	1593	966	green, sweet, grass	Smoked[17,18]
143	2-Methylpyrazine	1260	863	roasty, nutty	Smoked[18], roasted[22]
144	Pyrazine	1206	/	/	Stewed[6], smoked[20]
145	3-Ethyl-2,5-dimethylpyrazine	/	1078	/	Roasted[22,23]
	Hydrocarbons				
146	Toluene (Methyl benzene)	1039	759	fruity, sweet	Stewed[1,5], boiled[9], smoked[19,20], roasted[22,23], fried[10,14]
147	Hexane	/	/	spicy	Smoked[20], stir-fried[11]
148	Heptane	700	/	sweet	Smoked[16,20], fried[10]
149	Octane	800	788	sweet	Boiled[9], smoked[19,20], fried[10,12], stir-fried[11]
150	Limonene	1190	1034	lemon, wood, citric, fresh	Boiled[3], smoked[16,19], roasted[22], fried[14]
151	α-Pinene	/	937	sharp, pine	Smoked[19], roasted[22], fried[10], stir-fried[11]
152	Methylcyclohexane	/	724	/	Smoked[20], fried[10]
153	2-Octene	/	806	/	Smoked[20], fried[10]
154	4-Octene	/	813	/	Smoked[20], fried[10]
155	Ethylbenzene	1132	858	glue, unpleasant	Stewed[1,5,6], boiled[3], smoked[19,20], roasted[24], fried[10]
156	Naphthalene	1737	1185	camphoric	Stewed[1,2,5], boiled[3], smoked[16], roasted[22], fried[10,14]
157	1,3-Dimethylbenzene	/	872	/	Stewed[1], boiled[9], smoked[20], fried[10]
158	1,2-Dimethylbenzene (o-xylene)	1176	896	/	Stewed[1,6], boiled[3], smoked[20], fried[10], stir-fried[11]
159	Nonane	/	896	/	Stewed[6], fried[10]
160	1,2,4-Trimethylbenzene	1271	945	/	Stewed[1], boiled[3]
161	Decane	1025	993	/	Stewed[1,6], boiled[9], fried[10]
162	3-Carene	/	1013	/	Smoked[16,19], roasted[22], fried[10]
163	D-Limonene	1170	1014	sweet, citrus, mint	Stewed[1,2,7,5,6], boiled[9], fried[10]
164	Undecane	1100	/	/	Smoked[16], roasted[22,23], fried[10], stir-fried[11]
165	Dodecane	1210	1203	/	Stewed[1,6], boiled[3,9], smoked[16,19,21], roasted[23], fried[10], stir-fried[11]
166	Tridecane	1301	1293	/	Stewed[1,4,6], boiled[3], roasted[23], fried[10]
167	1-Tetradecene	/	1391	/	Stewed[7], roasted[22], fried[10]
168	Tetradecane	1399	1389	/	Stewed[1,4,6], boiled[3,9], smoked[16,21], roasted[23], fried[10]
169	camphene	/	943	/	Roasted[22], stir-fried[11]
170	β-pinene	/	976	/	Smoked[19], roasted[22], stir-fried[11]
171	Styrene	1261	895	herbaceous, fatty	Stewed[1,5,6], boiled[3], roasted[22], stir-fried[11]
172	Pentadecane	1495	1498	/	Stewed[1,4,6], boiled[3], smoked[16,20], roasted[22,23], fried[14], stir-fried[11]
173	2-Methylpentane	/	573	/	Smoked[20], fried[14]
174	1,2,4,5-tetramethylbenzene	1418	1218	/	Stewed[1], boiled[3]
175	Hexadecane	1594	1590	/	Stewed[4,7], boiled[3,9], smoked[16,20], roasted[23]
176	p-Xylene (Paraxylene)	1118	875	/	Stewed[1,6], boiled[3,9], smoked[16,19], roasted[24]
177	Caryophyllene	/	1421	/	Smoked[16], roasted[22]
178	Octadecane	1794	1792	/	Stewed[4,6], smoked[16]
179	1-Methylnaphthalene	1877	1303	medicinal, sweet, vanilla-like	Smoked[16,18]
180	γ-Cadinene	/	1513	/	Smoked[16], roasted[22]
181	2-Methylnaphthalene	1908	1299	bitter	Boiled[3], smoked[18]
182	Benzene	/	/	/	Stewed[1], smoked[20]
183	Nonadecane	1893	/	/	Stewed[4,6]
184	Docosane	2193	2199	/	Stewed[4,6]

