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Aroma Compounds of Flash-Fried Rice

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ABSTRACT

The flash-frying technique (*phad-fai-dang*, in Thai) is similar to stir-frying but it allows fire to contact with the food being fried to give a unique smoky/burnt aroma. This studycompared the aroma compounds of flash-fried rice (FFR) with those of stir-fried rice (SFR) and steamed rice (SR). Sensory evaluation using differences from the control test confirmed that 30 panelists were able to differentiate the unique aroma of FFR from that of SFR ($P \leq 0.01$). Volatile compounds were identified by gas chromatography-mass spectrometry. Aroma-active compounds were analyzed using gas chromatography-olfactometry. The most prominent volatile compounds of FFR that had the highest flavor dilution (FD) factors with a value of 81 were 2,4-heptadienal (stir-fried oil, burnt), nonanal (scented candle), heptanone (metallic, rust) and unknown compounds M (fishy, salty) and N (sweet, stale). There were two unknown compounds (O and Q) with FD factors of 9 and 0 that had a “wok” or flash fried aroma characteristic. SFR had octadienone (metallic, rust) and an unknown compound C (sweet) with an FD factor of 81 as its prominent aroma compounds. Steamed rice had 2-acetyl-1-pyrroline (sweet, pandan like) and an unknown compound P (sour) with FD factors of 27 and 3, respectively, as its aroma-active compounds.
Keywords: wok flavor, flash-frying, stir-frying, steaming, aroma compound, rice

INTRODUCTION

Stir-frying is common in Chinese and Asian cooking. The flash-frying (*phad-fai-dang*, in Thai) technique is less common because it requires a special skill to allow fire to contact with the food being fried. Flash-frying gives a unique smoky aroma to foods especially vegetables, noodle and rice dishes that is developed at higher temperatures than typical stir-frying.

Volatile compounds from fried foods are generated from edible oil and other ingredients. Volatile components of stir-fried oils are mostly aldehydes such as hexanal, (*E*)-2-heptenal, (*E*)-2-octenal and 2,4-decadienal (Wu and Chen, 1992). Other important groups are acids, alcohols and ketones.

Most studies on volatile compounds in fried foods have been conducted intensively on French fries prepared by deep-frying. French fries have 3-methylbutanal (malty), methional (boiled potato) and (*E,E*)-2,4-decadienal (deep-fried) as the character impact odorants (Wagner and Grosch, 1997). A study by van Loon *et al*. (2005) isolated and identified odor active compounds from French fries at mouth condition. A total of 122 compounds were identified and 41 compounds were perceived by the panelists. Approximately 85% of the volatile compounds originated from sugar degradation and Maillard reaction and 15% were derived from

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edible oils. Major carbohydrate-derived compounds were 2-methylpropanal, 2-methylbutanal, 3-methylbutanal and 26 pyrazines. Ethanol, 2-propanol, hexanal, and nonanal were the major lipid-derived volatile compounds.

Flash-frying involves heating foods at the flash point of the cooking oil for less than a minute. Volatiles from flash-frying, therefore, can be derived from pyrolysis. Major products from the pyrolysis of vegetable oils are *n*-alkanes and 1-alkenes, with minor compounds being alkylcycloalkanes (Alencar *et al*., 1983).

To date, data concerning the aroma components in flash-fried foods have not been reported in the literature. The objective of the present work was to study the aroma-active components generated from flash-frying in comparison to stir-frying using rice as a model.

MATERIALS AND METHODS

Materials

White rice (Sao Hai) (Tesco Brand, Tesco, Thailand) and soybean oil (Morakot, Thailand) were obtained from a local supermarket in Bangkok.

Diethyl ether and sodium chloride were purchased from Labscan (Dublin, Ireland). Anhydrous sodium sulfate was purchased from Ajax Finechem (Taren Point, Australia). Other compounds, 2-methyl-3-heptanone, decanal, nonanal and n-alkane series (C_5-C_{30}), were obtained from Aldrich (St. Louis, MO, USA).

Sample preparation

*Steamed rice (*SR*)* Polished white rice (200 g) was steamed with 650 mL odor-free water using an Otto rice cooker model CR-100T (Otto Kingglass, Thailand).

*Stir-fried rice (*SFR*)* Steamed rice (200 g) was added to 40 mL of heated soybean oil (200 °C) and stir-fried in a Chinese wok for 1 min.

