JOURNAL OF ENVIRONMENTAL SCIENCES 127 (2023) 389–398

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JES JOURNAL OF ENVIRONMENTAL SCIENCES

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Investigating aldehyde and ketone compounds produced from indoor cooking emissions and assessing their health risk to human beings

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ARTICLE INFO

Article history:
Received 2 February 2022
Revised 17 May 2022
Accepted 17 May 2022
Available online 30 May 2022

Keyword:
Aldehyde and ketone
Indoor cooking
Emission factor
Health risk

ABSTRACT

Aldehyde and ketone compounds are ubiquitous in the air and prone to adverse effects on human health. Cooking emission is one of the major indoor sources. Aiming to evaluate health risks associated with inhalation exposure to aldehyde and ketone compounds, 13 carbonyl compounds (CCs) released from heating 5 edible oils, 3 seasonings, and 2 dishes were investigated in a kitchen laboratory. For the scenarios of heating five types of oil, aldehydes accounted for 61.1%-78.0% of the total emission, mainly acetaldehyde, acrolein and hexanal. Comparatively, heating oil with added seasonings released greater concentrations of aldehyde and ketone compounds. The concentration enhancement of larger molecular aldehydes was significantly greater. The emission factors of aldehyde and ketone compounds for cooking the dish of chili fried meat were much greater compared to that of tomato fried eggs. Therefore, food materials also had a great impact on the aldehyde and ketone emissions. Acetone and acetaldehyde were the most abundant CCs in the kitchen. Acrolein concentrations ranged from 235.18 to 498.71 μg/m^3, which was about 100 times greater compared to the guidelines provided by Office of Environmental Health Hazard Assessment (OEHHA). The acetaldehyde inhalation for adults was 856.83-1515.55 μg and 56.23-192.79 μg from exposure to chili fried meat and tomato fried eggs, respectively. This exceeds the reference value of 90 μg/day provided by OEHHA. The findings of this study provided scientific evidences for the roles of cooking emissions on indoor air quality and human health.

Introduction

Aldehyde and ketone compounds are ubiquitous in the air and prone to adverse effects on human health (Hauptmann et al., 2004). A large number of previous studies show that primary pollutants such as motor vehicle exhaust (Biwer and Butler, 2010), industrial emission (Chen et al., 2014; Styler, 2015) and catering oil fume (Cheng et al., 2015) are important sources of aldehydes and ketones in urban atmosphere. Comparatively, the typical sources of indoor aldehyde and ketone compounds mainly include the release of architectural and decorative materials (Lim et al., 2014; Zhou et al., 2018), smoking (Fan et al., 2017; Lucas, 2018) and indoor cooking oil fume (COF) (Kabir and Kim, 2011). Consider that it is concluded sometimes indoor air quality is worse compared to outdoor air quality (Xu et al., 2017), people spend over 80% of time indoors,

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https://doi.org/10.1016/j.jes.2022.05.033

and COF is one of the major sources of indoor aldehyde and ketone compounds (Ho and Yu, 2006), it is necessary to understand and evaluate the concentration levels of aldehyde and ketone compounds in the kitchen microenvironment and human exposure, which is useful to assess the health effects of COF related aldehyde and ketone compounds inside kitchen and other rooms.

The aldehydes and ketones produced during the cooking process are not the ingredients contained in the edible oil, but the products of oxidation, cracking and hydrolysis of edible oil and other cooking ingredients occurred during heating at high temperature (Choe and Min, 2010). The concentrations and chemical compounds of aldehydes and ketones generated from COF are highly variable, which are affected by factors of oil types, heating temperature, ingredients of food material, cooking methods and catering types. Klein et al. (2016) showed that when heating different types of edible oils, over 5% mass concentration of volatile organic compounds (VOCs) belongs to aldehydes. The main emission products are acrolein, malondialdehyde, 2,4-heptadienal and nonanal for heating rapeseed oil, and are acrolein, hexanal, 2-heptanaldehyde and 2,4-decendialdehyde for heating sunflower seed oil. When the heating temperature is higher than the smoke point of a specific edible oil, its aldehyde emission increases nearly linearly with the change of heating temperature (Katragadda et al., 2010). Different kinds of food materials cause the diversity of aldehydes and ketones. Shi et al. (2015) measured that the concentrations of aldehydes and ketones emitted by fried chicken, fried potato, fried octopus and fried egg were 1.349 mg/m^3, 1.3 mg/m^3, 0.385 mg/m^3 and 0.108 mg/m^3, respectively. A recent study showed aldehyde and ketone compounds generated from the exhaust of restaurants in Beijing ranged within the range of 0.115-1.036 mg/m^3. The rank of concentration of different styles of restaurants was roast duck > Chinese barbecue > Home cooking > Western fast food > School canteen > Chinese fast food > Sichuan cuisine > Huaiyang cuisine (Cheng et al., 2015). Ho and Yu (2006) investigated the emissions produced from different cooking styles in Hong Kong, and found the highest concentration of aldehyde and ketone compounds was formaldehyde, accounting for 12%-60%. Acrolein took up about 30%. Formaldehyde, acetaldehyde, acrolein and nonanal accounted for 72% of the total VOC concentration. There are great differences existing in the composition of aldehyde and ketone compounds of cooking emissions from different types of restaurants. The proportion of aldehyde and ketone compounds (C_1-C_3) produced by Western restaurants was about 20%, which was significantly lower than that of Chinese restaurants, accounting for 40% (Cheng et al., 2015).