(*continued on next page*)

Table 3 (*continued*)

No.	Compounds	RIs[a] Polar	RIs[a] Non Polar	Odor description[b]	Processing method[c]
185	Tricosane	2287	2289	/	Stewed[4,6]
186	Tetracosane	2405	2397	/	Stewed[4,6]
Phenols					
187	2,4-Bis(1,1-dimethylethyl)-phenol	2248	1487	woody	Stewed[1,5]
188	2-Methylphenol (o-cresol)	2028	1063	vanilla-like, woody	Smoked[15,16,18,19,20]
189	3-Methylphenol	2109	1086	burning, leathery, stinky	Smoked[15,16,18]
190	4-Methylphenol (p-cresol)	2071	1093	Herbal, animal	Stewed[4,6], boiled[9], smoked[15,20,21]
191	2-Methoxyphenol (Guaiacol)	1888	1075	woody, sweet, smoky	Smoked[15,16,17,18,19,20]
192	2,5-Dimethylphenol	2099	1135	butyric acid, stink, leather	Smoked[15,18]
193	2,3-Dimethylphenol	/	1136	/	Smoked[15,16]
194	3-Ethylphenol	2105	1156	leathery, smoky	Smoked[15,16]
195	Phenol	1970	998	/	Boiled[9], smoked[16,21]
196	4-Ethyl Guaiacol (4-Ethyl-2-methoxyphenol)	2048	1279	wood, smoky, caramel-like	Smoked[16,18,19,21]
197	2,6-Dimethoxyphenol	2283	1352	leathery, green	Smoked[16,18,19,21]
198	2,6-Dimethylphenol	1937	1109	smoky, burning	Smoked[16,18,19]
199	4-Ethylphenol (p-Ethylphenol)	/	1172	/	Smoked[16,21]
200	4-Methyl guaiacol	1978	1196	sweet, wood, caramel-like, smoky	Smoked[16,18]
201	Butylated hydroxytoluene	1902	1484	/	Stewed[6], smoked[16]
202	2-Methoxy-6-methylphenol	1897	1257	woody, sweet	Smoked[18,19]
203	3,4-Dimethylphenol	2102	1194	butyric acid, stinky, leathery	Smoked[18,21]
204	Eugenol	2155	1361	clove, honey	Stewed[2], roasted[22,24]
Others					
205	Benzonitrile	/	997	/	Smoked[16], fried[10]
206	Estragole	/	1206	licorice, anise	Stewed[1,2], roasted[22]
207	*cis*-Anethole	/	1245	anissed-like, rubber, paint	Stewed[1,2], boiled[3], roasted[22]
208	*trans*-Anethole	/	1290	anissed-like	Roasted[22,24]

[a] Retention indices (RIs) relative to the *n*-alkanes in the polar (DB-wax) and non-polar (DB-5) columns documented in the NIST 14 database. "/", no data found.
[b] Odor descriptions were referred to the references of Nos. writing in this table. "/", no data found.
[c] The Nos. in the brackets are the references Nos. listed in the supplementary file 1.