*Flash-fried rice (*FFR*)* Steamed rice (200 g) was added to 40 mL of heated soybean oil (200 °C) and flash-fried in a Chinese wok for 15 s.

Sensory evaluation

A difference-from-control, discriminative test was used to investigate the differences among unique attributes of smoke-odor intensity associated with FFR, as the control, with SFR and SR, as samples, by 30 untrained panelists (Meilgaard *et al.* , 1999; Carpenter *et al*., 2000). The panelists were chosen for their experience and ability to recognize the unique smoky odor of fried rice. The panelists were oriented to become familiar with the unique smoky odor prior to the test. Each sample was prepared by placing 10 g samples in an odor-free plastic cup sealed with aluminum foil. The aluminum foil was pierced before serving each sample. Code "C" was provided to FFR as a control sample and a 3-digit number was provided to FFR (blind FFR), SFR and SR. Three pairs of samples of FFR-blind FFR, FFR-SFR and FFR-SR, were served randomly to each panelist to sniff the sample through the pierced aluminum foil. The panelists were asked to rate the difference in intensity of the smoky aroma between each sample and the control using an 11-point scale ranging from -5 to 5, with -5 meaning extremely less intense aroma, 0 meaning no difference, and 5 meaning extremely more intense aroma. Data were subjected to analysis of variance (ANOVA) and Dunnett's test at a confidence level of 99% using SPSS version 12.0 computer software (SPSS Inc., Chicago, IL, USA).

Isolation of volatile compounds

Volatile compounds were extracted from 80 g samples of steamed rice (SR), stir-fried rice (SFR) and flash-fried rice (FFR) using 120 mL diethyl ether. Twenty microliters of 2-methyl-3-heptanone was added as an internal standard. Each mixture were stirred using a magnetic stirrer for 30 min at room temperature. The extraction was repeated twice. The three portions of the extracts were combined and concentrated to 50 mL using a Vigreux column (30 cm, with 1 cm internal diameter) in a water bath at 40 °C. The volatile components were separated from the oil matrix by using high vacuum distillation at 1.33 mPa. The concentrated extracts were further concentrated to 5 mL under a mild nitrogen stream. The extracts were dried and filtered by passing through anhydrous Na_2SO_4 and glass wool. The sample was further concentrated to 0.5 mL under a mild nitrogen stream.

Analysis of volatile compounds

Volatile compounds were analyzed using mass spectrometry (MS) with an HP 6890 gas chromatograph equipped with an HP 5973 mass selective detector (Agilent Technologies, Palo Alto, CA, USA). One microliter of samples was injected by the cool on-column method into the capillary columns, HP-5 (60m × 0.25m × 0.25μm film thickness) and FFAP (60m × 0.25m × 0.25μm film thickness). The oven temperature program used with the the HP-5 column started at 35 °C, was held for 1 min, increased to 220 °C at the rate of 10 °C/min and then was held for 15 min. The oven temperature program for the FFAP column started at 45 °C, was held for 1 min, increased to 220 °C at the rate of 5 °C/min and then was held for 10 min. Helium was used as the carrier gas at a constant flow rate of 2.2 mL/min. The ionization energy level was 70 eV. Volatile compounds were identified by comparison of mass spectrum data and retention indexes (RI) with the Wiley 275 mass spectrum library, the literature and from authentic standards. RIs were calculated using the *n*-alkanes series (C_5-C_{30}). Relative concentrations of volatile compounds were calculated from total ion areas relative to those of the internal standard (2-methyl-3-heptanone).

Analysis of aroma active compounds

The flavor dilution (FD) factors of the odor active compounds were determined by aroma extraction dilution analysis (AEDA) using gas chromatography-olfactometry (GC-O). The extract sample was diluted sequentially with diethyl ether ratios of 1:3, 1:9, 1:27, 1:81 and 1:243. The determination of FD factors was done by two panelists. The GC-O system consisted of ann HP 5890 gas chromatograph (Agilent Technologies, Palo Alto, CA, USA) equipped with flame ionization detector, and a sniffing port (SGE, Australia). A sample of 1 μL was cool on-column injected into an HP-5MS column (30 m × 0.25 m × 0.5 mm film thickness) and an FFAP column (30 m × 0.25 m × 0.25 mm film thickness). The oven temperature programs used were as previously described.

The experiments were performed using a completely randomized design except for the sensory evaluation which was performed using a randomized complete block design. All experiments were duplicated.