A large proportion of aldehydes and ketones have strong irritation and toxicity to human health. Long term exposure to high concentrations of aldehydes and ketones can lead to dizziness, nausea and other symptoms (Andreini et al., 2000), which is harmful to human health. A previous risk analysis suggested that aldehydes accounted for over 91% of the total risk of non-cancer diseases, including cardiovascular and lung diseases (i.e., acrolein, 88.5%; acetaldehyde, 2.4%; formaldehyde, 0.4%) (Haussmann, 2012). Compounds such as acetaldehyde and acrolein can cause chronic or acute damage to human respiratory system (Bari and Kindzierski, 2018; Dai et al., 2017). Acrolein is also an eye irritant that worsens asthma (Ho et al., 2016). A recent study also showed that long-term inhalation of acrolein, even at low levels, may increase the risk of cardiovascular disease (Conklin et al., 2017). Acetone is a medium toxic reagent, which damages the central nervous system and liver of human (Pan and Ye, 2017). Given adverse effects of aldehydes and ketones, human exposure to aldehydes and ketones generated from COF can lead to a potential health hazard. However, Chinese National Indoor Air Quality Standard (GB/T 18883-2002) only sets the reference value of formaldehyde (0.10 mg/(m^3•hr)).

Although a number of studies have investigated personal exposures and health risks of aldehyde and ketone compounds inside cars, public transportation (Xu et al., 2017), and indoor living rooms (Fan et al., 2020), less attention has been paid to human exposure to aldehydes and ketones inside kitchen during cooking. Zhang et al. (2019) investigated the species of VOCs produced in COF from heating five edible oils and their corresponding health risk assessments. It was found that furans and various aldehydes (nonanal, hexanal, heptanaldehyde and octanal) had higher cancer risk than benzene compounds. Huang et al. (2020) studied the characteristics and health risk of VOCs in restaurants in Shanghai, and found that non-carcinogenic risk values (HQ) for acetaldehyde and acrolein monitored in hot pot restaurants all exceeded Environmental Protection Agency (US EPA) standards (HQ < 1), indicating that long-term exposures in hot pot restaurants would have a significant impact on human health and might bring a potential cancer risk. Sun et al. (2019) investigated toxic VOCs and their health risks from residential solid fuel burning and indicated the rural residents were exposed to toxic VOCs from indoor heating and cooking at levels higher than the recommended safety levels. Cancer risk from exposure to VOCs for women was 8.98×10^{-4} and 1.67×10^{-4} in both traditional and liquefied petroleum gas kitchens, respectively. These studies have provided valuable information for the pollution of aldehydes and ketones caused by cooking, indicating health risk from exposure to aldehydes and ketones was affected by factors of oil types, catering types and fuel. However, very few of studies examined male's exposure to aldehydes and ketones during cooking and assessed health risk from cooking different dishes.

Therefore, this study conducted cooking experiments in a kitchen laboratory built in Fudan university, aiming to investigate the species and concentrations of aldehyde and ketone compounds generated during various cooking processes and assess their underlying health effects on male and female. The findings of this study provided scientific evidences for the roles of cooking emissions on indoor air quality and human health.

1. Materials and methods

1.1. *Kitchen lab*

A kitchen laboratory was built to study the aldehyde and ketone compounds generated from COF released from various cooking processes. The size of the kitchen is 2.5 m in length, 2.0 m in width, and 3.0 m in height, as given by **Fig. 1**.

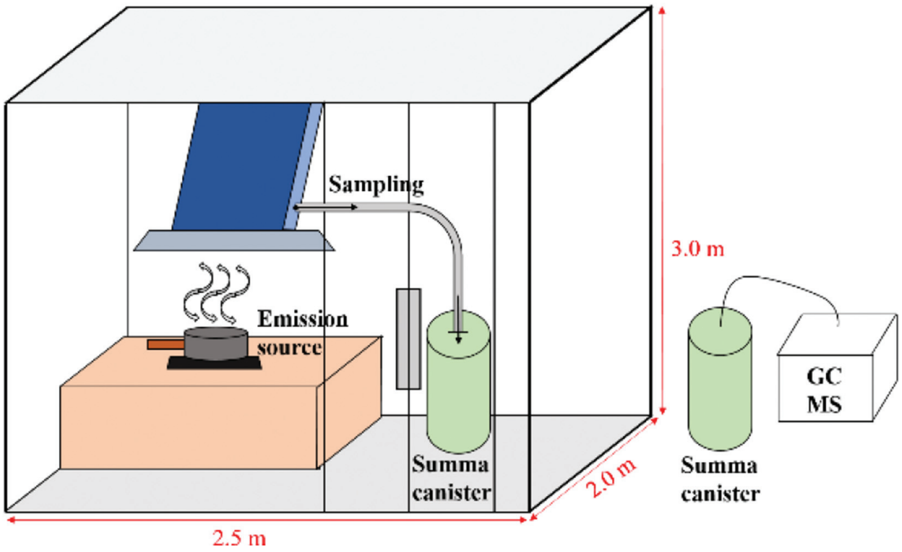

Fig. 1 – The kitchen lab and sampling point. GC MS–Gas chromatography mass spectrometry.

The cooking area was 1.0 m above the ground. An induction cooker with 1600 W power was adopted for heating edible oil and cooking dishes. A temperature monitor was used to monitor the temperature during cooking, aiming to maintain the temperature varying within a very small range during sampling time period, which can be considered as stable. The temperature during cooking was about 260°C. The time spent on the cases of only heating oil and adding seasoning to heated oil was about 30 min, and cooking dishes was 10 min. The cooking experiment started from the moment of adding oil, and the sampling process was carried out synchronously with the experimental process. Therefore, the sampling time for only heating oil and adding seasoning to heated oil was 30 min. The sampling time for cooking dishes was 10 min. A ventilation range hood was installed for sampling cooking emissions produced from cooking. Its sampling efficiency was over 96%. It was obtained by firstly monitoring COF concentration produced inside a cylinder chamber, and then removed the chamber, turned on the ventilation range hood, sampling COF from a small hole on the air duct right above the ventilation range hood. The ratio of the two concentrations was the sampling efficiency. The air volume of ventilation range hood was about 100 m^3/hr. The sampling point was about 2.5 m away from the ground. COF is undiluted before entering the sampling pipe for sampling by a Summa canister (29-10321, Entech, America). Before sampling, the Summa canister was vacuumed and connected with a flow limiting valve. The sampling flow was 86.6 mL/min. Each round of sampling was repeated for three times. Before each round of experiment, turned on the ventilation range hood for 30 min to remove COF. A condensation particle counter (3776, TSI, America) was adopted to monitor the indoor particle number concentration, aiming to ensure all COF was sucked up by the ventilation range hood. When it reduced to the background concentration and maintained the stable state for a while, a new round of experiment was initiated.

