Review article

Peanut oils from roasting operations: An overview of production technologies, flavor compounds, formation mechanisms, and affecting factors

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ABSTRACT

Fragrant peanut oils (FPOs) are commonly defined as edible peanut oils having strong natural roasted peanut flavor without peculiar unpleasant odors and produced from peanut kernels through roasting/steaming and pressing operations, etc. The flavor of FPOs plays a crucial role in their acceptability and applications and their flavor profiles are an important factor in determining their overall quality. This paper presents a systematic literature review of recent advances and knowledge on FPOs, especially their flavors, in which it is focused on the evaluation of volatile compounds, the factors influencing the formation of flavor compounds, and formation mechanisms of those typical flavor compounds. More than 300 volatiles are found in FPOs, while some key aroma-active compounds and their potential formation pathways are examined. Factors that have big influences on flavor are discussed also, including the properties of raw materials, processing technologies, and storage conditions. Ultimately, the paper highlights the challenges facing, including the challenges in flavor analysis, the relationship between volatile compounds and sensory attributes, as well as the opening of the blackboxes of flavor formations during the processing steps, etc.

1. Introduction

Peanut is one of the important oil crops in the world. In 2022/23, the global production of peanuts and peanut oils reached 50.31 million tons and 6.50 million tons, respectively [1]. Peanut oil is commonly produced as the refined peanut oils for edible uses, which is produced by conventional production technology involving pressing or extraction followed by refining and deodorization [2].

Unlike common refined peanut oils, there are two unusual production methods which end up with two different peanut oil products. One is the high-temperature pressing after a roasting/steaming treatment under high temperatures, which are named as the fragrant peanut oils (FPOs) in certain regions for its organoleptic properties particularly [3]. The other is produced by cold pressing usually with a temperature under 60 °C, named cold pressed peanut oils (CPPOs). Both processes have no conventional refining steps. The FPOs has strong natural roasted peanut flavor. More than 90 % of peanut oil production is performed by the roasting and pressing technique of the first method [4], because of their strong characteristic flavors, high oil yield, attractive color, and high oxidative

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stability [5,6]. Refined peanut oils are commonly utilized in cooking due to their high stability and mildly pleasant flavor [2,7], whose intensity of volatile compounds was 14.6 times lower than that of FPOs. Flavor and odor are fundamental quality indicators in fragrant oils. In addition to their nutritional facts, their applications and acceptabilities depend largely on their aromatic qualities [8]. The flavor of edible oils is contributed by a large number of volatile compounds, including heterocyclic compounds, aldehydes, ketones, acids, esters, alcohols, and phenols, etc. [9].

Many factors have great influence on flavor characteristics, including raw materials, processing technologies, and storage. Carbohydrates and proteins, more importantly, deriving sugars and amino acids, are integral precursors in the various nonenzymatic reactions which are largely responsible for the roasted peanut flavor [10]. As far as we know, there are no systematic reviews on the flavor compounds of peanut oils, including factors influencing the formation of flavor compounds and the formation mechanisms of the concerned flavor compounds. Therefore, the focus of this review is to give a comprehensive discussion of FPOs, especially in terms of the flavor characteristics. Thus, this review is targeted to systematically evaluate and discuss the current knowledge on the flavor volatiles of FPOs, focusing on the above aspects, as well as effects of raw materials and processing techniques on the formation of volatile compounds.

2. Production technology of FPOs

To prepare a better understanding of this commodity but also premier product, a typical process for the production of FPO is given in Fig. 1. A more detail discussion of process conditions for the selected steps can be found from literature [2,11]. The processing technologies of FPOs are mainly divided into three parts: pretreatment, mechanical pressing, and separation [4,12]. Peanut pretreatment refers to a series of treatment process before oil production, such as cleaning, grading, crushing/peeling, and thermal treatment, etc. [4]. Dehulling is also an essential step in the processing of peanut oil for the purpose of obtaining the kernels. It
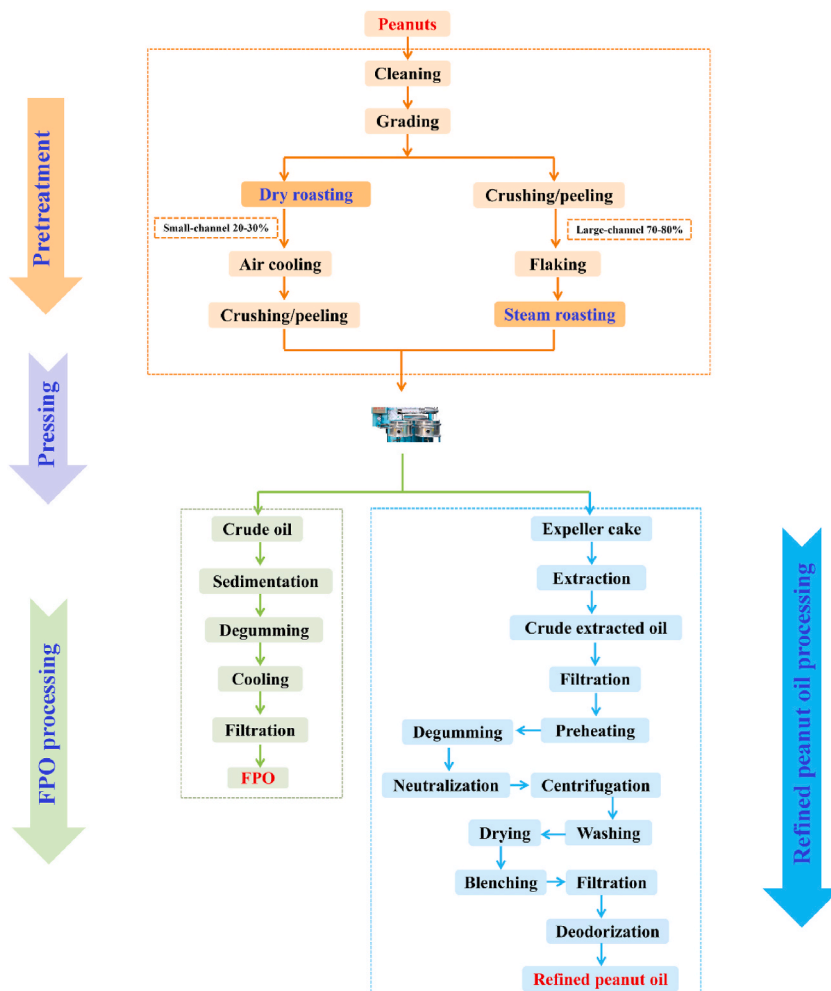

Fig. 1. Typical flow chart of the production of FPOs and Refined peanut oils (adapted) [2,4,14]. Abbreviations: FPOs, fragrant peanut oils.

Table 1
Comparison of commercially available heating techniques.

Name	Operating principles	Characteristics
Steam roasting	A moist-heat method that uses steam to transfer energy and heat materials	●The water vapor temperature can reach higher than 100 °C, and compounds degradation can be mitigated ●Oilseed moisture content increased ●Loss of certain polar nutrient compounds
Dry roasting	Achieved by heat transfer mechanisms, namely radiation from heat source, convection from hot air, and conduction from surfaces in direct contact with oilseeds	●Efficiency is relatively low ●Easily causes un-even heating ●May produce hazardous substances
Microwave roasting	Electromagnetic waves that transfer energy through molecular motions caused by dipole rotation and ion migration	●Inside-out heating ●Efficient heat transfer ●Reducing the loss of moisture and nutrients ●Water molecules vaporized to produce large vapor pressures and rupture cell walls
Infrared radiation roasting	Transport of thermal energy through electromagnetic waves via the penetration of infrared light into the oilseed layer	●Lower energy cost ●High heat efficiency ●Compact size of the equipment ●High diffusion coefficient and homogeneous ●Only suitable for treating oilseeds with thin walls in shallow layers

significantly reduces the chlorophyll pigments contents and produces oils with better sensory properties, such as mild flavor and bright yellow color [6,13].

Thermal treatment, including dry roasting and steam roasting, which is crucial for the formation of aroma-active volatiles and the promotion of desired sensory properties, is commonly indispensable for the production of fragrant oils [5,6]. Additionally, thermal treatment leads to the loss or increase of certain micronutrients such as chlorophylls, carotenoids, squalenes, phenolics, etc. [6,15,16] Usually, careful control of dry roasting or steam roasting conditions, including temperature and time, is essential to prevent detrimental effects on the oil quality [17].

A general comparison of commercially available dry roasting and steam roasting techniques is given in Table 1 [5,6]. Roasting methods differ in terms of the mode of heat applications and the types of heat transfer [18]. Dry roasting is one of the most common and traditional heat transfer methods, which is achieved by combining heat transfer mechanisms, such as radiating heat sources, hot air convecting, and conducting surfaces in direct contact with oilseeds [6,19]. Novel roasting technologies, including microwave [20, 21] and infrared radiation [22,23], serve as rapid heating methods and have the potential to enhance flavor characteristics, garnering significant attention in recent years.

As shown in Fig. 1, steam roasting is also an indispensable processing for FPOs in another processing route. Steam roasting is commonly used in plant oil production [17]. Steaming serves several important functions in oilseed processing, for example: (1) cell walls breaking to allow the oil release from the matrix; (2) coalescences of minute oil droplets into larger ones, which can be easily separated; (3) reducing oil viscosity; (4) adjusting moisture content for multiple functions; and (5) fixing certain phosphatides into the cake, which simplifies the following polishing operation as conventional refining and deodorization steps will not be conducted; etc. Steaming offers a similar function of dry roasting in the production of FPOs other than those listed above. Differences in heating styles and conditions make the flavor characteristics of oil different in actual production.

3. Flavor compounds in FPOs

Flavor is believed to be closely related to the profiles of volatile compounds in oils. The identification of the typical volatile compounds in peanut oil has attracted increasing interest from researchers over the past decades. Thus, studies have been carried out to analyze the volatile composition and to identify the key aroma-active compounds in FPOs, with the aim of better controlling and enhancing their flavor characteristics.

To gain a comprehensive understanding of the discovery process of flavor compounds in peanut oils, we have compiled a list of all recently reported peanut flavor compounds, presented in Table 2. The table shows the inconsistencies among various studies, revealing that different studies yield distinct profiles of volatile compounds, albeit with partial overlap in compound composition. Moreover, it can be intuitively found that the number of volatile compounds and the accuracy of structural identification have increased over time. The identification of the volatile compounds present in raw and roasted peanuts has been the subject of numerous studies over the past decades. For the purpose of better understanding the discovery and development process of volatile compounds in peanut oil, several progress papers will be analyzed below.

In 1966 [36], the identification of some low molecular weight pyrazines was made and a pyrrole was isolated from the roasted peanut aroma. Since then, more work was reported for the discoveries of the major monocarbonyls and some noncarbonyl compounds [37] from the roasted peanut aroma as well as the 12 acids and a few miscellaneous compounds [38]. In 1971 [32], about 187 volatiles of roasted peanuts were identified, while 142 of them, including 17 pyrazines, were reported for the first time. However, some isomers cannot be identified accurately. Much more work on identification and characterization of the volatile compounds had been carried out with the development of analytical methodologies in the last decade.

In 2011, Liu et al. [28] explored the volatile compounds in the roasted peanut oil, showing that about 118 peaks were observed and

Table 2
Volatile compounds in fragrant peanut oils (FPOs)/roasted peanuts.

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, µg/kg oil	OAV	RI Non-polar	Polar	References
Pyrazines	2,5-Dimethylpyrazine	123-4732-0	$C_6H_8N_2$	roasted, nutty, popcorn	512	2000		925	1322	1-2,4–7,9,14
	2,6-Dimethylpyrazine	108-50-9	$C_6H_8N_2$	roasted, nutty, sweet	256	8000		925	1327	1,5–6,8-9,14
	2,6-Diethylpyrazine	13067-27-1	$C_8H_{12}N_2$	roasted, nutty, sweet	256	6 (water)		1071	1432	1,5
	2,5-Diethylpyrazine	13238-84-1	$C_8H_{12}N_2$					1058		7
	3,5-Dimethyl-2-vinylpyrazine	157615-33-3	$C_8H_{10}N_2$					1067		7
	2-Acetylpyrazine	22047-25-2	$C_6H_6N_2O$	roasted		16		1033	1579	3,6,9,12,14
	2-Ethylpyrazine	13925-00-3	$C_6H_8N_2$	peanut-butter, nutty, woody, buttery	16	17,000		913	1315	1-2,4–6,9
	2-Ethyl-3,5-dimethylpyrazine	13925-07-0	$C_8H_{12}N_2$	roasty, earthy		1.7	3	1083	1483	1-2,7–9,12,14
	2-Ethyl-3,6-dimethylpyrazine	13360-65-1	$C_8H_{12}N_2$	roasted potato, earthy	128	76		1096	1443	1-9,12,14
	Trimethylpyrazine	14667-55-1	$C_7H_{10}N_2$	roasted, nutty	64	27,000		1018	1401	1-2,5–6,9,14
	2-Methylpyrazine	109-08-0	$C_5H_6N_2$	nutty, meaty, roasted	32	27,000		836	1266	1-2,4–7,9,14
	2-Methyl-5-(1-methylethyl)-pyrazine	13925-05-8	$C_8H_{12}N_2$	roasted, nutty, sweet	32			1069	1409	1
	5H-5-methyl-6,7-dihydrocyclopenta-pyrazine	23747-48-0	$C_8H_{10}N_2$	roasted, peanut	32			1156	1616	1,5,7,9
	2-Isopropenyl-3,6-dimethylpyrazine		$C_9H_{12}N_2$	roasted, peanut, sweet	16			1195		1
	2-Ethyl-6-methylpyrazine	13925-03-6	$C_7H_{10}N_2$	roasted, baked potato	8			1013	1384	1-2,6–7,9
	2-Ethyl-5-methylpyrazine	13360-64-0	$C_7H_{10}N_2$	nutty, roasted	8	50		1016	1390	1-2,4–6,8-9,14
	(E)-2-methyl-6-(1-propenyl)-pyrazine	18217-81-7	$C_8H_{10}N_2$	roasted, nutty	8			1116	1536	1,6
	3,5-Diethyl-2-methylpyrazine	18138-05-1	$C_9H_{14}N_2$	roasted, peanut, meaty	8			1175	1491	1-2,5-8
	3,5-Dimethyl-2-isobutylpyrazine	70303-42-3	$C_{10}H_{16}N_2$					1176		7
	2,5-Dimethyl-3-isobutylpyrazine	32736-94-0	$C_{10}H_{16}N_2$					1178		7
	3,5-Dimethyl-6,7-dihydro-5H-cyclopentapyrazine	38917-61-2	$C_9H_{12}N_2$					1189		7,9
	2,5-Dimethyl-3-isopentylpyrazine	18433-98-2	$C_{11}H_{18}N_2$					1295		7
	2-Ethyl-3-methylpyrazine	15707-23-0	$C_7H_{10}N_2$	roasted, nutty, earthy	4			1019	1403	1,7,9
	2-Isoamyl-6-methylpyrazine	91010-41-2	$C_{10}H_{16}N_2$	roasted, popcorn	4			1270		1
	2-Acetyl-6-methylpyrazine	22047-26-3	$C_7H_8N_2O$	mushroom, green	4			1131	1680	1,5,7,9
	2-Acetyl-3-methylpyrazine	23787-80-6	$C_7H_8N_2O$			4 (water)			1676	5–6
	2-Methyl-5-(trans-1-propenyl) pyrazine	18217-82-8	$C_8H_{10}N_2$						1713	5
	5-Methyl-2-pyrazinylmethanol	61892-95-3	$C_6H_8N_2O$						2065	5
	2,3-Dimethylpyrazine	5910-89-4	$C_6H_8N_2$	roasted, nutty, cocoa	2	35,000		932	1344	1-2,4–6,9,10,14
	Ethenylpyrazine	4177-16-6	$C_6H_6N_2$	popcorn, roasted	2			943	1437	1,9
	2,3-Diethyl-5-methylpyrazine	18138-04-0	$C_9H_{14}N_2$	roasted potato, nutty	2	7.2	27	1147	1468	1-3,8–9,12
	Pyrazinamide	98-96-4	$C_5H_5N_3O$	salty, sauce	2			1037	1724	1
	2-(1-Methylethenyl)-pyrazine	38713-41-6	$C_7H_8N_2$	popcorn, roasted	1			1034	1594	1
	2,3-Dimethyl-5-ethylpyrazine	15707-34-3	$C_8H_{12}N_2$	nutty, roasted	1	1 (water)		1103	1458	1-2,5-7
	2-Ethenyl-6-methyl-pyrazine	13925-09-2	$C_7H_8N_2$					981	1381	5-7,9
	Pyrazine	290-37-9	$C_4H_4N_2$					725		7
	2-Vinylpyrazine	4177-16-6	$C_6H_6N_2$					897		7
	2-Methyl-5-vinylpyrazine	13925-08-1	$C_7H_8N_2$					985		7,9
	Isopropylpyrazine	29460-90-0	$C_7H_{10}N_2$							9
	3-Isopropyl-2-methoxypyrazine	25773-40-4	$C_8H_{12}N_2O$	pea-like, earthy		0.07	35		1434	3–4
	3-Isobutyl-2-methoxypyrazine	24683-00-9	$C_9H_{14}N_2O$	bell pepper-like, earthy		0.8				3,11
	3-(Sec-butyl)-2-methoxypyrazine	24168-70-5	$C_9H_{14}N_2O$	earthy		0.46				3,12