RESULTS AND DISCUSSION

The rice samples were different in color. Steamed rice (SR) was white, stir-fried rice (SFR) was slightly off-white and flash-fried rice (FFR) was light brown.

Sensory evaluation

The aroma characteristics of the samples seemed to be different. SR had a typical cooked-rice odor, SFR had a strong oily and fatty odor, and the FFR aroma was oily and fatty with a smoky and burnt odor.

The sensory evaluation was conducted to confirm that aroma of FFR was different from SFR when evaluated by several panelists. The difference comparison from the control test was done by 30 panelists to investigate the differences in smoke odor attributes between blind FFR-FFR (control), FFR-SFR and FFR-SR. The mean difference scores when comparing FFR with FFR,

FFR with SFR and FFR with SR were -0.07, -2.13 and -4.17, respectively. ANOVA and Dunnett's test results revealed that flash-frying had a significant effect on the unique smoky odor intensity ($P \leq 0.01$). FFR had the strongest smoke odor intensity. SFR had a weaker smoke odor intensity than FFR, and SR had extremely less intense smoke odor.

Determination of volatile compounds

FFR, SFR and SR samples were cooked at different temperatures with and without oil. The SR samples were boiled in water without oil at 100 °C and the SFR samples were stir-fried with soybean oil at approximately 200 °C for 1 min. In the FFR samples, fire was allowed to touch the sample causing the soybean oil to flame for 15 s. The temperature during cooking of the FFR samples therefore reached the flash point of soybean oil at 328 °C (Pryde, 1980). The differences in cooking temperatures caused the differences in the volatile compounds of the rice samples.

Table 1 indicates that higher cooking temperatures generated more types and higher concentrations of volatiles compounds. The FFR samples had total volatiles of 18,520.07 ng/g which was more than twice the amount present in SFR (8,332.10 ng/g). Among the 188 volatile compounds in the FFR samples, hydrocarbons and aldehydes were the major components. Similarly, the SFR samples had hydrocarbons and aldehydes as the major components but with fewer compounds and lower concentrations. Several volatiles in both fried rice samples came from the soybean oil. Higher concentrations of hydrocarbons, aldehydes and ketones in samples of FFR than those in SFR were mainly the result of lipid oxidation and degradation (Kuo *et al*., 1989; van Loon *et al*., 2005). Aldehydes and ketones in the frying oil increased significantly when the heating temperature reached 200 °C (Lee *et al*., 1991). Furans, pyran and pyrazines were generated from carbohydrates. Pyrazines found only in FFR were generated through a Maillard reaction.

Table 1 Number of volatile compounds and total relative concentrations (ng/g) in flash-fried rice (FFR), stir-fried rice (SFR), and steamed rice (SR).

Compound group	FFR		SFR		SR	
	Number of compounds	Relative concentration	Number of compounds	Relative concentration	Number of compounds	Relative concentration
Acids	10	2,148.95	7	1,567.48	8	3,040.37
Alcohols	10	532.31	5	320.34	4	535.98
Aldehydes	24	5,854.97	24	3,593.30	0	0
Amides	0	0	1	6.81	0	0
Esters	5	417.32	3	63.09	1	27.44
Hydrocarbons	76	6,292.83	54	1,639.99	8	321.23
Ketones	10	313.27	5	80.09	1	69.13
Phenols	4	148.63	0	0	2	280.16
Furans	6	640.34	3	72	0	0
Lactones	1	95.41	1	21.32	2	48.18
Pyrans	1	160.45	1	63.23	2	174.89
Pyrazines	2	19.89	0	0	0	0
Others	4	82.23	3	36.33	3	56.35
Unknowns	35	1,813.47	47	868.12	26	736.77
Total	188	18,520.07	154	8,332.10	57	5,290.50

SR samples cooked without the addition of oil and at a lower temperature had only 57 volatile compounds and acids were the major component.

The volatile compounds in Table 2 are selectively listed based on their high concentrations (greater than greater than 100 ng/g) or because they were of specific interest. These compounds were tentatively identified by their RI and mass spectrum values. Acetic acid was the compound presented at the highest concentration in FFR followed by (*E,E*)-2,4-decadienal, (*E*)-2-heptenal, nonanal and 7-methyl-3,4-octadiene. Most aldehydes and ketones in FFR were found at higher concentrations when compared to those in SFR except for (*E,E*)-2,4-heptadienal and (*E,E*)-2,4-decadienal. The most prominent volatile compounds in SFR were similar to those of FFR except 7-methyl-3,4-octadiene was not the major volatile of SFR. The most prominent volatile compounds in SR were acetic acid and 2,3-butanediol.