1.2. *Cooking design*

Different cooking conditions included heating five types of edible oil (soybean oil, peanut oil, rapeseed oil, sunflower oil and lard), adding three types of seasonings (chili powder, Chinese prickly ash, garlic slices) into heated soybean oil and peanut oil, respectively. Two common dishes (tomato frying eggs, and chili frying meat) were also considered. For heating oils, 300 mL (279 g) was adopted for each type of edible oil, and the heating time was 30 min. For adding seasons into heated oils, 300 mL oil and 10 g seasonings were adopted, and the heating time was 30 min and the seasoning was added after 20 min. For the two dishes, 250 g tomato, 150 g egg, 20 mL oil, 10 g seasonings, and 3 g salt were adopted for tomato frying eggs. The 200 g chili, 150 g meat, 20 mL oil, 10 g seasonings, 3 g salt, and 10 mL soy sauce were adopted for chili frying meat. The seasonings were added after 1 min. Two min later, then added vegetables, egg, and meat. Eight min later, the salt was added. Another two-min cooking followed.

1.3. *Analysis of aldehyde and ketone emissions*

The samples were analyzed using a GC-FID/MS (GCMS-QP2020, Shimadzu, Japan). C_2-C_4 compounds were analyzed by GC-FID channel. The chromatographic column was PLOT Al_2O_3 capillary column with 15 m × 0.32 mm × 3.0 µm. The initial column temperature was 35°C lasting for 3 min, then heated to 180°C at 6°C/min lasting for 5 min. The determination of C_5-C_{12} compounds was performed using GC-MS channel with a DB-624 capillary column of 60 m × 0.25 mm × 1.4 µm. The carrier gas was high purity nitrogen (purity > 99.999%), and the carrier gas flow rate was 1.3 mL/min. The temperature of the FID detector was set to 200°C. The flow rate of gas (hydrogen) was 50 mL/min, that of auxiliary gas (air) was 400 mL/min, and that of compensating gas (nitrogen) is 20 mL/min. EI ionization source was used for mass spectrometry, with electron energy of 70 eV and ion source temperature of 200°C, which was detected by selective ion scanning. The detection limit of each substance ranged from 0.002 to 0.05 μg/L. Insert one N_2 sample and standard gas sample for each 8 samples to ensure the accuracy and stability of the test system.

In this study, 13 kinds of standard gases (Spectra Gases Inc., America) were selected for quantitative analysis, including acetaldehyde, acrolein, propanal, methylacrolein, *n*-butyl aldehyde, amyl aldehyde, hexanal, acetone, methyl vinyl ketone, butanone, 2 - pentanone, 3 - pentanone and methyl isobutyl ketone. Other aldehyde and ketone compounds have not been quantified. Calibration curves were performed by using eight standard concentrations (from 0.1 to 10 μg/mL) for the quantification of target aldehydes and ketones. The concentrations and responses for aldehydes and ketones followed linear relationships. The correlation coefficients were greater than 0.99. Emission factors of 13 aldehyde and ketone were determined in total.

1.4. *Emission factor and inhalation exposure*

The measurement for each condition was repeated for three times, and the relative standard deviation was less than 5%. In order to reduce the error, the average concentration was used to calculate the emission factor (EF), as given in Eq. (1).

$$\mathrm{EF} = \frac{C \times R \times Q}{M} \tag{1}$$

in which, C (μg/m^3) is the average concentrations of aldehyde and ketone compounds of the three samples measured by the instrument; R is the dilution factor; Q (m^3/hr) is the airflow; M (g) is the mass of cooking material; EF (μg/($g_{\mathrm{ingredients}}$•hr)) is the emission factor of aldehyde and ketone compounds during cooking.

The inhalation exposure (E) of aldehydes and ketones were calculated according to Eq. (2).

$$E = C \times \mathrm{IR} \times T \tag{2}$$

in which, E (μg) is the inhalation dose of aldehyde and ketone compounds in the kitchen; C (μg/m^3) is the average concentration of aldehyde and ketone compounds measured in the kitchen; IR is the inhalation rate, the values referred to Chinese exposure factors handbook (Adults), 14.5 m^3/day for adult women and 17.7 m^3/day for adult men (Duan et al., 2015); T (min) is the exposure time, cooking a dish spent in the kitchen.

2. Results and discussion

2.1. *Effects of heating different edible oils on aldehydes and ketones emission*

Fig. 2a and **Appendix A Tables S1-S5** show the average concentrations and emission factors of aldehydes and ketones from heating five different edible oils. The emission factor of aldehydes and ketones produced during heating rapeseed oil was the greatest, reaching up to 436.12 μg/(g_{oil}•hr), in comparison to the lowest value of 250.87 μg/(g_{oil}•hr) for the emissions of heating lard. The emission factor of aldehydes and ketones for rapeseed oil was 1.74 times of that for lard. Among these five types of edible oils, aldehydes accounted for 61.1%-78.0% of the total emissions, which were greater compared to ketones. The findings were consistent with previous studies (Fullana and Carbonell Barrachina, 2004; Katragadda and Fullana, 2010; Schauer and Kleeman, 2002). The emission factors of aldehydes for various edible oils ranged from 153.19 to 299.79 μg/(g_{oil}•hr) with the order of sunflower seed oil > soybean oil > rapeseed oil > peanut oil > lard. Acetaldehyde, acrolein and hexanal accounted for the largest proportions of aldehyde emissions. Acrolein was with the greatest concentration among the aldehyde emissions produced by heating soybean oil, which was up to 129.24 μg/(g_{oil}•hr), accounting for 32.2% of aldehydes and ketones emissions. Acetaldehyde was with the largest concentration of aldehyde emissions from heating rapeseed oil, accounting for 25.2% of aldehydes and ketones emissions. Hexanal emission reached up to 40.2% of aldehydes and ketones emissions for heating sunflower seed oil, and the concentration was 154.41 μg/(g_{oil}•hr). The largest contributor to heating peanut oil and lard was acrolein, followed by acetaldehyde and hexanal. The variation in emissions was mainly because edible oil contains different chemical components. Different double bond locations and fracture locations in triglycerides will induce the formation of different hydroperoxides, which further lead to the decomposition into different kinds of aldehydes. These aldehydes were not the original compositions of the oil, but were formed by chemical changes during heating oil.