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, μg/kg oil	OAV	RI Non-polar	Polar	References
	3-Methoxy-2,5-dimethylpyrazine	19846-22-1	$C_7H_{10}N_2O$	spicy, pepper					1385	8
Pyrroles	*N*-Furfuryl Pyrrole	1438-94-4	C_9H_9NO	vegetable, green	64			1200	1831	1,9
	2-Acetylpyrrole	1072-83-9	C_6H_7NO	caramel, nutty	2			1079	1976	1-2,4–5,7,9
	2-Pyrrolidinone	616-45-5	C_4H_7NO						2041	5
	2-Propionylpyrrole	1073-26-3	C_7H_9NO							9
	2-Formyl-5-methylpyrrole	1192-79-6	C_6H_7NO						2095	5,9
	Pyrrole	109-97-7	C_4H_5N	sweet, nutty	1			768	1522	1,9
	N-methylpyrrole	96-54-8	C_5H_7N						1140	2,4,9
	1H-Pyrrole-2-carboxaldehyde	1003-29-8	C_5H_5NO						2032	4,14
	2-Acetyl-1-pyrroline	85213-22-5	C_6H_9NO	roasty, popcorn-like		0.053	89	920	1318	3,12
	2-Propionyl-1-pyrroline	133447-37-7	$C_7H_{11}NO$	roasty, popcorn-like		0.10	37	1000	1382	3,12
	1-Ethyl-1H-pyrrole-2-carbaldehyde	2167-14-8	C_7H_9NO					1009		7,9
	2-Acetyl-1-methylpyrrole	932-16-1	C_7H_9NO							9
	1H-Pyrrole-1-carboxaldehyde	24771-28-6	C_5H_5NO							9
	2-Methylpyrrole	636-41-9	C_5H_7N							9
	2-Formyl-1-methylpyrrole	1192-58-1	C_6H_7NO						1612	5,9
Pyridines	2-Acetyl-3,4,5,6-tetrahydropyridine	27300-27-2	$C_7H_{11}NO$	popcorn, bread, rice	8			1061	1555	1
	Pyridine	110-86-1	C_5H_5N	medicinal, sharp	4			758	1172	1,9
	2-Acetylpyridine	1122-62-9	C_7H_7NO	roastey, steamed rice	4			1048	1601	1,4,9,3
	2-Acetyltetrahydropyridine	25343-57-1	$C_7H_{11}NO$	popcorn-like		1.2	6			3
	3-Methoxypyridine	7295-76-3	$C_5H_6N_2O$					961	1578	4-5,7
	Methyl nicotinate	93-60-7	$C_7H_7NO_2$					1095	1772	5,7,9
	Piperidin-2-one-, 5,6-didehydro-, 5-carboxylic acid methyl ester	80658-33-9	$C_7H_9NO_3$						2266	5
	3-Pyridinol	109-00-2	C_5H_5NO						2416	5
	1-Butylpyrrolidine	767-10-2	$C_8H_{17}N$						1155	5
	N-formyl pyrrolidine	3760-54-1	C_5H_9NO						1755	5
	N-acetyl pyrrolidine	4030-18-6	$C_6H_{11}NO$						1845	5
	2-Propylpyridine	622-39-9	$C_8H_{11}N$					1171		7
	5-Acetyl-2-methylpyrazine	36357-38-7	C_8H_9NO							9
	6-Acetyl-2-ethylpyrazine	34413-34-8	$C_8H_{10}N_2O$							9
	2-Methyl-6,7-dihydro-5H-cyclopentapyrazine	23747-46-8	$C_8H_{10}N_2$							9
	Quinoxaline	91-19-0	$C_8H_6N_2$							9
	5,6,7,8-Tetrahydroquinoxaline	34413-35-9	$C_8H_{10}N_2$							9
	2-Methylpyridine	109-06-8	C_6H_7N							9
	2-Pentylpyridine	2294-76-0	$C_{10}H_{15}N$							9
Furans	2,3-Dihydrobenzofuran	496-16-2	C_8H_8O	sweet, caramel	16			1240	2402	1-2,4-5
	2-Methyltetrahydrofuran-3-one	3188-00-9	$C_5H_8O_2$	fermented, fruity, wintergreen	8			822	1267	1,5
	2-Acetylfuran	1192-62-7	$C_6H_6O_2$	popcorn, sweet, coffee	4			927		1,5,7,9
	2-Ethyltetrahydrofuran	1003-30-1	$C_6H_{12}O$	popcorn, sweet	2			755		1
	1-(2-Furanyl)-1-pentanone	3194-15-8	$C_7H_8O_2$	sweet, caramel	2			927		1
	5-Methylfurfural	620-02-0	$C_6H_6O_2$	almond, caramel, spicy	2			979	1576	1,5,7,9,14
	2-Furanmethanol	98-00-0	$C_5H_6O_2$	bitter, spicy, burnt	2			821		1,2,4–5,7,9,14
	2-Vinylfuran	1487-18-9	C_6H_6O	garlic, smoky	1			733		1
	2-Pentylfuran	3777-69-3	$C_9H_{14}O$	buttery, vegetable	1	130		1007	1235	1-2,4,9,14
	3-Phenylfuran	13679-41-9	$C_{10}H_8O$							9

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, μg/kg oil	OAV	RI Non-polar	Polar	References
	2-Methylfuran	534-22-5	C_5H_6O						1233	4,14
	Dimethylmaleic anhydride	766-39-2	$C_6H_6O_3$						1730	4
	Methyl 2-furoate	611-13-2	$C_6H_6O_3$						1996	5
	5-Hydroxymethylfurfural	67-47-0	$C_6H_6O_3$	caramel-like, spicy					2495	5,13
Aldehydes	Benzeneacetaldehyde/Phenylacetaldehyde	122-78-1	C_8H_8O	floral, honey-like	512	37	29	1061	1645	1-5,7–9,12,14
	Benzaldehyde	100-52-7	C_7H_6O	sweet, malty				962	1512	2,4,5,7-9
	4-Hydroxy-3-methoxybenzaldehyde/Vanillin	121-33-5	$C_8H_8O_3$	vanilla-like		140		1351		3,7,10
	Pentanal	110-62-3	$C_5H_{10}O$						<1000	2,4–5,9,14
	Hexanal	66-25-1	$C_6H_{12}O$	green, oily, fruity, rancid	16	300	3	815	1088	1-5,7,9,10,14
	Heptanal	111-71-7	$C_7H_{14}O$	oily, rancid, pungent	2	500		917	1180	1-2,4–5,8,10
	Octanal	124-13-0	$C_8H_{16}O$	citrus-like, fatty	1	140	3	1020	1291	1-4,9,10
	Nonanal	124-19-6	$C_9H_{18}O$	green, oily, fruity, citrus-like,fatty	1	610		1122	1396	1-2,4,7–9,10
	Decanal	112-31-2	$C_{10}H_{20}O$	oily, orange, peel	1			1224	1501	1-2,5,8
	Tetradecanal	124-25-4	$C_{14}H_{28}O$	honey, hay				1618	1931	8
	(E)-2-hexenal	6728-26-3	$C_6H_{10}O$	bitter, almond-like		320		844	1188	4,8,10
	(Z)-3-hexenal	6789-80-6	$C_6H_{10}O$	green, apple-like						3
	(E)-2-heptenal	18829-55-5	$C_7H_{12}O$	green, oily, fried	16	1200		972		1,7,10,14
	(Z)-2-heptenal	57266-86-1	$C_7H_{12}O$							2,4
	2,4-Decadienal	2363-88-4	$C_{10}H_{16}O$	rancid, seaweed, oily	2			1336		1,4-5
	(E,E)-2,4-decadienal	25152-84-5	$C_{10}H_{16}O$	earthy, deep-fried, oily	16	66	5	1313	1808	1-4,7–9,10,14
	(E,Z)-2,4-decadienal	25152-83-4	$C_{10}H_{16}O$	fatty		4		1265		7,10
	(E,Z)-2,4-heptadienal	4313-02-4	$C_7H_{10}O$	fatty		55		968	1399	8,10
	(E,E)-2,4-nonadienal	5910-87-2	$C_{10}H_{20}O$	oily, waxy, green		30	22	1216	1670	2,10,14
	2-Methylbutanal	96-17-3	$C_5H_{10}O$	almond, fruity, chocolate, malty	8	10	97	<700		1,3–4,8,14
	3-Methylbutanal	590-86-3	$C_5H_{10}O$	malty, fruity, oily	4	5.4	118	<700		1,3–4,11,14
	2-Phenyl-2-butenal	4411-89-6	$C_{10}H_{10}O$	green, floral, woody	2			1292	1930	1-2,5,7,9
	Cinnamaldehyde	104-55-2	C_9H_8O						1829	4,9
	(E)-2-octenal	2548-87-0	$C_8H_{14}O$	fatty, nutty		120		1023	1422	2,4–5,7,10,14
	(E)-2-nonenal	18829-56-6	$C_9H_{16}O$	fatty		140		1127	1531	3-4,7,10
	(Z)-2-nonenal	60784-31-8	$C_9H_{16}O$	fatty, leaf-like		4	3			10
	(E)-2-decenal	3913-81-3	$C_{10}H_{18}O$	tallow, oily, orange	1	2200		1280	1643	1-3,5,7,10
	(Z)-2-decenal	2497-25-8	$C_{10}H_{18}O$	floral	1			1281		1,3
	2-Undecenal	2463-77-6	$C_{11}H_{20}O$	sweet, rancid	1	7700		1383	1750	1-2,5,10
	Furfural	98-01-1	$C_5H_4O_2$						1468	2,4,7–9,14
	2-Methylbenzaldehyde	529-20-4	C_8H_8O							9
	2-Ethylbenzaldehyde	22927-13-5	$C_9H_{10}O$							9
	4-Ethylbenzaldehyde	4748-78-1	$C_9H_{10}O$	burnt sugar				1163	1704	4,8-9
	p-Tolualdehyde	104-87-0	C_8H_8O						2405	4
	3-Phenylbutanal	16251-77-7	$C_{10}H_{12}O$						1783	4
	4-Oxononanal	74327-29-0	$C_9H_{16}O_2$					1198		7
	Hydratropaldehyde	34713-70-7	$C_9H_{10}O$						1627	5
	Acetaldehyde	75-07-0	C_2H_4O			0.2				9,10
	Isobutyraldehyde	78-84-2	C_4H_8O							9
	2-Methyl-2-butenal	1115-11-3	C_5H_8O							9
	2-Methyl-2-pentenal	623-36-9	$C_6H_{10}O$							9
	5-Methyl-2-phenyl-2-hexenal	21834-92-4	$C_{13}H_{16}O$							9