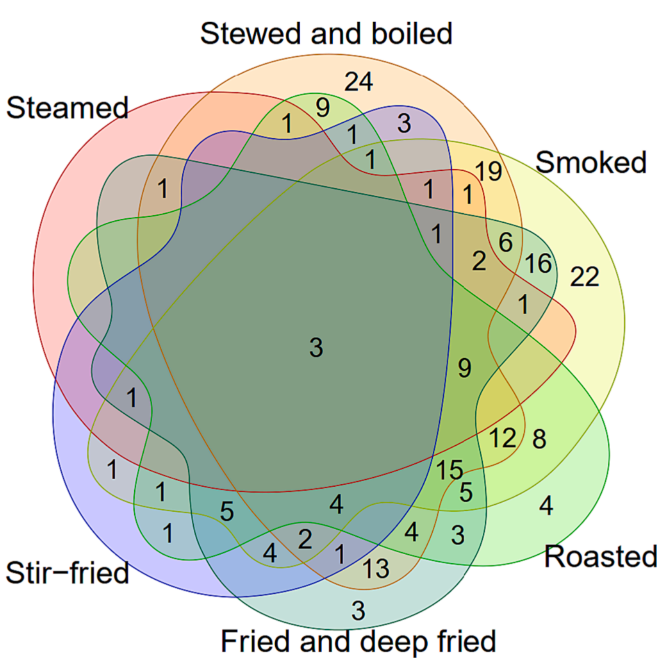

Fig. 3. Venn diagram of volatile compounds produced by different cooking methods of pork.

treatments before sous vide cooking can improve the appearance and palatability and enhance the usability of pork loin (Cho et al., 2021). Another study also indicated that vacuum conditions had no impact on any of the study variables of pork cooking (Sánchez del Pulgar, Gázquez, & Ruiz-Carrascal, 2012).

Microwave heating is a remarkable heat treatment technique, which includes lower energy consumption and shorter cooking times, preserves nutrients, and increases water retention. Compared to traditional methods, microwave heating and other techniques have been shown to reduce meat protein degradation at high heating rates, but can also lead to the deterioration of sarcoplasmic and myofibrillar proteins, resulting in increased texture hardness (Khalid et al., 2023). The effects of four cooking methods, including boiling, roasting, microwave heating, and frying, on the volatile flavor components of pork were studied and compared (Hur et al., 2014). The microwave heating method has a high content of total volatile flavor compounds but a low content of esters. During microwave reheating of pork cake patties, the contents of aldehydes, ketones, alcohols, and heterocyclic compounds initially increased and then decreased. However, prolonged microwave reheating can significantly reduce the total amount of volatile flavor compounds (Zhang et al., 2020).

High-pressure technology is a new non-thermal and eco-friendly method that can extend the shelf life and retain the intrinsic nutritional value and sensory quality of raw materials. High-pressure technology did not affect the color and flavor of cooked pork meat (Sazonova, Galoburda, Gramatina, & Straumite, 2018), and its effect was not affected by the amount, shape, or size of food materials (Khalid et al., 2023; Xu, Zhang, Wang, & Bhandari, 2021). Combining high-pressure technology with heat treatment at a specific temperature can not only improve the quality degradation of food during storage but also enhance the hardness of food samples (Lee, Choi, & Jun 2016). After high-pressure treatment combined with heat treatment, the number of compounds in the pork sample increased, and the stronger the treatment conditions, the more the amount of compounds increased, and the greater the change in the sample's flavor. Under the same pressure or temperature, the total peak area of volatile substances in the sample increased with increasing temperature or pressure. The increase in the peak areas of aldehydes, ketones, and alcohols was the primary reason for the increase in the total peak area (Huang, Li, Gong, & Li, 2018).

4. Sources of flavor compounds in pork

Raw meat has a faint odor, and the most volatile compounds present in raw meat are carboxylic acids, ketones, alcohols, and other compounds with low carbon content (Ramírez et al., 2004; Soncin, Chiesa, Cantoni, & Biondi, 2007). However, raw meat contains a wealth of non-volatile precursor compounds that generate the characteristic meat flavor through a series of reactions influenced by temperature (Kosowska et al., 2017). By examining the aroma dynamic changes of the Dongpo pork dish model throughout the production process, it was discovered that the number of volatile compounds increased as the processing deepened. Frying and steaming had the greatest impact on the aroma composition of Dongpo pork dishes. After frying and steaming, alcohols and aldehydes significantly increased, while hydrocarbons significantly decreased. In all three stages, alcohols and aldehydes had the highest relative content, followed by esters, furans, and pyrazines. Alcohols were highest during the frying stage, whereas aldehydes were higher in the fried samples but relatively lower in the pork after steaming (Li et al., 2022).