Acrolein is formed by dehydration of glycerol which is common in oil emission, while other aldehydes are produced by peroxy radical reaction of fatty acids (Gardner, 1989). Some studies concluded that linoleic acid is related to the emission of glutaraldehyde and hexanal, linolenic acid is related to acrolein and propionaldehyde (Fullana and Carbonell Barrachina, 2004; Katragadda and Fullana, 2010), while acetaldehyde is affected by both linolenic acid and oleic acid. Generally, owning to that unsaturated bond is easier to break and oxidize, so that the aldehyde emission of heating edible oil rich in unsaturated fatty acids is greater than that of edible oil rich in saturated fatty acids.

The aldehyde concentration produced from cooking vegetable with soybean oil was greater compared to that of potatoes fried with hydrogenated soybean (Schauer and Kleeman, 2002). The fatty acid composition of the five edible oils used in this study is shown in **Table 1**. **Fig. 2** indicates that the concentrations of glutaraldehyde and hexanal emitted from heating soybean oil and sunflower seed oil were rich in linoleic acid, which were greater than those of the other three oils. Because rapeseed oil contains more monounsaturated fatty acids (oleic acid) and polyunsaturated fatty acid (linolenic acid), acetaldehyde emission accounted for the largest proportion, and its concentration was significantly greater compared to that of other edible oils. Among vegetable oils, peanut oil contains the most saturated fatty acids, while lard as animal oil also contains more saturated fatty acids and oleic acid. Therefore, the emission concentration of aldehyde from peanut oil and lard was relatively low.

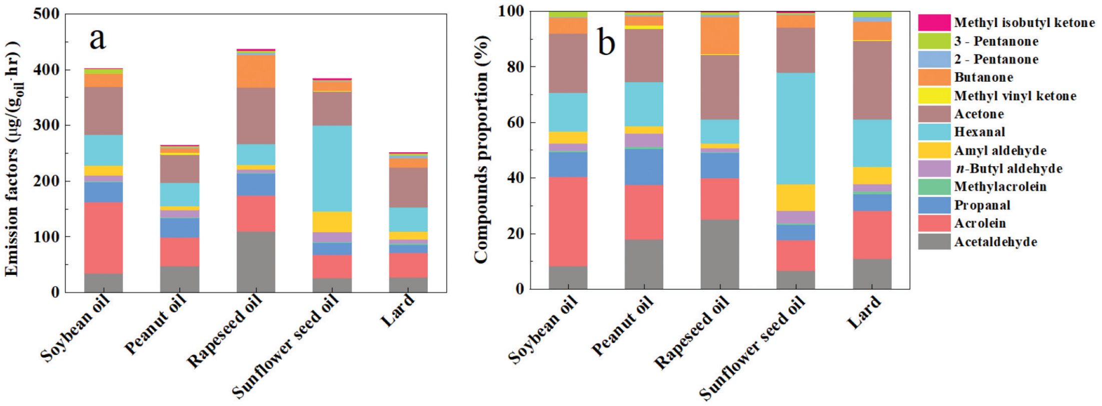

Fig. 2 – (a) Emission factors of aldehydes and ketones from heating different edible oils and (b) the percentage of aldehydes and ketones emitted by heating different edible oils.

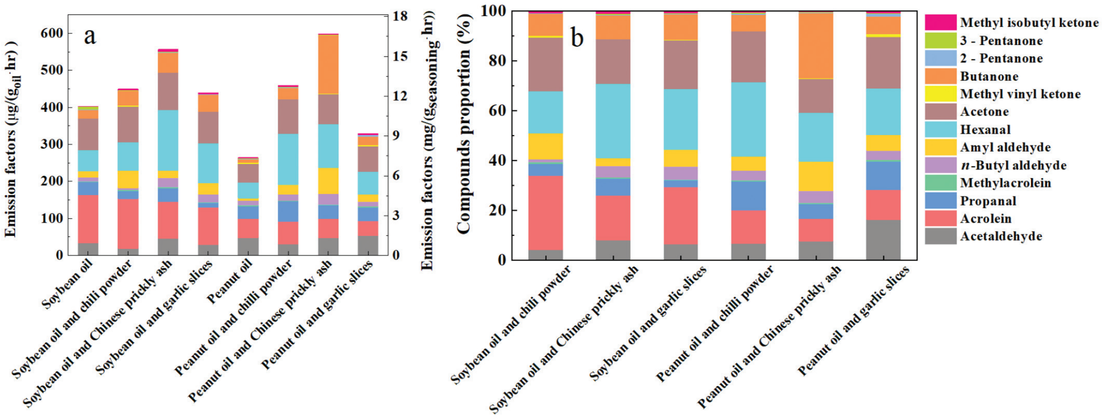

Fig. 3 – (a) Emission factors of aldehydes and ketones when seasoning is added to edible oil and (b) the percentage of aldehydes and ketones produced when seasoning is added to edible oil.

Table 1 – The fatty acid composition of the five edible oils used in this study.