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, µg/kg oil	OAV	RI Non-polar	Polar	References
	Trans-4,5-epoxy-(E)-2-decenal	188590-62-7	$C_{10}H_{16}O_2$	metallic, green		13	4	1382	2000	3,10
Ketones	2,3-Butanedione	431-03-8	$C_4H_6O_2$	butter-like		0.90	10	592	996	3,9,12
	2,3-Pentanedione	600-14-6	$C_5H_8O_2$	caramel, buttery, sweet	32	0.30	286	711	1065	3,9,12
	Acetoin	513-86-0	$C_4H_8O_2$	buttery, fermented	2			723	1289	1,14
	2-Propanone	67-64-1	C_3H_6O						<1000	4,9
	2-Heptanone	110-43-0	$C_7H_{14}O$	soapy, banana	2			907	1176	1-2,4–5,9
	4-Heptanone	123-19-3	$C_7H_{14}O$							9
	2-Octanone	111-13-7	$C_8H_{16}O$						1286	4,9
	6-Methyl-5-hepten-2-one	110-93-0	$C_8H_{14}O$						1340	4
	1-(Acetyloxy)-2-propanone	592-20-1	$C_5H_8O_3$							2
	2-Cyclopentene-1,4-dione	930-60-9	$C_5H_4O_2$							2
	5-Ethyldihydro-2(3H)-furanone	57129-70-1	$C_6H_{10}O_2$							2
	3-Methyl-1,2-cyclopentanedione	765-70-8	$C_6H_8O_2$						1822	5
	4-Hydroxy-2,5-dimethyl-3(2H)-furanone/Furaneol	3658-77-3	$C_6H_8O_3$	caramel-like		27	78	1071	2042	1,3,8,12
	3-Hydroxy-4,5-dimethyl-2(5H)-furanone/Sotolon	28664-35-9	$C_6H_8O_3$	seasoning-like		1.6	2			3
	3-Penten-2-one	625-33-2	C_5H_8O							9
	1-Octen-3-one	4312-99-6	$C_8H_{14}O$	mushroom-like		61			1294	3,5,10
	3-Octen-2-one	1669-44-9	$C_8H_{14}O$						1407	4
	3-Penten-2-one,4-methyl-/4-Methyl-3-penten-2-one	141-79-7	$C_6H_{10}O$						1129	4,9
	Acetophenone	98-86-2	C_8H_8O	fruity, sweet				1027		7–9
	2-Butanone	78-93-3	C_4H_8O							9
	2-Pentanone	107-87-9	$C_5H_{10}O$							9
	4-Methyl-2-pentanone	108-10-1	$C_6H_{12}O$							9
	Cyclopentanone	120-92-3	C_5H_8O							9
	Cyclohexanone	108-94-1	$C_6H_{10}O$							9
	2-Undecanone	112-12-9	$C_{11}H_{22}O$							9
	Ethyl phenyl ketone	93-55-0	$C_9H_{10}O$							9
	Benzyl methyl ketone	103-79-7	$C_9H_{10}O$							9
	2-Hydroxy-3-rnethyl-2-cyclopenten1-one	21835-01-8	$C_7H_{10}O_2$							9
	Carvone	6485-40-1	$C_{10}H_{14}O$							9
Acids	Acetic acid	64-19-7	$C_2H_4O_2$	pungent		350	24	610	1496	2-4,10,14
	3-Methyl-butanoic acid	503-74-2	$C_5H_{10}O_2$	sweaty, rancid		11			1663	5,10
	3-Methyl crotonic acid	541-47-9	$C_5H_8O_2$						1787	5
	Phenylacetic acid	103-82-2	$C_8H_8O_2$	honey-like		26	7			3,12
	Benzoic acid	65-85-0	$C_7H_6O_2$						2430	4–5
	Pentanoic acid	109-52-4	$C_5H_{10}O_2$	sweaty, pungent		400	922	1730		4-5,10,12
	Hexanoic acid	142-62-1	$C_6H_{12}O_2$	sweaty, pungent		460	1018	1837		4-5,10,14
	(E)-2-hexenoic acid	13419-69-7	$C_6H_{10}O_2$	fatty				1632	1938	8
	Heptanoic acid	111-14-8	$C_7H_{14}O_2$						1945	4–5
	Octanoic acid	124-07-2	$C_8H_{16}O_2$						2052	4–5
	Nonanoic acid	112-05-0	$C_9H_{18}O_2$						2159	4–5
	Decanoic acid	334-48-5	$C_{10}H_{20}O_2$			230,000			2298	4,9,10
	Stearic acid	57-11-4	$C_{18}H_{36}O_2$						2580	5
	Oleic acid	112-80-1	$C_{18}H_{34}O_2$						>2600	5

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, μg/kg oil	OAV	RI Non-polar	Polar	References
	Myristic acid	544-63-8	$C_{14}H_{28}O_2$						>2600	5
	Palmitic acid	57-10-3	$C_{16}H_{32}O_2$						>2600	5
Esters	Dimethylphthalate	131-11-3	$C_{10}H_{10}O_4$							2
	Geranyl butyrate	106-29-6	$C_{14}H_{24}O_2$	rose-like				1544	1888	8
	Methyl cinnamate	103-26-4	$C_{10}H_{10}O_2$	strawberry					2045	8
	1-Acetoxyacetone	592-20-1	$C_5H_8O_3$						1454	5
	Beta-terpinyl acetate	10198-23-9	$C_{12}H_{20}O_2$						1588	5
	Alpha-terpinenyl acetate	80-26-2	$C_{12}H_{20}O_2$						1688	5
	1-Phenylethyl acetate	93-92-5	$C_{10}H_{12}O_2$						1691	5
	Methyl furan-3-carboxylate	13129-23-2	$C_6H_6O_3$							9
	Ethyl furoate	614-99-3	$C_7H_8O_3$							9
	Ethyl Acetate	141-78-6	$C_4H_8O_2$							9
	Ethyl butanoate	105-54-4	$C_6H_{12}O_2$							9
	Butyl acetate	123-86-4	$C_6H_{12}O_2$						1071	4,9
	Furan-2-ylmethyl acetate	623-17-6	$C_7H_8O_3$							9
	1-Hexyl acetate	142-92-7	$C_8H_{16}O_2$						1267	5
	Ethyl caprate	110-38-3	$C_{12}H_{24}O_2$						1635	4
	Ethyl valerate	539-82-2	$C_7H_{14}O_2$	fruity				915	1116	8
	Methyl hexanoate	106-70-7	$C_7H_{14}O_2$	sweet				1015	1154	8
	n-Butyl butanoate	109-21-7	$C_8H_{16}O_2$						1861	5
	Ethyl 2-ethoxyacetate	817-95-8	$C_6H_{12}O_3$							9
	Phenyl acetate	122-79-2	$C_8H_8O_2$							9
	Tolyl acetate	1333-46-6	$C_9H_{10}O_2$							9
	2-Phenylethyl propanoate	122-70-3	$C_{11}H_{14}O_2$							9
Lactones	Gamma-valerolactone	108-29-2	$C_5H_8O_2$						1608	4
	3-Methylbutyrolactone	1679-49-8	$C_5H_8O_2$						1614	4
	Gamma-butyrolactone	96-48-0	$C_4H_6O_2$	sweet, caramel					1619	4-5,9,13,14
	Delta-valerolactone	542-28-9	$C_5H_8O_2$						1804	4
	Gamma-nonalactone	104-61-0	$C_9H_{16}O_2$	coconut-like			1313	2027		4,7,12
	Gamma-octalactone	104-50-7	$C_8H_{14}O_2$	coconut-like		120		1263	1920	9
	Delta-decalactone	705-86-2	$C_{10}H_{18}O_2$	sweet, fruity				1471	2209	8
	Pantolactone	599-04-2	$C_6H_{10}O_3$	burnt sugar				1689	2023	4,5,8
	4-Acetoxy-2,5-dimethyl-3(2H)-furanone	4166-20-5	$C_8H_{10}O_4$	burnt sugar				1386	1981	8
Alcohols	1-Hexanol	111-27-3	$C_6H_{14}O$	floral, green, woody	32			884	1357	1-2,4,9,11,14
	2-Hexanol	626-93-7	$C_6H_{14}O$							9
	Pentyl alcohol	71-41-0	$C_5H_{12}O$							9
	3-Hexen-1-ol	544-12-7	$C_6H_{12}O$							9
	Cyclohexanol	108-93-0	$C_6H_{12}O$							9
	Heptyl alcohol	111-70-6	$C_7H_{16}O$							9
	Methylbenzyl alcohol	98-85-1	$C_8H_{10}O$							9
	2-Ethyl-1-hexanol	50373-29-0	$C_8H_{18}O$						1486	5
	L-Linalool	126-91-0	$C_{10}H_{18}O$						1541	5
	Acetol	116-09-6	$C_3H_6O_2$						1291	5,14
	1-Dodecanol	112-53-8	$C_{12}H_{26}O$						1961	5
	Benzyl alcohol	100-51-6	C_7H_8O						1905	5,9
	1-Octen-3-ol	3391-86-4	$C_8H_{16}O$	mushroom, earthy	8			997	1454	1-2,4
	1-Octanol	111-87-5	$C_8H_{18}O$	soapy, oily	4			1089		1-2,4–5,7

(*continued on next page*)

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, µg/kg oil	OAV	RI Non-polar	RI Polar	References
	Eucalyptol	470-82-6	$C_{10}H_{18}O$	minty, oily, camphoraceous odor	2	17		1047	1206	1,12
	Ethanol	64-17-5	C_2H_6O						<1000	4
	2-Propanol	67-63-0	C_3H_8O						<1000	4
	2-Butanol	15892-23-6	$C_4H_{10}O$						<1000	4
	1-Pentanol	71-41-0	$C_5H_{12}O$						1250	2,4–5,14
	1-Nonanol	143-08-8	$C_9H_{20}O$	floral, soapy	1			1189	1662	1,4,14
	2,3-Butanediol	513-85-9	$C_4H_{10}O_2$	fruity				803	1582	2,4,8
	3,5-Octadien-2-ol	69668-82-2	$C_8H_{14}O$							2
	Isobutyl alcohol	78-83-1	$C_4H_{10}O$						1092	4,9
	3-Methyl-1-butanol	123-51-3	$C_5H_{12}O$						1207	4
	2-(2-Ethoxyethoxy)ethanol	111-90-0	$C_6H_{14}O_3$						1618	4
	2-(2-Butoxyethoxy)ethanol	112-34-5	$C_8H_{18}O_3$						1791	4
	Phenylethyl alcohol	60-12-8	$C_8H_{10}O$		211			1076	1912	4,7,9,11
	Sulfurol	137-00-8	C_6H_9NOS						2309	4
	Isopropyl alcohol	1344575-38-7	C_3H_8O							9
	1-Butyl alcohol	71-36-3	$C_4H_{10}O$							9
	2-Pentanol	6032-29-7	$C_5H_{12}O$							9
	3-Pentanol	584-02-1	$C_5H_{12}O$							9
	1-Penten-3-ol	616-25-1	$C_5H_{10}O$							9
	4-Methyl-2-pentanol	108-11-2	$C_6H_{14}O$							9
	2-Methylbutan-1-ol	137-32-6	$C_5H_{12}O$							9
	Ethylnaphthalene	104-76-7	$C_8H_{18}O$							9
	Alpha-Terpineol	98-55-5	$C_{10}H_{18}O$							9
Phenols	2-Methoxyphenol/Guaiacol	9009-62-5	$C_7H_8O_2$	smoky, burnt	16			1157	1863	1,3,5,8-9
	2-Methoxy-4-vinylphenol	7786-61-0	$C_9H_{10}O_2$	smoky, burnt, roasted peanut	16	98	40	1332	2199	2-3,5,7,9,12,14
	5-Ethenyl-2-methoxyphenol	621-58-9	$C_9H_{10}O_2$	burnt, smoky, nutty	4			1335		1
	4-Amino-2-methylphenol	2835-96-3	C_7H_9NO	popcorn	4			1066		1
	Phenol	108-95-2	C_6H_6O					949	1995	2,5,7,9
	4-Ethylphenol	123-07-9	$C_8H_{10}O$					1133		2,7,9
	3-Ethylphenol	620-17-7	$C_8H_{10}O$	old books, musty		8		1176		8,10
	4-Vinylphenol	2628-17-3	C_8H_8O	spicy, phenolic				1183		3,7,9
	Maltol	118-71-8	$C_6H_6O_3$	cotton candy, caramellic-sweet, warm-fruit				1106	1959	2,4,5,8
	p-Cresol	106-44-5	C_7H_8O			17		1041		7,12,14
	4-Ethyl-2-methoxyphenol	2785-89-9	$C_9H_{12}O_2$					1252		7
	Sesamol	533-31-3	$C_7H_6O_3$					1278		7
	4-(2-Butyl)phenol	99-71-8	$C_{10}H_{14}O$					1287		7
	2-Sec-butylphenol	89-72-5	$C_{10}H_{14}O$						2184	4,9
	Butylated hydroxytoluene	128-37-0	$C_{15}H_{24}O$					1488		7,9
Sulphury compounds	Dimethyl sulfone	67-71-0	$C_2H_6O_2S$	sulphury, rice	512			936		1
	Dimethyl trisulphide	3658-80-8	$C_2H_6S_3$	sulphury, cabbage	32	2.3		982	1378	1,3,11
	3-(Methylthio)propanal	3268-49-3	C_4H_8OS	cooked-potato		0.2	200			3
	Tetrahydrothiophen-3-one	1003-04-9	C_4H_6OS	sulphury, meaty, buttery	2			964	1563	1

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, µg/kg oil	OAV	RI Non-polar	RI Polar	References
	Methanethiol	74-93-1	CH_3S	sulfury		0.36	1889			3,12
	2-Furfurylthiol	98-02-2	C_5H_6OS	coffee-like, burnt		0.019	22	912	1418	3,12
	Dimethyl disulfide	624-92-0	$C_2H_6S_2$			44		652	1079	9,12
	Propyl disulfide	629-19-6	$C_6H_{14}S_2$							9
	2-Acetyl-2-thiazoline	29926-41-8	C_5H_7NOS	roasty, popcorn-like		1.8	1	1106	1780	3
	4-Methylthiazole	693-95-8	C_4H_5NS							9
	Benzothiazole	95-16-9	C_7H_5NS							9
	2-Methyltetrahydrothiophen-3-one	13679-85-1	C_5H_8OS							9
	Dihydrothiophen-3(2H)-one	1003-04-9	C_4H_6OS							9
	2-Acetylthiophene	88-15-3	C_6H_6OS							9
	3-Phenylthiophene	2404-87-7	$C_{10}H_8S$					1384		7
	5-Methylthiophene-2-carboxaldehyde	13679-70-4	C_6H_6OS							9
	Benzyl methyl disulfide	699-10-5	$C_8H_{10}S_2$							9
Hydrocarbons	5-Phenylundecane	4537-15-9	$C_{17}H_{28}$							2
	(1-Propyloctyl)-benzene	4536-86-1	$C_{17}H_{28}$							2
	(1-Methyldecyl)-benzene	4536-88-3	$C_{17}H_{28}$							2
	(1-Pentylheptyl)-benzene	2719-62-2	$C_{18}H_{30}$							2
	(1-Butyloctyl)-benzene	2719-63-3	$C_{18}H_{30}$							2
	(1-Propylnonyl)-benzene	2719-64-4	$C_{18}H_{30}$							2
	Benzene	71-43-2	C_6H_6							9
	Ethylbenzene	100-41-4	C_8H_{10}							9
	p-Xylene	106-42-3	C_8H_{10}							9
	m-Xylene	108-38-3	C_8H_{10}							9
	o-Xylene	95-47-6	C_8H_{10}							9
	Propylbenzene	103-65-1	C_9H_{12}							9
	Mesitylene	108-67-8	C_9H_{12}							9
	1,2,4-Trimethylbenzene	95-63-6	C_9H_{12}							9
	Butylbenzene	104-51-8	$C_{10}H_{14}$							9
	Indene	95-13-6	C_9H_8							9
	Methyl-2,3-dihydroindene	27133-93-3	$C_{10}H_{12}$							9
	1,2,3,4-Tetrahydronaphthale	119-64-2	$C_{10}H_{12}$							9
	Toluene	108-88-3	C_7H_8	sweet, chemical				756	1027	8
	Naphthalene	91-20-3	$C_{10}H_8$					1162		7
	Methylnaphthalene	1321-94-4	$C_{11}H_{10}$							9
	Dimethylnaphthalene	575-43-9	$C_{12}H_{12}$							9
	Biphenyl	92-52-4	$C_{12}H_{10}$							9
Alkanes	3,3,5-Trimethyl-heptane	7154-80-5	$C_{10}H_{22}$	popcorn, steamed rice	4			1039		1
	2,4-Dimethylheptane	2213-23-2	C_9H_{20}						<1000	4
	4-Methyloctane	2216-34-4	C_9H_{20}						<1000	4
	2,2,4,6,6-Pentamethylheptane	13475-82-6	$C_{12}H_{26}$						<1000	4
	n-Pentane	109-66-0	C_5H_{12}						<1000	2,4
	Heptane	142-82-5	C_7H_{16}						<1000	4
	Octane	111-65-9	C_8H_{18}	citrus, fruity	1			812		1,4
	Decane	124-18-5	$C_{10}H_{22}$						<1000	4
	Undecane	1120-21-4	$C_{11}H_{24}$					1100	1096	2,4,7
	Dodecane	112-40-3	$C_{12}H_{26}$					1200	1199	2,4,5,7
	Tridecane	629-50-5	$C_{13}H_{28}$					1300		7