Studies have demonstrated that high-temperature heat treatments, such as boiling, roasting, and frying, can alter the perception of specific odors in pork (Peñaranda et al., 2017) or directly modify the chemical reaction between flavor precursors, consequently impacting the overall meat flavour (Gao et al., 2023). Generally, volatile organic compounds produced by lipid degradation are positively influenced by cooking temperature but negatively influenced by cooking duration. Amino acids and volatile organic compounds produced by the Maillard reaction are positively influenced by both factors (Del Pulgar, Roldan, & Ruiz-Carrascal, 2013).

Regardless of whether pork is stewed, smoked, or fried, aldehydes are the most abundant and varied compounds present in cooked pork. Octanal (fatty and fruity) (Dang et al., 2016; Guo et al., 2021), nonanal (fatty aroma and fruity taste) (Guo et al., 2021; Lammers, Dietze, & Ternes, 2009; Wang et al., 2022), and (E)-2-undecenal (sweet, fruity) (Lammers et al., 2009) are primarily derived from the oxidation of oleic acid, whereas hexanal (fatty aroma and fruity taste) (Dang et al., 2016; Guo et al., 2021; Lammers et al., 2009; Li et al., 2022; Wang et al., 2022), (E)-2-nonenal (tallowy, cucumber-like) (Lammers et al., 2009), and (E, E)-2,4-decadienal (fried and oily aromas) (Dang et al., 2016; Lammers et al., 2009) are mainly derived from the oxidation of linoleic acid. Among these, hexanal is typically regarded as a useful indicator of oxidation levels (Guo et al., 2021). Some aldehydes are also produced via the Strecker degradation of the amino acid. Phenylacetaldehyde (rose odor) (Lammers et al., 2009), 3-methylbutanal (malty and chocolate odors) (Takakura et al., 2014; Xie, Sun, Zheng, & Wang, 2008), and 2-methylbutanal (Aaslyng & Schäfer, 2008) are produced through the Strecker degradation of phenylalanine, leucine, and isoleucine. Furfural (Lan et al., 2010) is the primary pyrolysis product of cellulose, which imparts a woody, baked goods, and caramel aroma to pork. Aldehydes are crucial contributors to the flavor of pork due to their low odor threshold. 3-(Methylthio)-propanal is a product of the Strecker degradation of the methylthioprotein (Aaslyng & Schäfer, 2008).

Alcohols are important volatile compounds in foods with mild characteristic flavors, primarily derived from lipid oxidation and substance degradation. Most alcohol compounds have a higher threshold and contribute less to flavor; however, 1-octene-3-ol (mushroom flavor) (Guo et al., 2021; Li et al., 2022) has a lower threshold. 1-octene-3-ol is mainly obtained by the oxidation of arachidonic and linoleic acid. 1-pentanol (fruity and oily odors) (V. B. Hoa et al., 2021) is considered to be a product of oxidized linoleic acid derived from meat during the cooking process. PCA and SLDA analysis indicate that 1-octanal/1-octene-3-ol and nonanal are the most important groups in characterizing pork samples when distinguishing the four pig breeds (Yang, Pan, Zhu, & Zou, 2014).