Edible oil	Saturated fatty acid (%)	Monounsaturated fatty acid (%)	Polyunsaturated fatty acid (%)		
			Linoleic acid	Linoleic acid	Total
Soybean oil	20.58	29.08	45.30	3.53	48.83
Peanut oil	22.49	41.65	31.00	2.86	33.86
Rapeseed oil	5.52	73.04	13.29	4.70	17.99
Sunflower seed oil	11.40	26.17	60.30	0.09	60.39
Lard	48.50	38.83	9.43	0.30	9.73

2.2. *Effect of seasoning on aldehydes and ketones emission*

Fig. 3a and **Appendix A Tables S6-S11** show the average concentrations and emission factors of aldehydes and ketones when seasoning was added to heated oils. The left and right Y axes represent the emission factors calculated by unit mass of edible oil and seasoning, respectively. While heating soybean oil and peanut oil without seasoning only calculate the emission factor based on unit mass oil. Compared with the previous contents, the aldehydes and ketones emissions increased when the seasonings were added into heated soybean oil or peanut oil. Aldehydes still accounted for the largest proportion of the total emissions, ranging from 59.3% to 71.5%, as shown in **Fig. 3b**.

When heating soybean oil, the addition of chili powder, Chinese prickly ash and garlic slices increased aldehyde emissions by a factor of 7.5%, 38.5% and 6.5%, respectively. Among

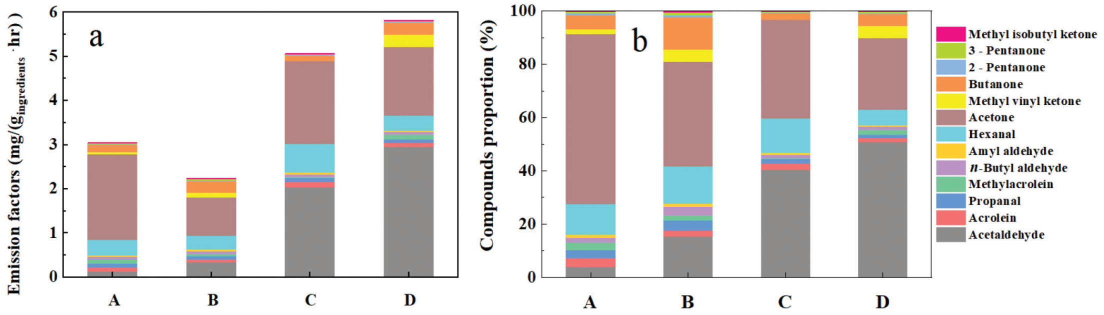

Fig. 4 – (a) Emission factors of aldehydes and ketones from cooking dishes and (b) the percentage of aldehydes and ketones from cooking dishes. A–Scrambled egg with tomato and soybean oil; B–Scrambled egg with tomato and peanut oil; C–Fried pork with chili and soybean oil; D–Fried meat with chili and peanut oil.

them, the impact of Chinese prickly ash was the largest, while garlic slices was the smallest. The emission factors were 393.55 $\mu g/(g_{oil}\cdot hr)$ and 302.77 $\mu g/(g_{oil}\cdot hr)$, respectively (11 and 8.45 $mg/(g_{seasoning}\cdot hr)$).

When seasonings were added into the heated peanut oil, the aldehyde emission increased significantly compared with heating peanut oil only. The addition of chili powder, Chinese prickly ash and garlic slices caused increase of 66.4%, 80.0% and 14.9% to the aldehyde emission, respectively. Similar to heating soybean oil, the aldehyde emission concentration of adding Chinese prickly ash was the largest, reaching up to 355.14 $\mu g/(g_{oil}\cdot hr)$ (9.91 $mg/(g_{seasoning}\cdot hr)$), while adding garlic slices increased the least. The maximum concentration was 1.57 times over the minimum concentration. For both heating soybean oil or peanut oil with added seasonings, the species accounting for the largest proportion of aldehydes were mainly acrolein and hexanal, reaching up to 28.5%-47.5% of aldehyde and ketone emissions. In addition, when garlic slices were added to heated peanut oil, the proportion of acetaldehyde was significantly greater compared to that of scenarios. Compared with the scenario of only heating peanut oil, the concentrations of glutaraldehyde and hexanal in each group increased by 6.8%-990.2% and 35.3%-223.9%, respectively. Except for a slight decrease in individual groups, the emission of *n*-butyl aldehyde in other groups increased by 32.8%-142.8%. And the emission of propionaldehyde increased by 4.2%-58.7%. It was further found that after adding seasonings, the concentration enhancement of larger molecular aldehydes was significantly greater compared to that of small molecular aldehydes, which was consistent with the previous studies (Liu et al., 2017). They added spices such as garlic powder, ginger powder and pepper at the initial stage during the cooking process, and the enhancement factor of aldehyde emission increased by an order of magnitude, which was much greater compared to that in our study, indicating that the time of adding seasoning may affect the aldehyde emissions.

2.3. *Effects of cooking dishes on aldehyde and ketone emissions*

The emission factors of aldehyde and ketone produced from cooking fried pork with chili and scrambled eggs with tomato are shown in **Fig. 4a**. The emission factors were calculated based on the unit mass of food materials. The aldehyde and ketone emissions of fried pork with chili were generally greater compared to that of scrambled eggs with tomato. The aldehyde and ketone emissions were the greatest when peanut oil was adopted for cooking fried pork with chili, reaching up to 5.809 $mg/(g_{ingredients}\cdot hr)$, which was 2.60 times of that for scrambled eggs with tomato using the same oil. Regarding to cooking scrambled eggs with tomato using soybean oil or peanut oil, aldehyde emissions accounted for 27.6% and 41.7% of the total emissions, respectively. In addition, acetone accounted for 63.9% and 39.4% of the total aldehyde and ketone emissions, respectively. When soybean oil and peanut oil were adopted to cook fried pork with chili, the aldehyde emissions accounted for 59.7% and 63.0% of the total emissions, respectively. And the concentration was much greater compared to the aldehyde emission from cooking scrambled eggs with tomato using the same oil, in which acetaldehyde was the largest contributor. The emission factors of acetaldehyde were 2.042 and 2.959 $mg/(g_{ingredients}\cdot hr)$, respectively, which were 16.78 and 8.66 times of that for scrambled eggs with tomato using the same oil. The interpretation was due to that the great fat content of pork easily causes peroxy radical reactions, in which fatty acids decompose to produce small molecules of aldehydes and ketones. It was concluded that the aldehyde and ketone emissions of roasted chicken and seafood were much greater than those of roasted vegetables using the same cooking methodology (Wood et al., 2004). Hence, the cooking materials can affect the aldehyde and ketone emissions to a certain extent.