Table 2 (*continued*)

Types	Volatile compounds	CAS	Molecular formula	Odor	FD	OT, µg/kg oil	OAV	RI Non-polar	Polar	References
	Tetradecane	629-59-4	$C_{14}H_{30}$					1400	1396	2,4,5,7
	Pentadecane	629-62-9	$C_{15}H_{32}$							2
Alkenes	(Z)-2-Octene	7642-04-8	C_8H_{16}						<1000	4
	(E)-2-Octene	13389-42-9	C_8H_{16}						<1000	4
	D-limonene	5989-27-5	$C_{10}H_{16}$	lemon, citrus	16			1044	1190	1,5
	Limonene	138-86-3	$C_{10}H_{16}$						1195	4,9
	Beta-Phellandrene	555-10-2	$C_{10}H_{16}$	popcorn	1			988		1
	Delta-elemene	20307-84-0	$C_{15}H_{24}$	wood				1361		8
	Myrcene	123-35-3	$C_{10}H_{16}$						1159	5,9
	p-Cymene	99-87-6	$C_{10}H_{14}$							9
	Alpha-pinene	80-56-8	$C_{10}H_{16}$						<1000	4
	Beta-pinene	127-91-3	$C_{10}H_{16}$							9
	Sabinene	3387-41-5	$C_{10}H_{16}$							9
	Styrene	100-42-5	C_8H_8					870		2,7,9
Others	2-Ethyl-1H-benzimidazole	1848-84-6	$C_9H_{10}N_2$	bitter	8			1403	1403	1
	1,2,3,4-Tetrahydro-quinoline	635-46-1	$C_9H_{11}N$	meaty	1			1254	1831	1
	Benzeneacetonitrile	140-29-4	C_8H_7N					1085		7
	Trigonelline	535-83-1	$C_7H_7NO_2$					1096		7

Note: the number of reference means: 1, [24]; 2, [25]; 3, [26]; 4, [27]; 5, [28]; 6, [29]; 7, [30]; 8, [31]; 9, [32]; 10, [33]; 11, [34]; 12, [35]; 13 [8],

Abbreviations: FPOs, fragrant peanut oils; RI, retention index; CAS, chemical abl abstracts ss service; FD, flavor dilution; OT, odor threshold; OAV, odor active value.

94 volatile compounds were identified and characterized by headspace solid-phase microextraction (HS-SPME)/gas chromatography-mass spectrometry (GC-MS). In 2019, 101 volatiles were identified in the hot-pressed peanut oil by Dun et al. [25]. Among them, 29 volatile compounds were reported for the first time. As a result, majority of research had been mainly focused on the profiling of volatile compounds in peanut oils and hundreds of volatile compounds have been identified and classified. However, among complex volatile compounds, only some key volatiles can remarkably affect the overall flavor quality, while other volatiles have almost no contribution. Hence, recent researchers focus on the separation and identification of such key volatiles or aroma-active compounds, rather than simply looking at the whole picture of volatiles [8].

The importance of individual volatile compounds can be assessed by means of GC sniffing, aroma extract dilution analysis (AEDA) coupled to gas chromatography-olfactometry (GC-O), odor-specific magnitude estimation (OSME), calculation of odor active values (OAV), and sometimes aroma recombination experiments [8]. In 2008, an investigation was performed to compare the primary odorants in raw and grounded roasted peanut meals. The identification experiments revealed that 20 flavor compounds were newly identified in roasted peanuts [39]. Very recently, Yin et al. [24] focused on the aroma-active compounds roasted peanut oils. Fifty-nine odorants were newly identified in the peanut oils. Both of the above experiments include recombination experiments to verify the importance of key aroma-active compounds.

In order to have a better understanding of the flavor substances in FPOs, volatile compounds in CPPOs were also summarized for comparison. The general species and contents of volatile compounds in FPOs and CPPOs were illustrated in Fig. 2. Despite similarities in the types of volatile compounds, the total quantity of volatiles in FPOs reaches approximately 300, representing a fivefold increase compared to CPPOs. The volatile profile covers alkanes/alkenes, aldehydes, alcohols, ketones, acids, phenols/phenolics, pyrazines, furans, sulphury compounds, esters, pyrroles, and aromatic hydrocarbons. In addition, it is important to note that only a limited number of key aroma-active compounds can contribute to the overall flavor of FPOs. These aroma-active compounds will be a hot topic for future studies of fragrant oils, and will also be the focus of discussion in the formation mechanism below. In the following discussion, a close look at the species of volatiles in FPOs is given for the purpose of better understanding the context of the findings and related information.

3.1. N-heterocyclic compounds

N-heterocyclic compounds, including pyrazines, pyrroles, pyridines, pyrrolines, etc., predominate in the flavor volatiles of FPOs. Liu et al. [28] indicated that the *N*-heterocyclic compounds possessed the highest relative percentage (61.68 %), followed by the O-heterocyclic group with a relative percentage of 24.57 % among the volatiles identified in FPOs. Twenty pyrazines were considered to be the key contributors to the intense nutty/roasty flavor, typical of flavor characteristic of FPOs.

3.1.1. Pyrazines
Pyrazines were the predominant volatile compounds, accounting for 18–39 % of the total amount of volatiles in FPOs. As shown in Table 2 and Fig. 2, more than 40 pyrazines had been reported, mainly belonging to alkylpyrazine and methoxypyrazine.

Alkylpyrazines, such as 2,5-dimethylpyrazine, methylpyrazine, and 2,5-dimethyl-3-ethylpyrazine [25], were frequently reported, providing a nutty and roasty flavor characteristic [28]. However, the odor threshold values (OTs) of the mono-, di-, trimethylpyrazines were relatively high [28], so these alkylpyrazines probably only play minor roles in the oil flavor. For example, the OTs of 2-methylpyrazine, 2,3-dimethylpyrazine, trimethylpyrazine, and 2,5-dimethylpyrazine are 27 mg/kg/oil, 35 mg/kg/oil, 27 mg/kg/oil and 2 mg/kg/oil, respectively. Besides, eight alkylpyrazines showed no contribution to the overall flavor of peanut through recombination experiments [26]. According to Motram [40], a marked decrease in the OT could be observed by replacing one or more methyl groups with ethyl groups. Thus, some ethyl-substituted pyrazines were demonstrated to have sufficiently low OTs for them to be important in
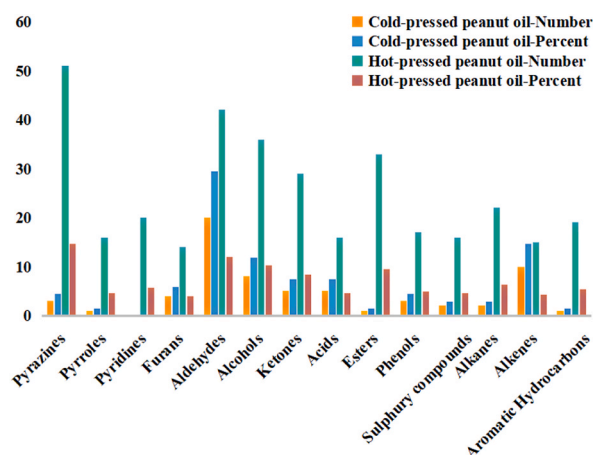
Fig. 2. Comparison of volatile components between FPOs and CPPOs. Abbreviations: FPOs, fragrant peanut oils; CPPOs, cold pressed peanut oils.

the roasted flavor of cooked foods. Interestingly also, 2,3-diethyl-5-methylpyrazine exhibited a roasted potato and nutty flavor in the pumpkin seed oil. Its OT and OAV were 0.5 μg/kg and 338, respectively [41], indicating the high sensitivity of flavor contribution. Acetylpyrazines are included in Table 2 and merit particular attention. They provide a popcorn-like flavor characteristic, whose OTs were in the low range [42]. 2-Acetylpyrazine is different from the alkylpyrazines not only in its structure but also in its formation pathway.

Another important pyrazine is methoxypyrazine, which is suggested to be the metabolites of raw peanut seeds [39]. In addition, these odorants are not lost to a significant degree during the roasting procedure [39]. Although their concentration was as low as ppb (μg/kg) levels, they showed high OAVs because of their extremely OTs. For example, 2-isopropyl-3-methoxypyrazine with a pea-like, earthy flavor, 2-(*sec*-butyl)-3-methoxypyrazine with an earthy flavor, and 2-isobutyl-3-methoxypyrazine with a bell pepper-like, earthy flavor, have FD factors of 2048, 32, and 512, respectively, in raw peanut meal [41].

3.1.2. Pyrroles

Pyrroles accounted for 2.03–4.65 % of the total amount of volatiles in FPOs [25,43]. *N*-Furfuryl pyrrole, 2-acetylpyrrole and *N*-methylpyrrole are the most frequently reported pyrroles, providing a vegetable/green flavor, a musty flavor, and a caramel/nutty flavor characteristic, respectively [26,44]. 2-Acetylpyrrole known as a typical Maillard reaction product contributes to the nutty/r-oasty flavor in pumpkin seeds, while the roasting process requires a roasting temperature of at least 90 °C [45]. Among the roasted (popcorn-like) smelling odorants in pan-roasted peanut meal, 2-acetyl-1-pyrroline had the highest concentration, followed by 2-ace-tylpyrazine, 2-propionyl-1-pyrroline, and 2-acetyl-2-thiazoline [26]. The specific precursor for 2-propionyl-1-pyrroline is 2-oxobutan-al, which is supplied by cleavage of carbohydrate skeletons [46]. 2-Acetyl-1-pyrroline can be suggested as the main contributor to the roasted (popcorn-like) note of roasted oils [26,41,47,48]. The production of 2-acetyl-1-pyrroline from proline and reducing carbo-hydrates has been reported, with 1-pyrroline and 2-oxopropanal serving as key intermediates [49,50]. Two other popcorn-like odorants, 2-propionyl-1-pyrroline and 2-acetyl-tetrahydropyridine, were also identified as constituents of roasted peanuts [26]. 1-Pyr-roline and hydroxy-2-propanone have been identified as effective intermediates in the formation of the roast-smelling food odorant, 2-acetyltetrahydropyridine [50].

3.2. O-heterocyclic compounds

Furans, a significant class of compounds, are primarily generated through lipid peroxidation, carbohydrate degradation, and Maillard reaction, providing sweet, malty, and caramel-like flavor characteristics in foods [51–53]. After heating, not only the variety but also the content of furans increase significantly [25]. As depicted in Table 2, a total of 14 furans were identified in FPOs, among which 2,3-dihydrobenzofuran, 2-acetylfuran, 5-methylfurfural, and 2-pentylfuran are detected most frequently. 5-Methylfurfural provides an almond, caramel, and spicy flavor characteristic, while 2-acetylfuran exhibits a sweet, popcorn, and coffee flavor characteristic.

2-Alkyl furans, such as 2-pentylfuran, 2-vinylfuran, and 2-methylfuran, are tertiary degradation products of lipid oxidation [54]. 2-Pentylfuran is one of the most reported frequency furans with a butter and green beans flavor. 2-Vinylfuran is known for its garlic and smoky flavor. It has been noticed that 2-vinylfuran can be produced by the degradation of 4-oxo-2-hexenal (OHE), which was formed by ω-3 polyunsaturated fatty acids peroxidation [55]. Acetylated furans, which are products of the automatic oxidation of lipids or the degradation of carbohydrates, have been reported in a variety of nuts and oilseeds, and generally exhibit a caramel, sweet flavor characteristic [45].

4-Hydroxy-2,5-dimethyl-3(2H)-furanone (HDMF) underwent a significant concentration change during the roasting procedure, whose FD factors increased from 32 to 2048 in the peanut meal [39]. HDMF with a caramel-like aroma contributes to the overall aroma of varieties of foods [56], such as roasted coffee [57], roasted meat [58], chocolate [59], wheat bread crust [60], and popcorn. HDMF also were detected in FPOs and microwave treated peanuts [24,31,61]. HDMF gained widespread attention because of its relatively low flavor thresholds of 0.03 mg (taste) and 0.1 mg per liter water (odor) [56]. 3-Hydroxy-4,5-dimethyl-2(5H)-furanone (Sotolon) is a chiral furanone, which is known to be responsible for seasoning-like flavor in peanut, as well as many other foods [62,63]. Maltol, another O-heterocyclic compound, had been found in roasted peanuts, providing caramellic-sweet and warm-fruity flavor notes [28]. Earlier research confirmed the important role of the disaccharide maltose in the formation of maltol [64].

3.3. Aldehydes

Aldehydes, small-molecule volatiles commonly present in edible oils, are formed through fatty acid oxidation and contribute to green, nutty, and even sour flavor characteristics [65]. About forty-three aldehydes have been reported in FPOs or peanuts, with phenylacetaldehyde and hexanal being the most frequently reported. The next most prevalent aldehydes include (*E,E*)-2,4-decadienal, 2-methylbutanal, 3-methylbutanal, heptanal, 2-phenyl-2-butenal, (E)-2-octenal, nonanal, decanal, benzaldehyde, and furfural, etc. The importance of lipid degradation products, in particular, (*E,E*)-2,4-decadienal, hexanal, (E)-2-decenal, *trans*-4,5-epox-y-(E)-2-decenal, octanal, (E)-2-nonenal, and (*E,E*)-2,4-nonadienal, in the characteristic aroma of the freshly roasted peanut materials were confirmed by aroma recombination experiments [26].