Carbohydrate derived compounds Unlike deep-frying that takes a long heating time, stir-frying and especially flash-frying allow food to be exposed to heat for only short periods. Such conditions seemed to generate low amounts of carbohydrate-derived volatile compounds. French fries prepared by deep frying contained carbohydrate-derived volatile compounds as 85% of the total volatiles (van Loon *et al*., 2005). Fried rice samples in the present study contained mostly lipid-derived volatile compounds. Only some compounds, such as acetic acid, butanoic acid, pentanoic acid, benzaldehyde, ketones, furans, pyran and pyrazines, were derived from rice starch (Table 2). The major carbohydrates derived from volatile components in the fried rice samples were acetic acid and furfural. Acetic acid was found in samples of FFR, SFR and also SR that were cooked without soybean oil. Furfural with a sweet/caramel aroma, formed by pyrolysis of sugar as well as Maillard reaction (Manley *et al*., 1999), was found in the FFR and SFR samples.

Other furans besides furfural, such as 5-(hydroxymethyl)-2-furancarboxaldehyde and other furans not listed in Table 2 (due to their low concentrations), such as 5-methyl-2-furancarboxaldehyde, 5-methyl-2(3*H*)-furanone, and hydroxy dimethylfuranone, were found only in FFR. These furans and corylone were derived from the pyrolysis of starch (Simkovic *et al*., 1997; Kuentzel and Bahri, 1999).

Pyrazine, methyl pyrazine and 1*H*-pyrrole found in FFR were produced from a Maillard reaction (Whitfield, 1992). From Table 2, it can be seen that the amounts of pyrazines and other carbohydrate-derived volatiles in the fried rice samples were lower than those found in deep-fried products such as French fries, which suggested that the aroma components of stir-fried and flash-fried rice samples were dependent more on lipid-derived volatile compounds.

Lipid derived compounds The major volatile components in the fried rice samples were generated from the degradation of lipids. The major volatiles from the degradation of lipids found in FFR and SFR were (*E,E*)-2,4-decadienal followed by (*E*)-2-heptenal, nonanal, 7-methyl-3,4-octadiene and (*E*)-2-decenal (Table 2).

Soybean oil is composed mainly of oleic acid and linoleic acid. Most aldehydes in the fried rice samples came from lipid oxidation. Nonanal was produced by the degradation of oleic acid whereas hexanal was produced mainly from linoleic acid (van Loon *et al*., 2005). The oxidation of linoleic acid during stir-frying also produced (*E,E*)-2,4-decadienal and (*E,Z*)-2,4-decadienal. Oxidation of linolenic acid generated (*E,E*)-2,4-heptadienal (Tressl *et al*., 1981; Chyau and Mau, 2001). Fatty aldehydes—namely, *n*-hexanal, *n*-heptanal, (*E*)-2-heptenal, (*E*)-2-octenal, nonanal, (*Z*)-2-nonenal and (*E*)-2-decanal—were associated with rancidity (Whitfield, 1992). Alkadienals such as (*E,E*)-2,4-heptadienal, (*E,E*)-2,4-nonadienal, (*E,E*)-2,4-decadienal and (*E,Z*)-2,4-decadienal

Table 2 Relative concentrations of selected volatile compounds in flash-fried rice (FFR), stir-fried rice (SFR) and steamed rice (SR).