2.4. *Inhalation exposure to 13 aldehydes and ketones produced during cooking for adult men and women*

Fig. 5 and Fig. 6 show the inhalation doses of 13 aldehydes and ketones caused by cooking pepper fried meat and tomato fried eggs, and the sampled concentration of aldehydes and ketones in the kitchen, respectively. The details are listed in Table 2, Table 3, Table 4, and Table 5. Fig. 5a and b show the inhaled dose of adult males is about 1.22 times of that for females, owning to the higher respiratory volume of males. The inhalation exposure dose of aldehydes and ketones caused by cooking chili meat with peanut oil was the greatest, reaching

Table 2 – Inhalation exposure from cooking scrambled egg with tomato using soybean oil.

Aldehydes and ketones	Mean ± SD			RSD
	Concentration (μg/m^3)	FE (μg)	ME (μg)	
Acetaldehyde	558.41 ± 27.47	56.23 ± 2.77	68.64 ± 3.38	4.92%
Acrolein	454.41 ± 21.46	45.76 ± 2.16	55.85 ± 2.64	4.72%
Propanal	424.23 ± 17.46	42.72 ± 1.76	52.15 ± 2.15	4.12%
Methylacrolein	403.47 ± 15.88	40.63 ± 1.60	49.59 ± 1.95	3.94%
n-Butyl aldehyde	246.85 ± 9.58	24.86 ± 0.96	30.34 ± 1.18	3.88%
Amyl aldehyde	158.12 ± 5.10	15.92 ± 0.51	19.44 ± 0.63	3.23%
Hexanal	1610.88 ± 52.72	162.21 ± 5.31	198.00 ± 6.48	3.27%
Acetone	8915.03 ± 100.73	897.69 ± 10.14	1095.81 ± 12.38	1.13%
Methyl vinyl ketone	230.50 ± 8.03	23.21 ± 0.81	28.33 ± 0.99	3.49%
Butanone	760.45 ± 12.50	76.57 ± 1.26	93.47 ± 1.54	1.64%
2 - Pentanone	95.85 ± 3.22	9.65 ± 0.32	11.78 ± 0.40	3.36%
3 - Pentanone	65.12 ± 2.65	6.56 ± 0.27	8.00 ± 0.33	4.07%
Methyl isobutyl ketone	29.76 ± 1.07	3.00 ± 0.11	3.66 ± 0.13	3.58%

SD: standard deviation; RSD: relative standard deviation; FE: female inhalation exposure; ME: male inhalation exposure.

Table 3 – Inhalation exposure from cooking scrambled egg with tomato using peanut oil.

Aldehydes and ketones	Mean ± SD			RSD
	Concentration (μg/m^3)	FE (μg)	ME (μg)	
Acetaldehyde	1568.43 ± 77.85	157.93 ± 7.84	192.79 ± 9.57	4.96%
Acrolein	235.18 ± 10.01	23.68 ± 1.01	28.91 ± 1.23	4.26%
Propanal	396.03 ± 19.74	39.88 ± 1.99	48.68 ± 2.43	4.98%
Methylacrolein	182.53 ± 7.00	18.38 ± 0.70	22.44 ± 0.86	3.83%
n-Butyl aldehyde	327.38 ± 14.98	32.97 ± 1.51	40.24 ± 1.84	4.58%
Amyl aldehyde	147.79 ± 7.15	14.88 ± 0.72	18.17 ± 0.88	4.84%
Hexanal	1413.97 ± 63.47	142.38 ± 6.39	173.80 ± 7.80	4.49%
Acetone	4029.31 ± 161.22	405.73 ± 16.23	495.27 ± 19.82	4.00%
Methyl vinyl ketone	469.90 ± 16.26	47.32 ± 1.64	57.76 ± 2.00	3.46%
Butanone	1234.18 ± 53.55	124.27 ± 5.39	151.70 ± 6.58	4.34%
2 - Pentanone	68.93 ± 2.92	6.94 ± 0.29	8.47 ± 0.36	4.24%
3 - Pentanone	103.79 ± 4.02	10.45 ± 0.40	12.76 ± 0.49	3.87%
Methyl isobutyl ketone	56.88 ± 2.53	5.73 ± 0.26	6.99 ± 0.31	4.46%

Table 4 – Inhalation exposure from cooking fried pork with chili using soybean oil.