As shown in Table 2, saturated aldehydes, such as hexanal and octanal, provide a green, oily, fruity, rancid flavor and citrus-like, fatty flavor characteristics, respectively. Monounsaturated aldehydes, (E)-2-decenal and (E)-2-nonenal, provide a tallow, oily, orange flavor and a fatty flavor characteristic, respectively. Polyunsaturated aldehydes, (*E,E*)-2,4-decadienal and (*E,E*)-2,4-nonadienal, pro-vide an earthy, deep-fried, oily flavor and an oily, waxy, green flavor characteristic, respectively. In addition, an epoxyaldehyde,

known as *trans*-4,5-epoxy-(E)-2-decenal with a green, metallic odor, had a FD factor being 512 in the peanut meal.

Prior studies indicate that Strecker aldehydes, including methylpropanal, 2-methylbutanal, 3-methylbutanal, phenylacetaldehyde, and 3-(methylthio)propanal, play a crucial role in the generation of peanut aroma, which undergoes a significant enhancement during the roasting process. Benzaldehyde and phenylacetaldehyde are well known as Strecker degradation products of phenylalanine, provided almond-like and honey-like, floral flavor notes [28,39]. However, different studies may present various flavors for the same volatile compounds. An early research result revealed the increased formation of phenylacetaldehyde in the off-flavored peanuts, which resulted in the stale/floral flavor noted by a trained panelist [31]. Lately, more work reported that phenylacetaldehyde, an important flavor compound, provided a honey-like flavor [41,66], with an FD factor being 256 in roasted peanuts [26].

3.4. Ketones

About twenty-nine ketones are shown in Table 2, of which 2-heptanone has been reported frequently, followed by 2,3-pentanedione, 2,3-butanedione, 2-octanone, 1-octen-3-one, 2-propanone, and acetophenone. Thermal treatment is more conducive to the formation of these compounds. The saturated ketone, 2-heptanone, was identified at the beginning stage of the roasting, probably intensified the slightly fruity or fatty attributes of slightly roasted peanut oils [28]. 2-Heptanone with a soapy and banana flavor, was also previously identified as an aroma-active compound in roasted sesame oils [67]. 2-Octanone, a product of oleic acid oxidation, was detected both in the roasted normal- and high oleic (HO) peanut oils, exhibiting a slightly elevated concentration in the latter [27]. Methyl ketone, for example, 2-heptanone, 2-nonanone, and 2-undecanone, can be produced by bioconversion [68,69].

High levels of 2,3-pentanedione and 2,3-butanedione (both with buttery odor) were found in roasted peanut seeds [32,26]. The concentration of 2,3-pentanedione increased from 6.1 µg/kg to 83 µg/kg after roasting processing in peanut meals, while 2,3-butanedione increased from 0 to 90 µg/kg under the same operating condition. Both 2,3-pentanedione and 2,3-butanedione are typical Maillard reaction products [70]. Unsaturated ketone, 1-octen-3-one was likely to contribute to the overall flavor of roasted peanuts with a FD factor of 1024, which is the product of the 10-hydroperoxide of linoleic acid through the β-scission route [39,51]. It was known to be a product of the peroxidation of unsaturated fatty acids and provides a mushroom-like flavor in peanut meal, which also showed a clear increase after roasting [39].

3.5. Acids

Approximately sixteen acids were found in the FPOs shown in Table 2. Notably, several acids, including butanoic acid (sweaty), 2-methylbutanoic acid (sweaty, cheese-like, rancid), 3-methylbutanoic acid (sweaty, cheese-like, rancid), phenylacetic acid (honey-like), and acetic acid (pungent) were found to be typical aroma-active compounds in roasted peanuts based on the molecular sensory science method, which contributed sweaty, pungent, and vinegar-like aroma characteristics [26].

Phenylacetic acid provides a honey-like flavor, and its content is 109 µg/kg and 2363 µg/kg in raw and roasted peanut meal, respectively. The level of phenylacetic acid increased significantly after roasting, as it is a product of Maillard reaction [26,71]. Short chain and medium chain fatty acids, including pentanoic acid, hexanoic acid, heptanoic acid, octanoic acid, nonanoic acid, and decanoic acid, had also been reported in peanut oils after roasting [28,27]. Saturated fatty acids such as acetic acid, hexanoic acid, and nonanoic acid are produced by oxidation of their corresponding aldehydes, were important for the flavor of edible oils. For example, nonanoic acid presents a low odor threshold (12 ng/L) and contributes to the green and fatty flavor in peanut oils. Its content increases with the degree of oil oxidation [72].

3.6. Esters

About thirty-one esters had been reported in FPOs, including nine lactones. Lactones were related to the fruity and flowery-like odor with relatively low FD factors [51].

Two lactones with high reporting frequency, namely butyrolactone and pantolactone, were also identified, whose formations attributed to lipid peroxidation [73]. Butyrolactone, providing a sweet, caramel flavor, was detected in both normal- and HO peanut oils using a semi-quantitative method, with the contents of 0.53 % and 0.74 %, respectively [28,27]. In 1971, about ten esters were reported in peanut oils by Walradt et al. [32], including ethyl acetate, ethyl butanoate, and ethyl furoate, etc. Owing to the constraints in the testing conditions during that period, the accuracy of structural identification was comparatively low. Lactones can arise through various routes, including biogenetical and various chemical routes with thermal, oxidative, and enzymatic pathways [74].

3.7. Sulfur compounds

Small amounts of sulfur compounds have previously been reported in peanut oils. Methanethiol (sulfury), 3-(methylthio)propanal (cooked-potato), 2-furfurylthiol (coffee-like, burnt), and dimethyl trisulfide (sulfury) were reported, whose OAVs are 1889, 200, 22, and 1, respectively, in the roasted peanut meal [26]. Methanethiol was proved to be of great importance for the overall aroma of the roasted peanut. With regard to the formation mechanism of sulfur compounds in beer, methanethiol, a potential precursors of dimethyl polysulfide, is usually co-present with dimethyl sulfur and dimethyl trisulfide [75]. 3-(Methylthio) propanal (methional) plays an important role in peanut flavor generation, whose formation pathway was suggested to be the degradation of free amino acids via a Strecker-type reaction [76]. The concentration of 3-(methylthio)propanal increased by 5 times after thermal treatment [26]. 3-(Methylthio)propanal and other sulfur compounds were detected when methionine was heated together with another precursor

[77]. Model experiments performed by Yu and Ho [78] showed that a very high amount of the Strecker aldehydes were proposed to be generated from methionine or methional sulfoxide with glucose.

Another kind of *S*- and *N*-heterocyclic compounds, specifically, 2-acetyl-2-thiazoline, 2-acetylthiophene, and 4-methylthiazole, were also reported in peanut oils [32,26]. The former, with a roasted and popcorn-like flavor, had a FD factor of 32 in the roasted peanut meal, with an even lower OT (1.8 μg/kg) [26]. 2-Acetyl-2-thiazoline is a compound resulting from the Maillard reaction between cysteine and carbohydrates. It have been proven through the validation experiment that 2-(1-hydroxyethyl)-4,5-dihydrothiazol serves as one of the precursors for 2-acetyl-2-thiazoline [79,80].

3.8. Alcohols

A total of 37 alcohols have been reported in previous studies, as depicted in Fig. 2. Among the various alcohols, phenylethyl alcohol (grassy, floral), 1-hexanol (floral, green, woody), 1-octen-3-ol (mushroom, earthy), benzyl alcohol (fresh bread-like), 1-octanol (oily, sweet), 1-pentanol (sweet, fruity), 2,3-butanediol (burning, plastic flavor), and 1-nonanol (floral, oily) are the most prevalent. The content of nine alcohols in the peanut seeds showed few changes after a 50 min roasting at 200 °C [28]. Synthesis pathways for alcohols with 5–6 carbons have been studied in edible oils, mainly including biological and chemical pathways [25,81,82].

Interestingly, 1-octen-3-ol was the characteristic flavor sources of roasted walnut and peanut oil [24,83]. It was reported as a product of linoleic acid oxidation [84]. These compounds, including 13-hydroxy-9,11-octadecanedioic acid (13-HPOD) and 10-oxo-trans-8-decanoic acid, have been found to be the main nonvolatile metabolites associated with the formation of 1-octen-3-ol from linoleic acid [85]. Benzyl alcohol and phenylethyl alcohol were commonly associated with fresh bread-like and sweet rose-like flavor notes, respectively, but their concentration did not exhibit significant increases during the roasting process in peanut oil [28]. It was found that 2,3-butanediol, with the burnt and plastic flavor, was the characteristic flavor volatile compounds in CPPOs [25], but with a fruity flavor in microwave blanched peanuts [31]. Acetoin was found to be the precursor of 2,3-butanediol in *Paenibacillus polymyxa DSM 365* system [86].

3.9. Phenols

The two phenols, 4-vinylphenol and 2-methoxy-4-vinylphenol, emerged as the primary aroma-active compounds in FPOs. 4-Vinylphenol exhibited a spicy, phenolic, and smoky flavor, whereas 2-methoxy-4-vinylphenol provided a clove-like and burnt flavor [39,
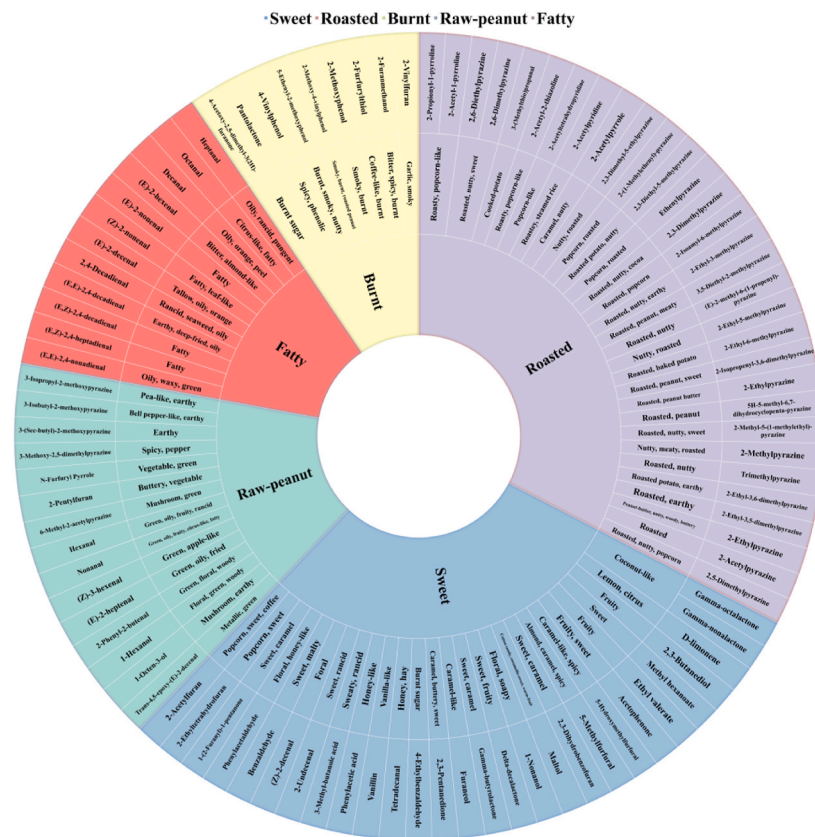
Fig. 3. Flavor wheel of peanut oil. The volatile compounds in the flavor wheel were selected from Table 2 and plotted in excel 2021 [8,26].

67]. These two volatiles were first reported in peanut oils by Walradt et al. [32], whose concentration increased significantly after roasting in peanuts, which were expected to be formed through thermal degradation of 4-hydroxycinnamic acid and ferulic acid (existing in ester form in peanuts), respectively. 2-Methoxyphenol/guaiacol has a gammon-like and smoky flavor and its precursors might be vanillic acid, vanillin, and ferulic acid through various studies and thereby evidences [87–89].

3.10. Others

Compounds that are widely detected in peanuts or peanut oil, while contributing little to peanut flavor due to threshold values and other reasons will be discussed in this section. Thirteen alkanes were found in peanut oils, but only 3,3,5-trimethyl-heptane (popcorn, steamed rice) and octane (citrus, fruity) contribute flavor [24,27]. It is clear that the formation of the alkanes, including ethane, n-pentane, and others, is induced by hydroxyl radicals that were formed during lipid peroxidation. At least two isolated double bonds were needed to form monohydroperoxides of fatty acids to form alkanes [72,14]. Several alkenes have previously been detected in peanut oil. Terpenes, including α-pinene, α-terpinene, ᴅ-limonene, and γ-terpinene, were reported in peanut oils [32,24,27]. γ-Terpinene, ᴅ-limonene, α-pinene, and anethole, providing green, citrus, or woody flavor characteristics, which might be important for the overall aroma profile of CPPOs [24,90]. The aforementioned alkenes are frequently detected in other vegetable oils [67,91,92]. Alkenes are mainly formed during lipid peroxidation via the decomposition of lipid hydroperoxides [51]. ᴅ-limonene may be generated from α-pinene or lipids during roasting [67].

After all the above discussions in the section, we can generate a flavor wheel in this version for the summary. As shown in Table 2, 96 volatile compounds were selected to map the flavor wheel of FPOs based on their contribution to flavor attributes. The flavor wheel is showed as Fig. 3. Roasted flavor is the most important flavor attribute of FPOs, which contain 31 volatile compounds. Most of them are heterocyclic compounds, such as pyrazines, pyrrolines, and pyridines, etc. The compounds contributing to sweet flavor attributes are highly complex, comprising 28 volatile compounds: 5 furans, 8 aldehydes, 2 ketones, 2 acids, 6 esters, 2 alcohols, 2 phenols, and 1 terpene. Similarly, the flavor wheel includes 9, 15, and 13 representative volatile compounds for the burnt, raw-peanut, and fatty flavor attributes, respectively.

The above discussions of the volatile compounds and their flavor attributes in peanut oils, as well as the map of the flavor wheel, are expected to provide readers with high inspirations, such as the aroma recombination of the overall flavor of peanut oils and the visualization of the flavor characteristics of peanut oils. Unfortunately, as early mentioned, high inconsistency of reported volatiles existed from case to case, likely due to the methodologies of flavor analysis, other variations such as material differences and different processing and handling conditions, as well as unknown happenings such as attenuation of flavor volatiles during storage, etc. All these observations indicate the necessity for more research work in the subject.