Compound	RI		Relative concentration (ng/g)		
	HP-5	FFAP	FFR	SFR	SR
Acids					
acetic acid	n.a.	1429	1,371.15	1,292.62	2,526.83
isobutyric acid	n.a.	1546	n.a.	22.59	64.97
butanoic acid	n.a.	1606	85.19	45.55	35.96
pentanoic acid	n.a.	1716	61.91	35.06	n.a.
hexanoic acid	n.a.	1824	101.94	53.82	133.39
heptanoic acid	n.a.	1932	109.01	21.51	n.a.
octanoic acid	n.a.	2039	72.74	n.a.	34.57
nonanoic acid	n.a.	2145	55.53	n.a.	n.a.
decanoic acid	n.a.	2251	19.60	n.a.	n.a.
benzeneacetic acid	n.a.	2545	n.a.	n.a.	148.46
Alcohols					
1,3-butanediol	785	1558	89.39	104.22	178.02
2,3-butanediol	795	1522	113.02	110.78	321.87
1-pentanol	n.a.	1233	133.06	92.04	n.a.
Aldehydes					
n-hexanal	800	1072	335.12	82.27	n.a.
n-heptanal	900	1174	193.37	79.34	n.a.
(*E*)-2-heptenal	957	1313	706.45	429.19	n.a.
benzaldehyde	964	1514	161.06	21.53	n.a.
2-octenal	n.a.	1414	239.45	109.24	n.a.
2,4-heptadienal	997	1482	195.65	41.30	n.a.
(*E,E*)-2,4-heptadienal	1011	1453	198.09	210.94	n.a.
(*E*)-2-octenal	1059	n.a.	282.28	120.52	n.a.
nonanal	1104	1379	528.18	313.81	n.a.
(*Z*)-2-nonenal	1160	n.a.	164.69	49.40	n.a.
n-decanal	1204	n.a.	101.94	46.71	n.a.
(*E,E*)-2,4-nonadienal	1215	n.a.	5.02	n.a.	n.a.
(*E*)-2-decenal	1263	1626	432.60	291.29	n.a.
2,4-decadienal	1295	n.a.	367.43	342.70	n.a.
(*E,Z*)-2,4-decadienal	n.a.	1751	n.a.	221.47	n.a.
(*E,E*)-2,4-decadienal	1319	1797	739.57	785.00	n.a.
3-dodecen-1-al	1365	1734	295.43	266.45	n.a.
dodecanal	1407	n.a.	63.59	27.75	n.a.
undecenal	n.a.	1736	268.61	n.a.	n.a.
Esters					
(*Z,Z*)-9,12-octadecadienoic acid, methyl ester	1569	n.a.	91.52	n.a.	n.a.
(*E,E*)-9,12-octadecadienoic acid, methyl ester	n.a.	1550	175.37	38.26	n.a.

Table 2 (Cont.)

Compound	RI		Relative concentration (ng/g)		
	HP-5	FFAP	FFR	SFR	SR
Hydrocarbons					
1,3-(*Z*)-5-(*Z*)-octatriene	879	1092	120.10	22.95	n.a.
styrene	893	n.a.	125.73	n.a.	n.a.
(*E*)-1,3-nonadiene	924	n.a.	77.55	13.60	n.a.
(*E,E*)-2,4-nonadiene	961	n.a.	47.71	n.a.	n.a.
1-decane	989	<1000	114.00	18.96	n.a.
limonene	1032	1184	115.89	53.70	7.26
(*E*)-β-ocimene	1048	1237	n.a.	159.12	n.a.
1*H*-indene	1051	1471	158.97	n.a.	n.a.
undecene	1089	1135	217.67	39.19	n.a.
(3*E*,5*Z*)-1,3,5-undecatriene	1174	n.a.	128.91	15.40	n.a.
(*E,E*)-1,3,5-undecatriene	1183	1388	351.74	46.71	n.a.
4-dodecene	1187	n.a.	243.80	137.74	n.a.
azulene	1195	1729	323.05	n.a.	n.a.
dodecane	1196	1198	160.31	44.17	n.a.
(*Z*)-cyclodecene	1223	n.a.	123.12	12.78	n.a.
cyclododecane	1268	1656	145.96	6.34	n.a.
1-dodecene	1285	1235	180.86	28.88	n.a.
methylenecyclohexane	1351	n.a.	249.33	n.a.	n.a.
vanillin	1412	2564	34.64	n.a.	104.24
acenaphthalene	1470	2193	51.91	n.a.	n.a.
7-methyl-3,4-octadiene	1482	n.a.	491.73	207.62	n.a.
pentadecane	1495	1499	101.82	24.10	n.a.
6(*E*),8(*E*)-heptadecadiene	1669	n.a.	161.95	23.92	n.a.
(*E*)-6-dodecene	n.a.	1221	226.67	52.39	n.a.
1-dodecene	n.a.	1320	112.48	39.78	n.a.
cyclodecene	n.a.	1342	121.41	n.a.	n.a.
Ketones					
3-hydroxy-2-butanone	712	1273	37.24	34.31	69.13
3-cyclohepten-1-one	824	n.a.	78.41	n.a.	n.a.
2-hydroxy-2-cyclopenten-1-one	927	n.a.	51.34	n.a.	n.a.
3-methylcyclopent-2-enone	969	n.a.	20.66	n.a.	n.a.
(*Z*)-8-methyl-1-hydrindanone	1157	n.a.	20.10	n.a.	n.a.
2-heptanone	n.a.	1171	13.44	n.a.	n.a.
corylone	n.a.	1816	39.38	n.a.	n.a.
Phenols					
phenol	981	1995	34.72	n.a.	11.45
4-vinyl-2-methoxy-phenol	1321	2190	10.29	n.a.	89.28
o-cresol	n.a.	1992	87.30	n.a.	n.a.
m-cresol	n.a.	2071	16.32	n.a.	n.a.
2,4-di-*tert*-butylphenol	n.a.	2294	n.a.	n.a.	179.43

Table 2 (Cont.)