Aldehydes and ketones	Mean ± SD			RSD
	Concentration (μg/m^3)	FE (μg)	ME (μg)	
Acetaldehyde	8509.24 ± 136.17	856.83 ± 13.71	1045.93 ± 16.74	1.60%
Acrolein	498.71 ± 20.13	50.22 ± 2.03	61.30 ± 2.47	4.04%
Propanal	383.26 ± 14.35	38.59 ± 1.44	47.11 ± 1.76	3.74%
Methylacrolein	68.26 ± 3.37	6.87 ± 0.34	8.39 ± 0.41	4.94%
n-Butyl aldehyde	239.45 ± 9.10	24.11 ± 0.92	29.43 ± 1.12	3.80%
Amyl aldehyde	175.33 ± 7.64	17.65 ± 0.77	21.55 ± 0.94	4.36%
Hexanal	2710.24 ± 49.64	272.91 ± 5.00	333.13 ± 6.10	1.83%
Acetone	7804.71 ± 325.27	785.89 ± 32.75	959.33 ± 39.98	4.17%
Methyl vinyl ketone	10.08 ± 0.49	1.01 ± 0.05	1.24 ± 0.06	4.89%
Butanone	515.11 ± 9.24	51.87 ± 0.93	63.32 ± 1.14	1.79%
2 - Pentanone	56.35 ± 2.17	5.67 ± 0.22	6.93 ± 0.27	3.86%
3 - Pentanone	52.98 ± 2.37	5.33 ± 0.24	6.51 ± 0.29	4.48%
Methyl isobutyl ketone	51.26 ± 2.33	5.16 ± 0.23	6.30 ± 0.29	4.54%

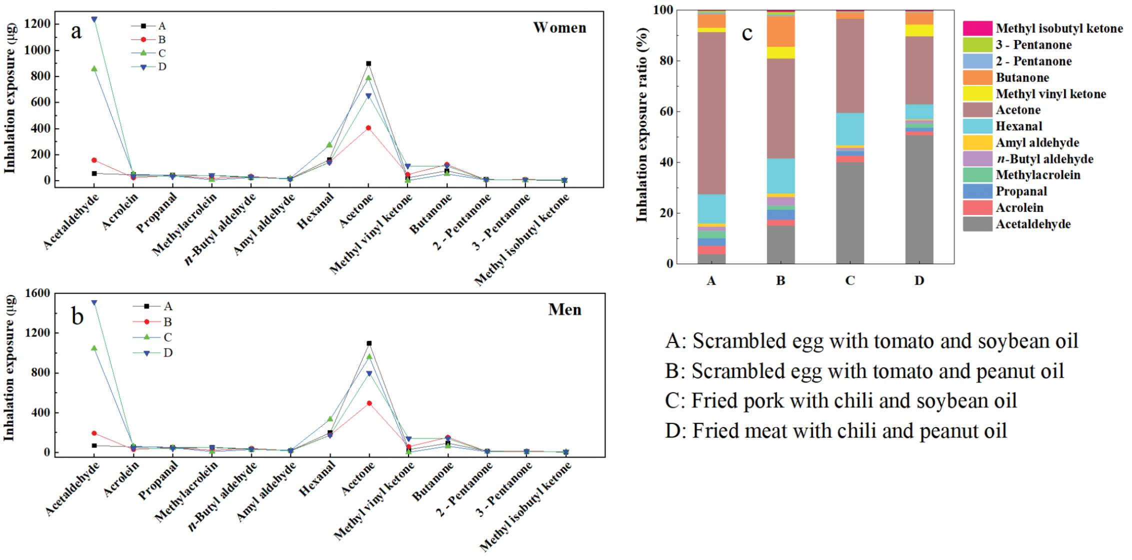

Fig. 5 – (a) Inhalation dose of 13 aldehydes and ketones from cooking a meal in adult women and (b) inhalation dose of 13 aldehydes and ketones from cooking a meal in adult men and (c) proportion of inhalation exposure caused by cooking dishes.

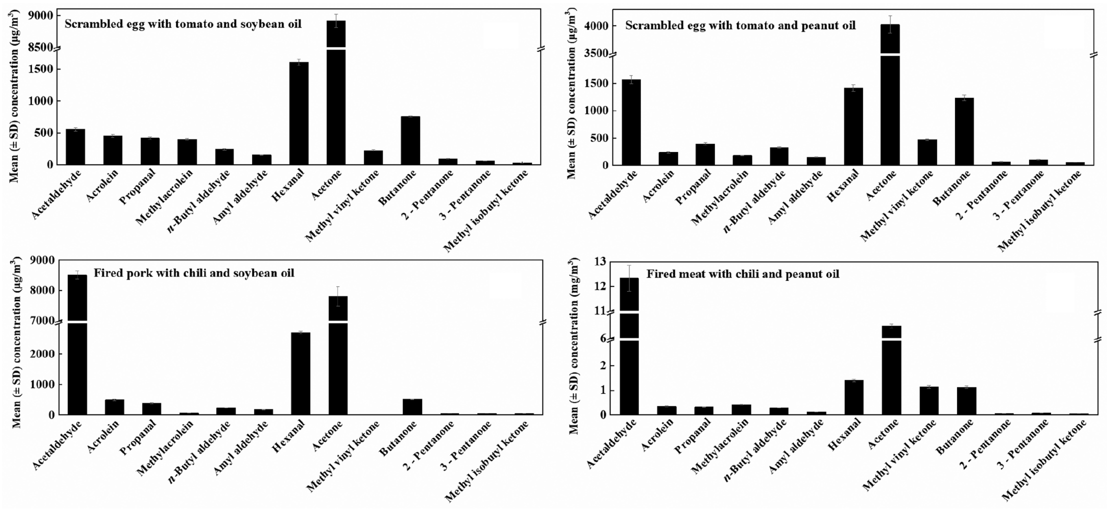

Fig. 6 – Mean ± SD concentrations of 13 aldehydes and ketones from cooking chili fried meat and tomato fried eggs in the kitchen.