Although there is a great diversity of volatile compounds found in FPOs, their formation pathways share some common features [8]. Most volatile compounds are products of thermal reactions. The following part will give a brief introduction to the formation mechanisms of flavor compounds based on the formation pathways and, in particular, a detailed introduction to the formation pathways of some key aroma-active compounds. By summarizing and concluding the formation pathways of flavor compounds in peanut oil, the types and contents of flavor compounds in peanut oil can be effectively controlled in terms of reaction pathways and reaction conditions.

4. Mechanisms of flavor formations under processing conditions

For the processing of FPOs particularly, the reactions and what is happened under roasting and other processing steps are nearly unknown. Although we commonly understand there could be many reactions happened under high temperature conditions in the matrix of peanut seed such as Maillard reactions, etc. It is still a blackbox during the roasting and related processing conditions, especially referring to the variations of chemical compositions of peanut kernels. However, there has been a good understanding and progress of volatile identifications in FPOs as well as in other related oils or products. We now know that there are many volatiles in FPOs that are occur in other food products, which have received certain studies. With advances in many other areas, we actually have the possibility of pooling together to form discussions and hypotheses that propose possible mechanisms for what happens in peanuts under roasting and related processing steps. Hopefully, it gives inspirations for readers to make discoveries in the actual systems.

4.1. Maillard reactions

The Maillard reaction is an organic chemical reaction in which reducing sugars react with amino acids to form a complex mixture of compounds. In food flavor chemistry, the products of Maillard reactions were primarily O-heterocyclics, N-heterocyclics, and S-heterocyclics, such as furans, furanones, pyrans, pyrazines, cyclic ketones, etc. [8], which provided roasty, nutty, burnt, and caramelic flavors. This reaction is responsible for the characteristic flavor and aroma of browned foods in food chemistry textbooks. Maillard reaction has been the subject of enormous historical research. Maillard reaction is usually divided into three stages. The initial stage starts with a condensation between an amino group and a reducing sugar, leading to an N-glycosylamine, and Amadori product as an intermediate product. Sugar fragmentation products are formed and amino group are released in the intermediate stage. In the final stage, volatile compounds, including heterocyclic compounds and Strecker aldehydes are formed by various dehydration, fragmentation, cyclization, and polymerization reactions [93–96]. Being part of the Maillard reaction, Strecker degradation is responsible for the generation of Strecker aldehydes and pyrazines, constituting a crucial component of peanut oil's flavor profile [8].

Both the types and concentrations of precursors as well as reaction conditions had great influence on compositions of reaction

products. The precursors of Maillard reactions are commonly regarded as free amino acids, small peptides, and reducing sugars, etc. There are three main sources of amino acids and small peptides in peanuts, including naturally existing in peanuts, formed under high-temperature hydrolysis, and formed from enzymatic hydrolysis in vivo or in vitro [97,98], from peanut protein during processing or storage [27,99,100].

Several products of the Maillard reaction were selected based on their contribution to important flavor characteristics of peanut oil, such as roasted, sweet, and burnt. It is important to clearly understand the reaction mechanisms and their reaction conditions so that the formation pathways of these flavor compounds are essential for being able to control the formation of desired levels of these key flavor components. The compounds selected for elaborations were pyrazines, 4-hydroxy-2,5-dimethyl-3(2H)-furanone (HDMF), Strecker aldehydes, and 2-furanmethanethiol (FMT).

Formation pathway of pyrazines: Pyrazines are the most diverse compounds in FPOs, which are mainly generated by Maillard reactions. Many scholars had paid more attention on the formation pathway of alkylpyrazines [101–104], and the result showed that there is more than one chemical pathway involved in its formation in complex Maillard systems [101,105]. In general, the most accepted pathway of pyrazines formation are shown in Fig. 4(I)A, in which dicarbonyl or hydroxycarbonyl compounds are key precursors of α-aminoketones [106]. The pyrazines were produced through dimerization of α-aminoketones [96]. The aldol-type
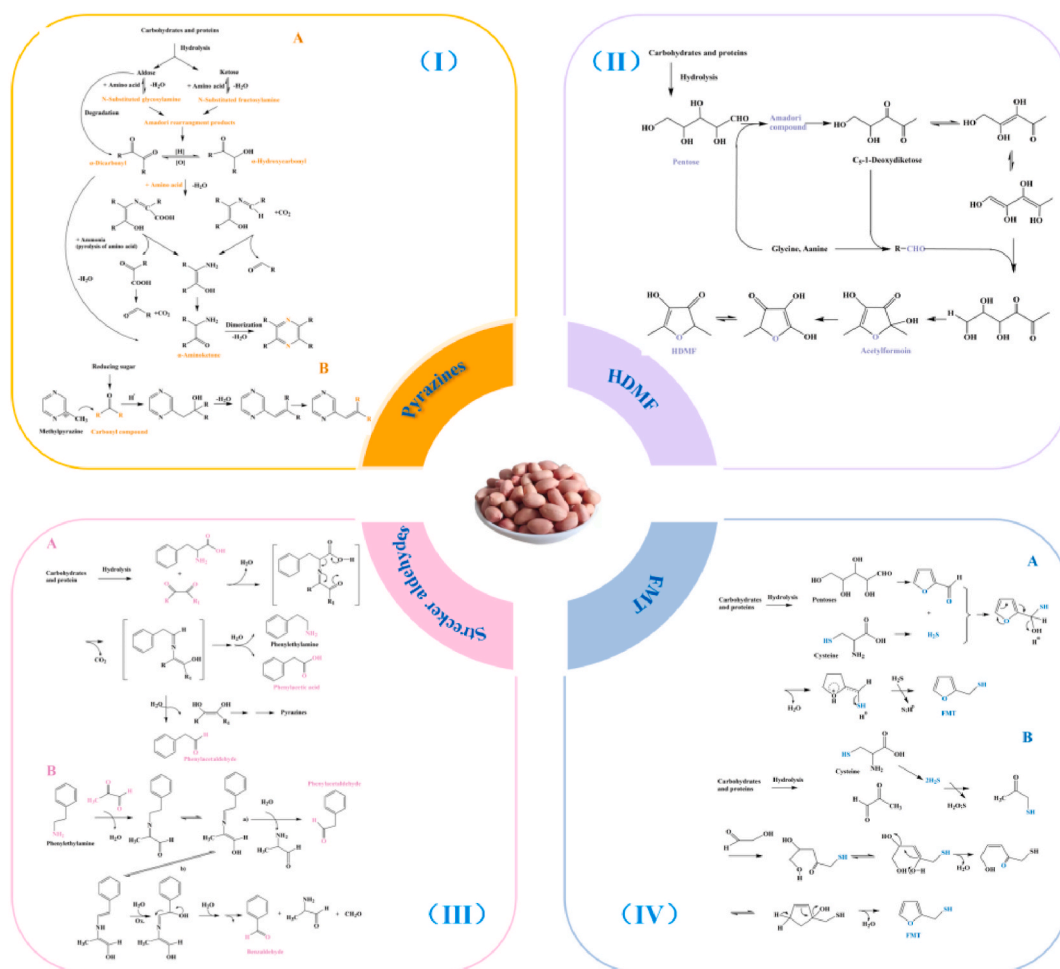
Fig. 4. Formation pathways of pyrazine, HDMF, phenylacetaldehyde, and FMT from Maillard reaction.
(I)Generation mechanisms of pyrazines: A) classic pathway through the Strecker degradation, the reaction between ammonia from amino acid pyrolysis and α-dicarbonyl compounds (adapted from Yu et al. [106]); B) The scheme of the aldol-type condensation between methylpyrazine and carbonyl compounds (adapted from Yu et al. [106]).
(II)Formation pathway of HDMF from pentose with glycine and alanine (adapted from Blank and Fay [107]).
(III)Formation pathway of phenylacetaldehyde: A) Pathway of the Strecker reaction, exemplified for 2-phenylalanine, leading to phenylacetaldehyde, phenylethylamine, phenylacetic acid (adapted from Buhr et al. [76]); B) Pathway of the Strecker degradation of ʟ-phenylalanine leading to phenylacetaldehyde and benzaldehyde in a reaction of 2-phenylethylamine with 2-oxopropanal (adapted from Granvogl et al. [108]).
(IV)Reaction pathways of 2-furanmethanethiol: A) Hypothetical pathway leading to FMT via 2-furaldehyde and hydrogen sulfide as the intermediates; B) Reaction pathway explaining the formation of FMT from 2-oxopropanal, hydroxyacetaldehyde, and hydrogen sulfide (adapted from Münch et al. [109]). Abbreviations: HDMF, 4-hydroxy-2,5-dimethyl-3(2H)-furanone; FMT, 2-furanmethanethiol.

condensation is an important mean of extending side chain of the generated pyrazines for producing more types of pyrazines with lower OTs. The formation pathway of pyrazines via the aldol-type condensation is showed as Fig. 4(I)B. In model experiments [103], it was demonstrated that formaldehyde and acetaldehyde play a key role in the formation of pyrazine, as they can be incorporated into the side chains of the alkylpyrazine molecules. Formaldehyde and acetaldehyde are Strecker degradation products of glycine and alanine, respectively. Furthermore, glycine participates in the formation of one of the methyl groups in trimethylpyrazine. Additionally, alanine contributes to the formation of ethyl groups in compounds such as ethylmethylpyrazines, ethyldimethylpyrazines and diethylmethylpyrazines [103].

Over time, the formation pathways of specific Maillard reaction products have gradually become clarified and diversified, warranting further attention. A new mechanism for the generation of 2-ethenyl-3-ethyl-5-methylpyrazine has been proposed and validated in the model systems [101]. Both 3-deoxythreosone and 2-oxopropanal are then transaminated via the Strecker reaction, leading to 2-amino-4-hydroxy-1-butanal and 2-aminopropanal, respectively. After that, the dihydropyrazine derivative was formed by condensation reaction of the C3 and C4-amino compounds. Finally, both acetaldehyde and the subsequent dehydration reactions are indispensable for the formation of 2-ethenyl-3-ethyl-5-methylpyrazine.

Formation pathway of HDMF: HDMF is an important flavor compound in FPOs [28,24,26,31]. HDMF is one of typical 3(2H)-furanone derivatives, which are notable for their low OTs, significantly contributing to the characteristic flavor in foods, possessing a fruity, sweet, and caramel flavor [110]. As reported, the formation pathways for HDMF are either from a Maillard reaction between the interaction of amino acids and reducing sugars [110,107] or naturally produced by plants and fruits [111], or microbial fermentation [112]. As the thermal treatment is an essential step in the production of FPOs, the formation pathway of HDMF through Maillard reaction will be carefully elaborated.

Much work had been reported on the formation pathway of furanones, although some of them are hypotheses. Generally, HDMF can be originated either by the sugar degradation reaction or by the Maillard reaction [110]. Blank and co-authors published three papers on how HDMF was generated through Maillard reactions in 1996 and 1997. They put forward a hypothesis that HDMF was formed in both pentose/glycine and pentose/alanine systems as well as directly from pentoses. Experiments using ^{13}C-labeled glycine and alanine suggested the incorporation of the Strecker degradation products (formaldehyde) into the pentose moiety, so that eventually forming HDMF [107]. Later, according to quantitative results in pentose sugar-based Maillard model systems, the above hypothesis was substantiated. Besides, it was also found that HDMF was favored in the presence of glycine [113]. The formation pathway is shown in Fig. 4(II). HDMF were generated from pentose in the presence of glycine and L-alanine by a series of complex reactions, including Amadori rearrangement, degradation via 2,3-enolization, keto/enol or vinylogous keto/enol tautomerization, Strecker reaction, cyclization, dehydration, aldol-type condensation, and reduction [107,114]. From studies done by another team, it was demonstrated that rhamnose is more effective than glucose and fructose in the formation of HDMF as 6-deoxysugar rhamnose is an important precursor for HDMF [110,115].

There were more proposals of formation pathways for HDMF. In 2005, a new formation pathway of HDMF from glucose via a reduction of acetylformoin as the key transient intermediate was figured out. This reduction may occur either in a disproportionation reaction or by a Strecker reaction with amino acids [116]. Besides, Wang and Ho [117] studied the formation pathway of HDMF through methylglyoxal in the presence and absence of amino acids during the Maillard reaction. When amino acids are involved, HDMF can only be formed via glucose, leading to acetylformoin as the intermediate. However, in the absence of amino acids, HDMF is formed by condensation of methylglyoxal with 1-hydroxy-2-propanone. 1-Hydroxy-2-propanone was produced from methylglyoxal by the Cannizzaro reaction.

As a result, the precursors of HDMF are various, including sugars, amino acids and their degradation products. An understanding of the formation pathways and precursors of HDMF is essential to originating desirable flavors of FPOs in the future.

Formation pathway of Strecker aldehydes: Phenylalanine is the primary precursor of Strecker aldehydes, namely phenylacetaldehyde, and benzaldehyde. As shown in Fig. 4(III)A, the reaction of 2-phenylalanine with an α-dicarbonyl compound leads to the formation of the two transient intermediates given in brackets. These intermediates have not been isolated and identified due to their unstable structure [76]. The products of this Maillard reaction include phenylacetaldehyde, phenylethylamine, phenylacetic acid, and pyrazines. In addition, the content of phenylacetaldehyde is influenced not only by reaction temperature, but also by the amount of water present in the system [76,109,118]. The formation pathway of phenylacetaldehyde has been extensively studied in model systems. α-Dicarbonyl compounds are effective intermediates for the formation of phenylacetaldehyde [108,119]. And 2-oxopropanal was proved to be the most effective precursor in generating phenylacetaldehyde from phenylalanine. In addition, a hypothetical formation pathway for phenylacetaldehyde and benzaldehyde were proposed, in which 2-phenylethylamine and 2-oxopropanal act as substrates, is shown in Fig. 4(III)B [108].

Branched-chain aldehydes, such as 2-methylbutanal (almond, fruity, chocolate, malty) and 3-methylbutanal (malty, fruity, oily), are important flavor compounds in FPOs. As reported, both 3-methylbutanal and 2-methylbutanal can be generated by Strecker degradation. Leucine undergoes a deamination and decarboxylation reaction in the presence of dicarbonyl compounds to produce 3-methylbutanal [120].

Formation pathway of 2-Furanmethanethiol (FMT): A hypothetical pathway was proposed leading to FMT via 2-furaldehyde and hydrogen sulfide as the intermediates in thermal treatment of yeast extracts [109]. The formation pathway is shown in Fig. 4 (IV)A. Among the intermediates, hydrogen sulfide is known to be one of the primary Strecker degradation product of cysteine [109]. Furthermore, 2-furaldehyde is one of the major products generated from pentose in the presence of amino acid [121]. Alternative pathway was been proposed that lead to FMT from 2-oxopropanal and hydroxyacetaldehyde in the presence of hydrogen sulfide. As previously reported, 2-oxopropanal and hydroxyacetaldehyde are the degradation products of carbohydrates. The formation pathway of FMT is showed in Fig. 4(IV)B [109].