Compound	RI		Relative concentration (ng/g)		
	HP-5	FFAP	FFR	SFR	SR
Heterocyclic compounds					
Furans					
furfural	835	1456	247.79	21.38	n.a.
5-(hydroxymethyl)-2-furancarboxaldehyde	1234	2501	113.74	n.a.	n.a.
Lactones					
γ-butyrolactone	915	1623	95.41	21.32	11.97
Pyrans					
2,3-dihydro-3,5-dihydroxy-6-methyl-4*H*-pyran-4-one	1151	2261	160.45	63.23	168.26
Pyrazines					
pyrazine	737	n.a.	11.12	n.a.	n.a.
methyl pyrazine	n.a.	1257	8.77	n.a.	n.a.
Others					
1*H*-pyrrole	755	n.a.	21.93	n.a.	n.a.

n.a. = not available

were responsible for the deep-fried aroma (Wagner and Grosch, 1997). From Table 2, FFR had a higher content of fatty aldehydes than SFR but the alkadienal concentrations of the FFR and SFR were not much different. This fact suggested FFR and SFR were similar in frying aroma characteristics but the aroma of FFR was probably more pronounced with regard to rancidity than SFR.

Pyrolysis of vegetable oil generates hydrocarbons such as 1-octene, decane, 1-undecene, 1-dodecene and 1-tridecene that were found in both SFR and FFR, while 1-nonene, 1-decene, and undecane were found only in FFR. These compounds were reported in tropical vegetable oils that had been pyrolyzed at 300–500 °C (Alencar *et al*., 1983)

Some hydrocarbons such as azulene, 1*H*-indene, cyclododecene, and styrene were found only in FFR. Styrene is an intermediate product from the reaction between amino acids and alkadienals through a Maillard reaction under anaerobic conditions (Hidalgo and Zamora, 2007). Limonene was found in all samples but was at the highest concentration in FFR. There were also reports of limonene in French fries and heated peanut oil (Chung *et al*., 1993; van Loon *et al*., 2005)

Flash frying that allowed soybean oil to flame for 15 s also generated polycyclic aromatic hydrocarbons (PAH) such as acenaphthalene (Table 2). Acenaphthalene was found only in FFR at 51.91 ng/g. Several PAHs that are carcinogenic were found in volatiles from vegetable oils heated at 220 °C for 2 h (Chen and Chen, 2001).

Aroma active compounds

Aroma-active compounds of FFR, SFR and SR were studied using GC-O and AEDA. The aroma-active compounds listed in Table 3 were tentatively identified by their odor description and RI through comparisons with the literature. Compounds could be grouped by their aroma descriptions as stir-fried oil/oily, burnt, metallic, fishy/salty, sweet, sour and a few other categories.

Table 3 Selected aroma-active compounds in flash-fried rice (FFR), stir-fried rice (SFR) and steamed rice (SR).