up to 2975.12 μg and 2437.24 μg for adult men and women, respectively. The lowest mass of men and women's inhalation dose caused by scrambled egg with tomato and peanut oil was 1257.97 μg for males and 1030.54 μg for females. Two carbonyl compounds with the greatest concentrations were acetaldehyde and acetone, attained up to 12,329 and 8915 μg/m^3, respectively. Apparently, scrambled eggs with tomato caused a much greater inhaled dose of acetone compared to other compounds. The inhalation exposure of acetone produced during cooking using soybean oil was 2.21 times greater compared to that of cooking using peanut oil. For adult women, cooking scrambled eggs with tomato using soybean oil and peanut oil resulted in acetone inhalation doses of 897.69 μg and 405.73 μg, while the inhalation exposure for men was 1095.81 μg and 495.27 μg, respectively. Similarly, acetone inhalation from cooking fried pork with chili was also greater. Acetone is a medium toxic reagent and it damages the central nervous system and liver of human (Pan and Ye, 2017). Hence, the risk of acetone exposure during cooking cannot be ignored. It should be noted that cooking fried pork with chili for adults causes acetaldehyde inhalation of 856.83-1515.55 μg, while the inhalation exposure from cooking scrambled eggs with tomato was 56.23-192.79 μg. Proposition 65 of OEHHA of US-CA gave No Significant Risk Levels (NSRLs) of chemicals for carcinogens, which was defined as the daily intake level resulting in a 10^{-5} risk of cancer for an adult weighting 70 kg (Fan et al., 2020). For acetaldehyde, NRSLS is 90 μg/day. Thus, cooking scrambled eggs with tomatoes and fried pork with chili can cause acetaldehyde intake far beyond the safe limits of exposure dose. As early as 1987, the International Agency

Table 5 – Inhalation exposure from cooking fried meat with chili using peanut oil.

Aldehydes and ketones	Mean ± SD			RSD
	Concentration (μg/m^3)	FE (μg)	ME (μg)	
Acetaldehyde	12329.93 ± 524.66	1241.56 ± 52.83	1515.55 ± 64.49	4.26%
Acrolein	352.94 ± 10.43	35.54 ± 1.05	43.38 ± 1.28	2.95%
Propanal	329.09 ± 12.52	33.14 ± 1.26	40.45 ± 1.54	3.80%
Methylacrolein	419.82 ± 13.83	42.27 ± 1.39	51.60 ± 1.70	3.30%
n-Butyl aldehyde	290.09 ± 9.20	29.21 ± 0.93	35.66 ± 1.13	3.17%
Amyl aldehyde	122.68 ± 5.52	12.35 ± 0.56	15.08 ± 0.68	4.50%
Hexanal	1400.59 ± 62.96	141.03 ± 6.34	172.16 ± 7.74	4.49%
Acetone	6497.25 ± 72.98	654.24 ± 7.35	798.62 ± 8.97	1.12%
Methyl vinyl ketone	1137.98 ± 54.45	114.59 ± 5.48	139.88 ± 6.69	4.79%
Butanone	1124.11 ± 53.18	113.19 ± 5.35	138.17 ± 6.54	4.73%
2 - Pentanone	60.36 ± 2.78	6.08 ± 0.28	7.42 ± 0.34	4.60%
3 - Pentanone	83.22 ± 4.04	8.38 ± 0.41	10.23 ± 0.50	4.86%
Methyl isobutyl ketone	56.26 ± 2.08	5.67 ± 0.21	6.92 ± 0.26	3.69%

for Research on Cancer (IARC) has confirmed acetaldehyde is a carcinogen (Xu et al., 2017). Considering the daily number of dishes for a family, the evaluation may be underestimated. The results indicates that cooking emissions may bring negative impact on human health. For acetaldehyde and acrolein, the acute inhalation reference exposure limits (RELs) in OEHHA (2015) were 470 μg/m^3 and 2.5 μg/m^3, while the chronic non-carcinogenic RELs were 140 μg/m^3 and 0.35 μg/m^3, respectively (Xu et al., 2017). The acetaldehyde concentration of cooking dishes was well above the guidelines of OEHHA, among which fried pork with chili and peanut oil was 26.2 times of the acute inhalation RELs.

In our study, acrolein concentration ranged from 235.18 to 498.71 μg/m^3. The concentration was about 100 times greater compared to the standard level. Therefore, the inhalation exposure of carbonyl compounds cannot be ignored in the cooking process.

3. Conclusions

The results of this study indicated the types of edible oil and seasonings had different impacts on aldehyde and ketone emissions produced during cooking. For only heating five types of oils, aldehydes accounted for 61.1%-78.0% of the total emission, mainly acetaldehyde, acrolein and hexanal. The emission factors of aldehydes for various edible oils ranged from 153.19 to 299.79 μg/(g$_{oil}$•hr) with the order of sunflower seed oil > soybean oil > rapeseed oil > peanut oil > lard. These differences were mainly due to the difference in fatty acid composition of edible oils. Aldehydes emissions increased when chili powder, Chinese prickly ash and garlic slices were added into soybean oil or peanut oil. Among them, the impact of Chinese prickly ash was the largest. In general, the concentration enhancement of larger molecular aldehydes was significantly greater compared to that of small molecular aldehydes. And the time of adding seasoning may affect the aldehyde emissions. Food material was also an important factor affecting aldehydes and ketones emission. Due to the great fat content of pork, it is easy to cause peroxide free radical reaction, so the emission factor when cooking chili fried meat was much greater than cooking tomato fried eggs. The emission of aldehydes from chili fried meat was 3-4 times that from tomato fried egg cooked with the same oil, and acetaldehyde accounted for the largest proportion.

In this study, tomato fried egg and chili fried meat were taken as examples to evaluate human inhalation exposure during cooking. The inhalation exposure dose of aldehydes and ketones caused by cooking chili meat with peanut oil was the greatest, reaching up to 2975.12 μg and 2437.24 μg for adult men and women, respectively. More acetone and acetaldehyde were inhaled during cooking. The acetaldehyde inhalation caused by fried meat with pepper was much greater than that caused by scrambled egg with tomato. Compared with the reference value of 90 μg/day provided by OEHHA, inhalation exposure was more than 10 times. Acrolein concentration ranged from 235.18 to 498.71 μg/m^3. The concentration was about 100 times greater compared to the standard level. Considering the daily number of dishes for a family, the evaluation may be underestimated. It was concluded that cooking emissions may bring negative impact on human health.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can in appropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be constructed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 22076025), Talent Introduction Project of Fudan University (No. JIH1829013), and the National Natural Science Foundation of China (No. 32101191).

Appendix A Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.05.033.

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