4.2. Lipid oxidations

Lipid oxidation is a radical chain propagation reaction, which includes three steps: initiation, propagation, and termination [122, 123]. The primary oxidation products, lipid hydroperoxides, are readily decomposed to alkoxy radicals in the presence of metals or at high temperatures, and then form small molecules volatile compounds [122]. Most noteworthy, oil oxidation will produce a large number of flavor substances [124]. Lipid oxidation products contribute to the development of deep-fried flavors, which were determined by extraordinary complex volatiles in various quantities [95,125]. In addition, the importance of lipid degradation products in the characteristic flavor of the freshly roasted peanuts had been confirmed by aroma recombination experiment [26].

Aldehydes, such as propanal, hexanal, and 2-alkenals, are suitable as markers for the early phase of lipid oxidation [54,126]. But at an advanced stage, they were further converted into 2-alkylfuran by aldol-type condensation reaction, reactive oxygen oxidation or thermally induced degradation. Consequently, these tertiary degradation products, mainly including aldol-type condensation products, 2-alkylfuran, and methyl ketone, are also well-suited markers for indicating the level of lipid oxidation [54]. Oxidation products of lipids, 2-vinylfuran and 2-pentylfuran, are the flavor compounds that had been extensively studied by researchers. The formation pathway of 2-vinylfuran is as follow: The first step would be the isomerization of the double bond of OHE from trans to cis, then its enol tautomer was further formed. One study demonstrated that OHE came from the oxidation of ω-3 fatty acids [127]. 2-Pentylfuran can be formed by cyclization of the alkoxy groups in vinyl hydroperoxides. Vinyl hydroperoxides were generated from the conjugated diene radicals, which were the products of the cleavage of 9-hydroxy radicals in linoleic acid [72]. *Trans*-4,5-epoxy-(E)-2-decenal is an
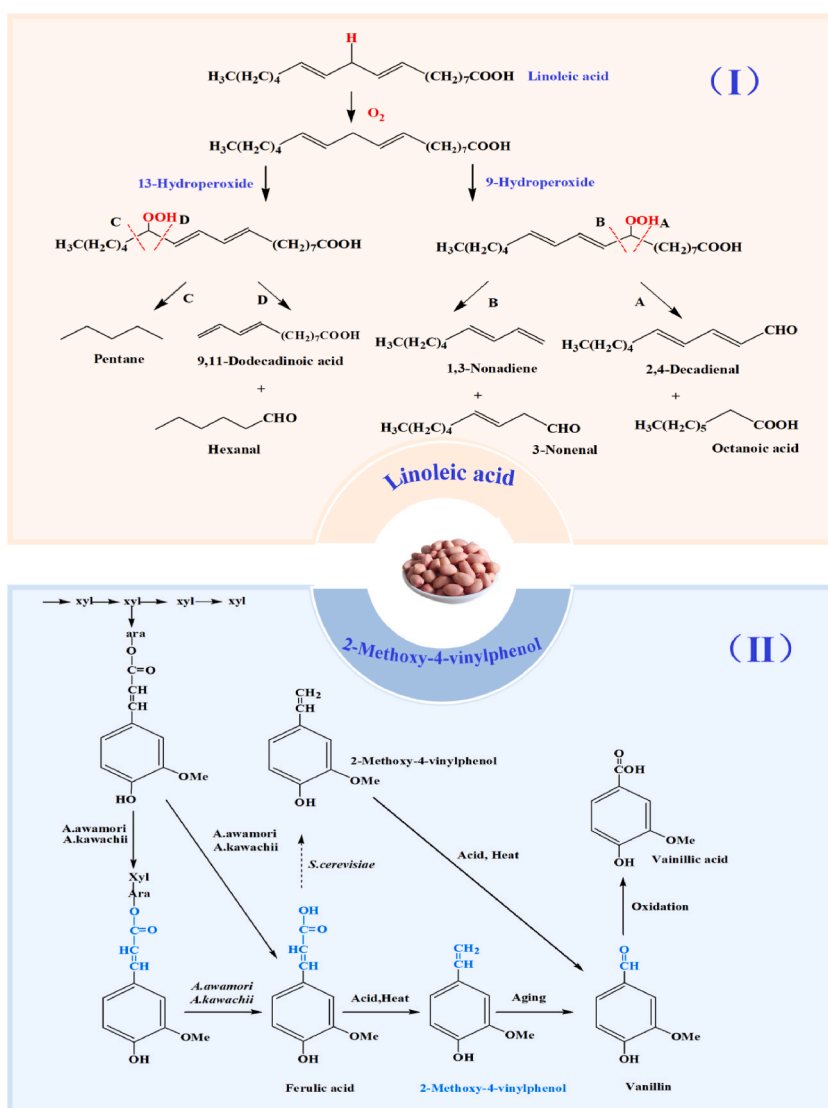
Fig. 5. Degradation reaction of linoleic acid and ferulic acid. A) Typical initial scission patterns of oxidized linoleic acid (adapted from Schaich [14]). B) A proposed mechanism for the conversion of ferulic acid in *shochu* (adapted from Koseki et al. [87]).

epoxyaldehyde that contributes to the overall flavor of peanut [26]. The key intermediates in the generation of this epoxyaldehyde were found to be 2,4-decadienal and 12,13-epoxy-9-hydroperoxy-10-octadecenoic acid. In addition, 2,4-decadienal is formed by 9-hydroperoxy-10,12-octadecadienoic acid (9-HPOD), and 12,13-epoxy-9-hydroperoxy-10-octadecenoic acid is a degradation product of 13-HPOD [128].

Many factors, such as oil fatty acid compositions, processing technologies, minor components (free fatty acids, mono-and diacylglycerols, metals, chlorophylls, carotenoids, tocopherols, and phospholipids), and treatment conditions (temperature, light, and oxygen), have great influence on oxidative stability of edible oils [122]. Furthermore, the composition of lipid oxidation products is highly related to the types of fatty acids. (E)-2-pentenal, (E)-2-butenal, ethyl furan, 4-hydroxy-2-hexenal, benzaldehyde, (E,Z)-2, 4-heptadienal, and (E,E)-2,4-heptadienal could be generated by linolenic acid oxidation [129]. In a few other studies, octanal, nonanal, (E)-2-nonenal, (E)-2-decenal, and (E)-2-undecenal are closely related to oleic acid, while (E)-2-hexenal, (E,E)-2,4-decadienal, (E,Z)-2, 4-decadienal, and pentyl furan are related to linoleic acid [25,126,130]. Fig. 5(I) shows the typical initial fracture pattern of oxidized linoleic acid and the formation pathway of oxidation product [14,122].

On the other hand, oxidation of edible oil produces off-flavor compounds and decreases oil quality. Aliphatic carbonyl compounds have more influence on the oxidized oil flavors due to their low threshold values. Most of the decomposition products of hydroperoxides are responsible for the off-flavor in the oxidized edible oils [122]. Furthermore, the lipid oxidation generally leads to the reduction and damage of oil quality. It creates potential safety issues for the edible applications. Therefore, it is of great practical significance to study the oxidation products and their formation pathway of peanut oils. It is important to balance the flavor promotion and quality reduction in other aspect.

4.3. Thermal degradation reactions of other compounds

Some degradation products of certain trace components, such as isothiocyanates and phenols, also significantly contribute to the overall flavor of fragrant oils [8,131]. For example, both 2-methoxyphenol/guaiacol and 2-methoxy-4-vinylphenol are responsible for the smoky, burnt flavor characteristic in FPOs. They are suggested to be formed through thermal degradation of 4-hydroxycinnamic acid and ferulic acid, respectively. Therefore, it is of practical significance to clarify the formation pathways of certain degradation products.

In many food substrates, the preparation of 2-methoxy-4-vinylphenol by degradation of ferulic acid has been widely studied [132–134]. The formation pathway of 2-methoxy-4-vinylphenol in FPOs to a certain extent can refer to the reaction pathway in Shaojiu, as shown in Fig. 5(II). The mechanism for the formation of 2-methoxy-4-vinylphenol from ferulic acid in *shochu* is as follows: It was firstly liberated by the hydrolytic enzymes from *Aspergillus awamori* and *Aspergillus kawachii*, as ferulic acid initially bound to the hemicellulose of plant cell walls. Ferulic acid was then converted to 2-methoxy-4-vinylphenol by acid and heating during distillation. Alternatively, this conversion process can also be achieved by degradation of *S. cerevisiae* in moromi mash. 2-Methoxy-4-vinylphenol might be transformed into vanillin and vanillic acid by oxidation and aging during storage [87].

5. Factors affecting the flavor of FPOs

As discussed in Section 2, the production of FPOs involves a number of processing conditions, such as the choice of materials, the temperature and time of roasting or steaming, and other relevant factors. We also understand that flavor compounds are produced by different reaction pathways, which include enzymatic reactions as well as thermal reactions such as Maillard reactions, Strecker degradations, caramelizations, lipid oxidations, and thermal degradations of other compounds during roasting and other operation conditions [5]. Furthermore, the primary precursors of thermal reactions that generate volatiles in peanuts are proteins, carbohydrates, lipids, and their derivatives [135], where different peanut backgrounds such as different peanut genotypes, different storage and handling situations, pretreatments, etc. can lead to different precursor situations. With these understanding, it can be clear that there are correlations between flavor performances and related factors or conditions.

Therefore, the following will focus on the discussions concerning raw materials, processing technologies, and storage conditions, etc., on how they affect the profiles of volatile compounds in FPOs.

5.1. Effect of chemical compositions of raw materials on the flavor characteristics

Sugars, lipids and proteins are integral precursors in the various nonenzymatic reactions, such as Maillard reactions, lipid oxidations, and Strecker degradations, largely responsible for the roasted peanut flavor [8,10]. Consequently, the influences of peanut maturity and storage history as well as peanut strains and species, which have effect on chemical compositions, are all factors that cannot be ignored in terms of the effect on the flavor characteristics.

Peanuts in dry matter typically contain about 49 % lipids, 26 % protein, and 16 % carbohydrates [10], although their contents can vary with cultivars, market types, environments, maturities, and seed sizes, among other factors [136,137]. In particular, oleic, linoleic, and linolenic acids, represent 90 % of the total fatty acids, are prominent precursors of peanut volatile compounds [129]. Different fatty acid compositions of peanut oils, especially the oleic/linoleic (O/L) ratio, will have great influence on the composition of flavor substances [129,138].

The effect of genotype on the flavor compounds and sensory properties of peanuts has received considerable attention. Sensory properties of HO varieties are different from those of traditional varieties. HO lines exhibited slightly greater intensities of certain attributes, including roasted peanut, astringent, over-roasted, and nutty attributes, compared with traditional varieties [137]. Baker

et al. [139] showed that a mid-oleic variety formed the highest pyrazines under the same roasting conditions, followed by three HO varieties. Hu et al. [27] also reported that normal peanut oils had stronger roasted, peanutty, and sweet flavors than HO peanuts. It was also confirmed that the initial concentration of characteristic precursors (arginine, tyrosine, lysine and glucose) in normal peanuts was higher than of in HO peanuts, which led to the difference in content of aroma-active volatile components. Other two studies in Asia also confirmed that the flavor compounds and sensory characteristics of peanuts related to peanut varieties [90,140].

Another issue is the effect of peanut maturity on flavor performance. The relationship between the different maturities of peanuts and the sensory performances of the corresponding peanut oils was also studied by many researchers. Increased levels of maturity had been shown to correlate with the increased flavor potential in a variety of samples studied [139]. In studies with immature peanuts, similar conclusions were obtained [141,142]. These studies suggested there was a trend for increased intensities of flavor descriptors such as roasted peanut and sweet aromatic with the maturity increase of peanuts. For the same suggestion, intensities of flavor descriptors such as painty and fruity fermented had the correspondent trend with the immaturities of peanuts.

In addition, although it is not the focus of this paper, we should be known that the raw material composition of peanuts is affected by many factors, such as peanut genotype, seed maturity [139], climatic conditions [143], planting year/date [144,145], growing location [143,145,146], harvesting time [147,148], and the interaction between these factors. The raw material compositions of peanuts mainly include fatty acids composition, sugar content, amino acid content, etc., are important precursors of flavor compounds.

5.2. Effects of thermal processing technologies on flavor performances

We know it is very important for proper processing so that to form flavor characteristics as described in the introduction and section 2. The definition of FPOs is also directly related to the processing technology. Obviously, the effects of thermal treatment processing are the central concern affecting the formation of flavor compounds. Thermal treatments, including dry roasting, microwave roasting, infrared radiation roasting, and steam roasting, are important for the production of FPOs [5]. Thermal treatments induce complex chemical reactions, such as Milliard reactions, sugar degradations, protein denaturations, and lipid oxidations as well as many more unknown reactions. Based on these reactions, some specific compounds are formed, with stronger fragrances, darker colors, and higher antioxidant activity [149]. However, excessive roasting results in adverse effects such as unpleasant flavor generation, micronutrient loss, and formation of toxic compounds [6,150]. So, the proper conditions for roasting are extremely important for FPOs production.

Thermal treatment is a necessary and traditional step for FPOs, which facilitates the release of oil from the oilseeds when pressed and the production of flavor compounds [6,151]. There were clear changes in the formations of the pyrazines and furans, increases in odorants from lipid oxidations, and loss of terpenes after the thermal treatments of peanuts, which explained the apparent differences in the aroma perceptions between the CPPOs and FPOs [24], as well as the volatile differences in intensity, particularly (Fig. 2).

With the increase of thermal treatment temperatures, the flavor volatile profiles could be highly different. Dry roasting processes promote the typical nutty/roasty aroma of FPOs via the Maillard reactions, particularly those derived from *N*-heterocyclic compounds (such as pyrazines and pyrroles) [28,152]. A study indicated that dry roasting temperatures more than 100 °C are necessary to obtain the flavor characteristic of pumpkin seeds [45]. The content of 1-octen-3-one may be related to the temperature and time of thermal treatment. The concentration of 1-octen-3-one in the roasted peanut meal is 1.3 μg/kg after roasting in a frying pan for 11 min, about 5 times higher than that of the raw peanut meal [28]. Both the content of pyrazines and the sensory scores for roasted peanut flavor reach their highest levels when roasted at a temperature of 175 °C for 15 min [139]. Unlike other pyrazines, 5-methyl-2-pyrazinyl methanol was identified for the first time from peanut sources when the dry roasting temperature reaches 200 °C. It is conjectured that the formation of this pyrazine requires a more violent reaction than the others [28].