Compound	Description [a]	RI		FD factor [b]		
		HP-5	FFAP	FFR	SFR	SR
1,3-butanediol [c]	solvent	785	n.a.	3	-	-
hexanal [c,h]	green	799	n.a.	9	9	-
heptanone [f]	metallic, solvent	885	n.a.	27	3	-
unknown A	sweet	907	n.a.	27	3	-
unknown B	fishy	917	n.a.	-	27	-
acetylfuran [n]	sweet	923	n.a.	27	3	0
2-acetyl-1-pyrroline [d, j]	sweet, pandan like	939	1220	27	3	27
hexanoic acid [g]	sour, stale	990	n.a.	-	-	0
octadienone [f]	metallic, rust	997	n.a.	27	81	-
unknown C	sweet	1023	n.a.	-	81	-
benzylmethyl ether [f]	metallic	1030	n.a.	-	-	0
limonene [c,h,i]	citrus	1035	n.a.	27	-	-
(*Z*)-2-nonenal [k, l, r]	stir-fried oil, sweet, burnt	1151	1497	9	-	-
decanal [std]	waxy, scented candle-like	1205	n.a.	27	9	-
(*Z*)-2-decenal [m, d]	stir-fried oil, burnt	1256	1586	27	-	-
decanoic acid [c, f]	oily, sweet	1393	2251	3	0	-
dodecanal [c, f]	stir-fried oil, burnt	1407	n.a.	27	9	-
2-dodecenal [f]	stir-fried oil	1461	n.a.	27	-	-
methyl dodecanoate [f]	stir-fried oil	1511	n.a.	-	27	-
hexyl octanoate [f]	stir-fried oil, burnt	1568	n.a.	27	27	-
butyl laurate [f]	frying oil	1680	n.a.	-	9	-
unknown D	stir-fried oil, burnt	1701	n.a.	27	3	-
unknown E	stir-fried oil, burnt	1744	n.a.	27	-	-
unknown F	frying oil	1751	n.a.	-	27	-
unknown G	sweet	1810	n.a.	-	-	0
unknown H	stir-fried oil, sweet, burnt	1815	n.a.	27	-	-
unknown I	stir-fried oil	1890	n.a.	-	27	-
unknown J	frying oil	1982	n.a.	-	27	-
2-methylpropylhexadecanoate [f]	stir-fried oil, burnt	2014	n.a.	0	9	-
unknown K	oily	2016	n.a.	27	-	-
oleic acid [f]	stir-fried oil, burnt	2070	n.a.	27	27	-
unknown L	stir-fried oil, burnt	2164	n.a.	27	-	-
octadecanol [f]	oily, salty	2232	2574	3	9	-
butanal [f]	green	n.a.	<1000	27	3	-
unknown M	fishy, salty	n.a.	1061	81	3	-
1-hexen-3-one [r]	metallic, solvent	n.a.	1095	9	-	-
unknown N	sweet, stale	n.a.	1135	81	3	-
heptanone [e]	metallic, rust	n.a.	1204	81	9	-
propyl butyrate [f]	solvent	n.a.	1221	27	-	-
unknown O	wok	n.a.	1266	9	-	-
unknown P	sour, vinegar-like	n.a.	1319	27	3	3
unknown Q	wok	n.a.	1321	0	-	-
nonanal [std]	waxy, scented candle-like	n.a.	1370	81	3	-

Table 3 (Cont.)

Compound	Description [a]	RI		FD factor [b]		
		HP-5	FFAP	FFR	SFR	SR
(*E*,*E*)-2,4-heptadienal [c]	stir-fried oil, sour	n.a.	1461	27	0	-
2,4-heptadienal [c]	stir-fried oil, burnt	n.a.	1475	81	-	-
3,6-dihydro-4-methyl-2-(2-methyl-1-propenyl)-2*H*-pyran [f]	oily	n.a.	1485	-	3	-
propanoic acid [f]	sour, rancid	n.a.	1506	-	3	-
2-nonenal [f]	stir-fried oil	n.a.	1522	9	-	-
(*E*)-2-nonenal [d, l, q]	stir-fried oil	n.a.	1531	27	3	-
linoleic acid [c]	stir-fried oil	n.a.	1556	9	0	-
isobutyric acid [f, r]	sour, rancid, salty	n.a.	1565	0	3	0
(*E*)-2-decenal [m, q]	stir-fried oil	n.a.	1630	3	-	-
(*E*,*E*)-2,4-nonadienal [h, l, r]	stir-fried oil	n.a.	1704	9	-	-
(*E*,*Z*)-2,4-decadienal [p]	stir-fried oil	n.a.	1770	9	-	-
heptanoic acid [c]	oily, sweet	n.a.	1938	9	-	-
(*E*)-4,5-epoxy-(*E*)-2-decenal [o]	oily	n.a.	1984	-	3	-
octanoic acid [o]	stir-fried oil	n.a.	2052	3	-	-
6,10,14-trimethyl-2-pentadecanone [f]	stir-fried oil, sweet	n.a.	2111	3	0	-
3-phenyl-2-propen-1-ol [f]	oily, sweet	n.a.	2304	0	3	-
dodecanoic acid [o]	stir-fried oil, sweet	n.a.	2473	3	-	-