Sulfur-containing, nitrogen-containing, and oxygen-containing heterocyclic compounds are typically produced by the Maillard reaction. Sulfur compounds are characteristic aromas of meat, often generated by the reaction of cysteine or glutathione with reducing sugars. For example, 3-methylthiopropanal (cooked potato odors) is formed via the Strecker degradation of methionine. Thiamine is a key precursor for 2-methyl-3-furanthiol, 2-methyldithiofuran, and bis(2-methyl-3-furyl) disulfide, all of which have a 'meaty-cooked ham' aromatic note (Thomas, Mercier, Tournayre, Martin, & Berdagué, 2014, 2015). In ham processing, microbial metabolism is also a source of sulfur-containing compounds (Xu, Shui, Chen, Ma, & Feng, 2022). Oxygen-containing heterocyclic compounds are typically derived from the skeleton of reducing sugars. 2-pentylfuran (fruity and buttery odor) (Dang et al., 2016; Guo et al., 2021; Hoa et al., 2021; Wu, Zhan, Tang, Li, & Duan, 2022; Ying Xu et al., 2022) is primarily derived from the oxidation of linoleic acid. Thermal degradation of thiamine can produce compounds such as 2-methyl-3-furanthiol (meaty, cooked ham), 2-methyl-3-furan (meaty, roasted meal), bis(2-methyl-3-furyl)disulfide (cooked ham), and 2-methylthiophene (Thomas et al., 2014). Pyrazinone has a unique baking aroma and is the particular odorant of Maillard reacted peptides obtained by the reaction of dicarbonyl compounds with glycine dipeptide (Sun et al., 2022). Pyrazine compounds, such as 2,6-dimethyl-pyrazine (roast and burnt odor) (Dang et al., 2016; Lammers et al., 2009) and 3-ethyl-2,5-dimethylpyrazine (Tamura, Iwatoh, Miyaura, Asikin, & Kusano, 2022), are characterized by a baking flavor and are a major byproduct of the Maillard reaction in the smoking process. 2,5-dimethyl-3-(3-methylbutyl)pyrazine can also be formed from leucine and lysine.

Phenolic compounds are ideal materials that form through the pyrolysis and oxidation of lignin at low temperatures (200–400 °C), imparting strong woody, pungent, and smoky characteristics. They are the primary cause of the unique smoky aroma and taste of bacon (Guo et al., 2021) and are commonly found in smoked foods, such as guaiacol (Pu et al., 2020), 3,5-dimethoxyphenol (Pu et al., 2020), 2,6-dimethylphenol (Pu et al., 2020), and 4-ethylguaiacol (Guo et al., 2021). Moreover, the threshold values of guaiacol and 4-ethylguaiacol are relatively low, which accounts for the strong smoky flavor in smoked foods.

Most methyl ketones in cooked meat, such as 3-hydroxy-2-butanone, 2,3-butanedione, and 2-heptanone (Dang et al., 2016), may arise from lipid degradation and be recognized as precursors to the fatty aroma associated with meat products. 2,3-octanedione (creamy and fatty-like flavor) (Wu et al., 2022) is the characteristic component of pork aroma.

Hydrocarbons are generally believed to be products derived from lipid oxidation or Strecker degradation of amino acids, such as toluene (Hoa et al., 2021) and 1,3-xylene (Hoa et al., 2021), which may originate from the Strecker degradation of amino acids. Due to the high odor detection threshold of hydrocarbons, they contribute less to the flavor of cooked meat (Wu et al., 2022). Esters have a minimal impact on pork flavor, but ethyl acetate is considered a significant flavor substance in dry-cured ham (Dang et al., 2016).

5. Conclusions

The findings presented in this review show that the majority of aroma compounds in pork were from the Maillard reaction, lipid degradation, and the lipid-Maillard interaction. Among the different cooking methods, steaming, boiling, and stewing, baking, smoking, pan-frying, stir-frying and deep frying have a major influence on the volatile composition of pork. In total, 208 odorants were summarized in pork processed by various cooking methods based on the relevant literatures, including aldehydes, ketones, alcohols, acids, esters, sulfur-containing or nitrogen-containing compounds. Nevertheless, these compounds have different odor-thresholds, and the extent to which they contribute to the aroma of pork is unknown, so further research is needed. In addition to traditional processing methods, many new processing technologies, such as ohmic heating and irradiation, are increasingly being applied to pork processing. With respect to these processing methods, the formation mechanisms of aroma compounds in these processes should be further studied.

Informed consent

Not applicable.

CRediT authorship contribution statement

Shuwei Wang: Conceptualization, Software, Methodology, Writing – original draft. **Haitao Chen:** Project administration, Writing – review & editing, Validation. **Jie Sun:** Validation, Writing – review & editing. **Ning Zhang:** Formal analysis. **Shuqi Wang:** Validation. **Baoguo Sun:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.100884.

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