Microwave roasting is another heating technology with different mechanisms. The advantages lie in not only its efficiency on improving the extraction yields, nutritional values, physicochemical and sensory properties of the oil, but also its speed of operations, energy savings, and efficiencies of process controls [8,31,153]. The most critical characteristic of microwave roasting is inside-out heating, which achieves high heating rates and better heating uniformity in just a few minutes, while reducing energy consumption [154].

Microwave roasting has a great influence on the composition of flavor substances in fragrant oils. The volatile compounds in the roasted camellia seed oils with less than 3 min microwave treatment of the seeds were mainly alcohols and esters, while those were mainly heterocyclic compounds and aldehydes with 4–6 min microwave treated [155]. The relative content and peak area of pyrazines in oils significantly increased after microwave treatment. After 4 min microwave pretreatment, the relative content of the three most abundant pyrazines, 2,5-dimethyl-pyrazine, trimethylpyrazine, and 2,5-dimethyl-3-ethyl-pyrazine, increased from 0 to 5.56 %, 3.86 % and 4.61 %, respectively [29].

Moreover, microwave roasting improved the production of certain valuable flavor compounds in fragrant oils, as it can enhance the thermal reactions, such as Maillard reactions and oil oxidations. Although processing time can be greatly reduced, microwave roasting still increase the concentrations of phenylacetaldehyde, 2-methoxyphenol, and 2,6-dimethylpyrazine [31]. The pyrazines, namely 3-ethyl-2,5-dimethylpyrazine and 2,3-diethyl-5-methylpyrazine, only exist in microwave treated camellia seed oils, compared with other production technologies through steam roasting or dry roasting. The possible reason for this phenomenon is that their formation is greatly influenced by temperature. The internal temperature of the camellia seeds during microwave roasting can reach 180 °C [156].

Infrared radiation roasting has the energy in the range of the electromagnetic spectrum between microwaves and visible light. The advantages of infrared radiation are low energy consumption, high heat efficiency, compact size of the equipment, and high diffusion coefficient [5,22]. In a recent study, the short-wave infrared radiation was used to pre-roast the peanuts before enzyme assisted aqueous extraction process [157]. It was found that the combination could effectively increase the quantity and intensity of volatiles of

the produced peanut oil (p < 0.05), and accordingly enhance its flavor intensity.

Steam roasting is extensively employed in the production of sesame oil, cocoa beans, and virgin rapeseed oil [158–160]. Studies reveal that this process alters the composition of flavor compounds and related substances, including sugars and amino acids. Moreover, steam roasting, in contrast to dry roasting, exhibits a significant impact on the physicochemical characteristics of peanut oil [161]. However, extensive research is still required to thoroughly understand its influence on the flavor compound profile of peanut oil.

5.3. Effect of storage of FPOs on their flavor stability

Both flavor characteristics and flavor intensity can change during the storage of FPOs in practice. The composition of volatile compounds in FPOs is also commonly known to be affected by storage conditions. Caipo et al. [162] found that a lack of consideration for storage conditions could result in the appearance of sensory defects in the oil, and thus leads to a decrease in the quality of extra-virgin olive oils (EVOOs). The EVOOs stored at different conditions could be well differentiated by principal component analysis (PCA) according to the composition of volatile compounds.

Storage will result in changes in the fatty acid composition and trace element content of peanut oil. The O/L ratio, as well as α-tocopherol, was decreased during the two months storage [163]. In another study, tocopherols in the peanut oil were fully decomposed after a 35-day storage period [164]. In addition, during storage at 40 °C for a period of time (more than 29 days), total tocopherols in the roasted peanuts decreased, especially α-tocopherol [150]. As discussed in Section 5.1, chemical composition of raw materials is high related to the stability and flavor quality of peanut oil. Obviously, due to the change of fatty acid profiles from linoleic to oleic acids, the roasted HO peanuts had better flavor quality and stability than normal peanuts [165,166].

Storage has a significant impact on the stability and flavor profiles of peanut oil, and in addition, storage conditions such as shelled/unshelled are non-negligible factors. During storage at 40 °C, sensory analysis indicated an increase in cardboard flavors and a decrease in the intensity of the characteristic roasted peanutty flavor [150]. Five brands of peanut oil were stored in simulated home storage conditions for six weeks, and sensory evaluations showed that flavor attenuation in peanut oil was clearly detected after three weeks of storage, and that levels of pyrazines decreased significantly after five or six weeks of storage [167]. The volatiles, namely, 3-ethyl-1,5-octadiene, 3-ethyl-1,5-octadiene isomer, 1-octen-3-ol, and n-decane were the representative volatile compounds in the oxidized soybean oil, when stored at 60 °C for 5 days [168]. However, these four compounds were not found in the ambient storage of soybean oils [72]. In a particular study, shelled/unshelled peanut samples were stored at room temperature (23 °C) for 675 days. The sensory and chemical changes in the shelled peanut samples were not significant compared with the unshelled peanut samples, suggesting that the shell may protect the kernel from deterioration [169].

Thus, depending on the structures, volatile compounds can have different stability under storage conditions. Structures can change through different mechanisms or reactions can occur between the compounds. The oxidation of lipids during storage could produce new volatiles, which can also interfere with the flavor profiles and flavor characteristics. In general, flavor is dynamic during the
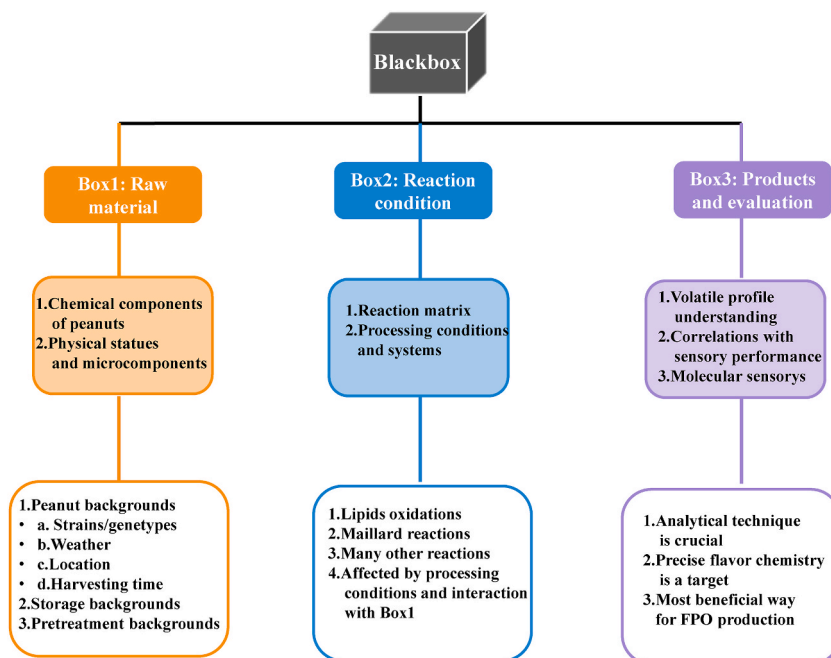

Fig. 6. An illustration of the challenges facing of FPOs production through three blackboxes and their interactions. Abbreviations: FPOs, fragrant peanut oils.

storage stage. The flavor attenuation happens in all storage conditions along with possible leakage loss. However, the storage conditions can be optimized to slow down the flavor attenuation as well as quality deterioration.

6. Future perspectives

As discussed in the introduction, FPOs are more welcomed by consumers in certain parts of the world than refined peanut oils. There is a trend of increase in consumption steadily year by year, indicating the geographical preference of consumers are expanding due to the spreading of awareness through all modern community activities. As flavor is the most distinguished character for the preference of the oil from consumers, producers are doing all the efforts to improve flavor performance of the peanut oils. This often involves in enhanced roasting operations including higher and higher temperatures with longer and longer times or other intensified thermal treatments.

There were several challenges within the FPOs industry. One side for FPOs is the high preference from consumers. The other side is the shortcomings of the FPO production technologies. Obviously, there is a need of new technologies that can produce the FPOs in better quality in terms of flavor characteristics and intensity while using milder thermal treatments to reduce the negative effects of heating in terms of food safety and protein applications. This looks as a paradox for the solutions. Furthermore, we should give enough trust on the progress of modern science and technology which can provide better solutions. At least, a much-improved compromise between the positive and negative aspects can be targeted on for the achievement.

To have a better solution for the target with the possibilities from the progress of science and technology, we need to have a clear analysis and diagnosis for the traditional technology. Based on the discussion in the first and second sections, we can put the technology into three knowledge boxes, as illustrated in Fig. 6.

Box 1 covers the knowledge of chemical compositions, which provide a basis of precursor profiles before reactions happen. This also provides a basis of explanations of our concerns or experience on how the peanut backgrounds can affect the flavor performance of FPOs, including peanut strains/genotypes, locations, weather conditions, environmental situations, harvesting times/maturities, storage conditions and times, pretreatment conditions and types which can lead to the changes of chemical compositions or physical states before reaction happens, etc. Through the discussion in the above, we have certain knowledge for box 1, but far from a quantitative and decisive understanding. There is a demand of detailed and quantitative understanding on how we should prepare an effective precursor mixture that gives best flavor characteristics and intensity without forming excessive volatiles that have no contributions to the flavor quality so as to minimize useless reactions. Box 1 is still largely black or partially black at least, especially for FPOs.

Box 2 is the reaction stage under processing conditions. We have discussed the reactions and formation pathways of certain selected flavor volatile compounds. The discussion is mostly on the qualitative and hypothetic basis although there have been some quantitative evidences in literature. What the microenvironment is good for reactions under various processing conditions and instrumentations is highly unknown so far. We have no knowledge to define a precise, specific, and effective reaction system for the high-quality flavor performance. Box 2 has strong interactions with box 1. The situation of chemical compositions and maybe also the physical structures may affect the reaction matrixes in the system, so as to interactively affect the flavor outcomes. Thus, box 2 is also largely black in terms of a controlled reaction system with precision, specificity, and effectiveness.

Box 3 is the understanding of how natural formulation of volatiles contributes to the favorable flavor in terms of flavor characteristics and intensity. There has been comparably more work on this aspect in literature and also more text in this paper. With the progress of analytical technology, we do have more deep understanding in terms of volatile identification and flavor contribution. There have been more than 300 volatile compounds recognized in FPOs. There are also lists of volatiles that are identified with little content but with a high threshold value. The progress is huge for the last 20 years. On the other hand, we still have challenges to be able to reconstruct the flavor with the knowledge of flavor analysis. We do not know very well what the functions of those volatiles in majority of the contents that assumingly have no contributions to the flavor performance. We like to know whether we can minimize the contents of those volatiles through the interactions with box 2 and box 1. We also like to know whether volatile compounds have interactions in terms of synergy to increase the flavor sensory performance between the compounds. We also like to know whether the volatile compounds are stable in shelf life and how they reduce in terms of contents. There is a lot of knowledge missing for the understanding of flavor vs. quality. Obviously, the box is also quite black although more work has been done in this aspect.

In general, box 3 presents a comprehensive evaluation of the flavor quality of FPOs, including the flavor compound composition, sensory properties, and their correlation, as well as the methodologies for flavor evaluation. The key factors influencing the flavor profile in box 3 are raw materials and chemical reactions, of which are elaborated in box 1 and box 2, respectively. In essence, FPOs is produced through the combined effect of box 1 and box 2, and the flavor-related properties of these oils are subsequently assessed using the indicators and methodology outlined in box 3.

Into details, there is a list of difficult problems needed to be solved in the field of oil flavor. We can pick up some for the discussion. (1) It is a knotty problem about how to ensure the accuracy and unity of sensory data as the differences of individual sensory and limitations of instrument sensitivity. (2) For now, the accurate and quantitative detection of flavor substances requires isotope internal standards, which are expensive or even need to be synthesized in house. On the other hand, the qualitative determination of volatile compounds predominantly relies on GC-O, mass database, and retention indices (RIs) value calculation, so that the absence of a comprehensive database often results in an incomplete characterization of trace compounds. (3) From a scientific point of view, it is very important to determine the correlation between flavor compounds content data and sensory attributes, while the methodologies for determining this correlation are critical and not easily available. (4) Few studies focus on safety evaluation of volatile products in oils and fats, including in vivo and in vitro metabolism studies and toxicological evaluations. More challengingly, the safety evaluation

studies are difficult to perform due to the volatility and poor absorption of volatile compounds. (5) The inference and verification of formation mechanisms of flavor substances are complicated in complex peanut systems. The study methodology is not quite convenient to approach the real situations. Model systems to mimic the real system require a lot of understanding of the real systems.

There could be a long list of such challenges in the study of flavor chemistry of oils and fats. On the other hand, we also see great progresses to illustrate the understanding of the technology. We are confident that more progress will be made to elucidate the inside stories so that the industry will follow up the progress and find out solutions to update the products and technologies for the production. Very lately, Lee et al. [170] in Science published a study with a title on a principal odor map unifies diverse tasks in olfactory perception. Molecular structures and odor perceptions were built up correlations quantitatively. A close understanding of flavor with volatile formulation as well as its rational processing technology is on the way.

7. Conclusion

Research on flavor compounds in strongly flavored peanut oil has yielded phased outcomes, yet critical work remains needed to offer a clear understanding. Despite numerous reports on the overall flavor compound profiles of peanut oils, challenges persist in confirming and precisely quantifying key flavor compounds. Hence, up to now, achieving the natural flavor of peanut oil through recombination experiments remains challenging. In model experiments or other food systems, the formation pathway of several key aroma-active compounds in FPOs have been hypothesized and, in some cases, been verified. These achievements offer some guidance, yet due to the intricate interplay of various factors, the formation mechanism of these compounds in peanut oil necessitates further practical validation. Complex factors influencing flavor quality of peanut oil, primarily peanut quality, thermal treatment technologies, and storage conditions. In the future, scholars and entrepreneurs aim to comprehensively assess these factors to produce FPOs with superior and consistent quality. Naturally, such an achievement would not have been possible without the extensive scientific research conducted in the initial stages. Consequently, given the aforementioned facts and observations, the authors aim to encourage researchers to work together in addressing the three blackbox issues discussed in this work.

Ethics statement

This research falls outside of human or animal studies and institutional ethical approval was not required.

Data availability statement

All data generated or analyzed during this study are included in this published article or are otherwise publicly available.

CRediT authorship contribution statement

Sumin Ma: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caixia Ding:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Chuan Zhou:** Supervision, Formal analysis, Data curation. **Haiming Shi:** Writing – review & editing, Supervision, Methodology, Data curation. **Yanlan Bi:** Writing – review & editing, Supervision, Funding acquisition. **Hong Zhang:** Writing – review & editing, Supervision. **Xuebing Xu:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

Here on behalf of all the coauthors, we declare that there is no conflict of interest for the submitted manuscript titled Peanut oils from roasting operations: an overview of production technologies, flavor compounds, processing factors, and formation mechanisms for the publication in Heliyon.

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