[a] Odor description at the sniffing port from GC-O. [b] FD Factor on HP-5MS or FFAP columns; FD factor = 0 means the extract before dilution by AEDA method, - = no detected odor. [c] Identified by comparing with retention index (RI) on HP-5MS or FFAP columns, mass spectra obtained by MS and odor at the sniffing port on the same column. [d] Identified by comparing with retention index (RI) on HP-5MS or FFAP columns and odor description at the sniffing port with the data from Jezussek *et al*. (2002) [e] El-Sayed (2010) [f] Acree and Arn (2009) [g] Karagul-Yuceer *et al*. (2003) [h] Steinhaus *et al*. (2007) [i] Buettner *et al*. (2003) [j] Roberts and Acree (1994) [k] Reiner and Grosch (1998) [l] Schnermann and Schieberle (1997) [m] Wagner and Grosch (1997) [n] Varlet *et al*. (2006) [o] Karagul-Yuceer *et al*. (2001) [p] Kirchhoff and Schieberle (2001) [q] Tairu *et al*. (2000) [r] Rychlik *et al*. (1998) [std] Identified based on standard compound.

The steamed rice samples had only seven aroma active compounds; 2-acetyl-1-pyrroline (2AP), the character impact compound of fragrant rice, had the highest impact on the overall aroma of the cooked rice samples. 2AP was not detected with the mass selective detector because it presented at a low concentration in all samples; it was only with GC-O that 2AP was detected in the study. The other compounds that contributed to the sour aroma in the SR samples were isobutyric acid and hexanoic acid (FD factor = 0) and the unknown compound P (FD factor = 3).

Most aroma-active components in the fried-rice samples were from the degradation of soybean oil and had a stir-fried oil/oily characteristic. Stir-frying generated octadienone (metallic) and an unknown compound C (sweet) as the most prominent (FD factor = 81) aroma compounds in stir-fried rice. In the SFR samples, most aroma compounds with a high FD factor of 27, possessed stir-fried oil aroma characteristics. They were methyl dodecanoate, hexyl octanoate, oleic acid and unknown compounds F, I and J. The unknown compound B with a fishy characteristic was among the major aroma-active compounds in SFR. The fishy characteristic was associated with linoleic acid that accounted for approximately 7% in soybean oil (Warner and Gupta, 2005). The compounds that were responsible for the fishy odor from linoleic acid were not detected with the mass selective detector used in the present experiment and have not been identified in any of the literature.

While flash-frying rice involves heating for only 15 s, it generated more aroma-active compounds with higher FD factors when compared to SFR. The most prominent compounds (FD factor = 81) in FFR consisted of 2,4-heptadienal (stir-fried oil), nonanal (waxy, scented candle), heptanone (metallic) and unknown compounds M (fishy, salty) and N (sweet, fatty). FFR had more than 20 compounds that had FD factors with a value of 27. Aldehydes that were described as having a stir-fried oil/ burnt aroma dominated this category. Octadienone contributed to the metallic characteristic and 2AP, acetylfuran and the unknown compound A contributed to the sweet aroma of FFR.

It should be noted that FFR had unknown compounds O and Q with a "wok" aroma characteristic that is associated with flash-fried foods. Unknown O had RI = 1266 on the FFAP column and its FD factor was 9 whereas unknown Q had RI = 1321 and an FD factor of 0. Neither compound was perceived in the SFR sample. Several aroma-active compounds including the unknown compounds O and Q in FFR were detected only from GC-O and not by mass spectroscopy. Thus, these compounds presented at very low concentrations but they had very low thresholds.

CONCLUSION

Flash-frying gave a unique burnt aroma characteristic that was different from the aroma of typical stir-fried rice. This unique aroma came from the greater number of compounds and the high amount of aroma compounds especially aldehydes and ketones resulting from the degradation and oxidation of lipids. Flash-frying also generated high concentrations of hydrocarbons but they did not contribute much to the aroma of the samples. Compounds that had a high impact on the aroma of flash-fried rice were 2,4-heptadienal (stir-fried oil), nonanal (scented candle), heptanone (metallic, rust) and two unknown compounds that had fishy/salty and sweet/stale characteristics, respectively. FFR had more aldehydes from the degradation and oxidation of lipids that gave the stir-fried oil a burnt aroma. Most importantly, there were two unknown compounds that had the characteristic of a wok-cooked aroma or flashed-fried aroma that were not detected in SFR. It was also a concern that flash frying could produce carcinogenic PAHs such as acenaphthalene even though the cooking time was only 15 s.

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