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Role of Chinese cooking emissions on ambient air quality and human health

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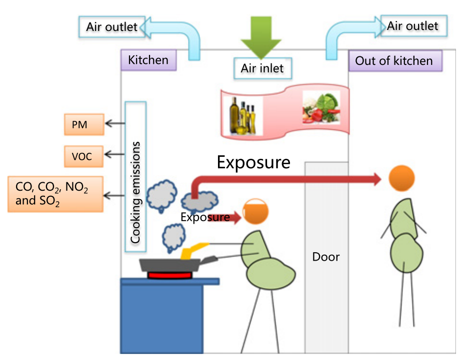
HIGHLIGHTS

- Chinese-style cooking produces large amount of pollutants.
- 79 publications are reviewed and compared. Food material, oil type, cooking style are discussed.
- PM ranged between 0.14 and 24.46 mg/cm^3.
- VOC varied from 0.35 to 3.41 mg/m^{3}PAHs ranged from 0.0175 μg/m^3 to 83 μg/m^3.
- Gaseous pollutants varied between 0.16 to 228.89 mg/m^3.

GRAPHICAL ABSTRACT



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ABSTRACT

Chinese-style cooking often involves volatilization of oils which can potentially produce a large number of pollutants, which have adverse impact on environment and human health. Therefore, we have reviewed 75 published studies associated with research topic among Mainland China, Hong Kong and Taiwan, involving studies on the roles of food ingredients and oil type, cooking style impacting on generated pollutants, and human health. The highest concentration occurred including: 1) when peat, wood, and raw coal were used in stoves; 2) olive oil was adopted; 3) cooking with high temperatures; and 4) without cleaning technology. We conclude that PM concentrations for cooking emissions were between 0.14 and 24.46 mg/cm^3. VOC concentrations varied from 0.35 to 3.41 mg/m^3. Barbeque produced the greatest mass concentrations compared to Sichuan cuisine, canteen and other restaurants. The PAHs concentration emitted from the exhaust stacks, dining area and kitchen ranged from 0.0175 μg/m^3 to 83 μg/m^3. The largest amount of gaseous pollutants emitted was recorded during incomplete combustion of fuel or when a low combustion efficiency (CO2/ (CO + CO2) < 0.5) was observed. The variation range was 6.27–228.89 mg/m^3, 0.16–0.80 mg/m^3, 0.69–4.33 mg/m3, 0.70–21.70 mg/m^3 for CO, CO_2, NO_2 and SO_2 respectively. In regards to the toxicity and exposure, current findings concluded that both the dose and exposure time are significant factors to be considered. Scientific research in this area has been mainly driven by comparison among emissions from various ingredients and cooking techniques. There is still a need for more

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comprehensive studies to fully characterise the cooking emissions including their physical and chemical transformations which is crucial for accurate estimation of their impacts on the environment and human health.

1. Introduction

China has the largest population in the world and its cuisine is one of the world's greatest ones, marked by variety in style and taste. Chinese cuisine is characterized by versatile cooking materials, special seasoning, different cooking techniques and distinctive flavour, which made it very popular around the globe. Chinese cuisine has a number of different styles categorised into the Eight Culinary Traditions of China (i.e. Guangdong (Cantonese), Shandong, Jiangsu, Sichuan, Fujian, Hunan, Anhui and Zhejiang) while the first four are perhaps the best known and most influential.

Cooking emissions are influenced by many factors, such as fuels, cooking oils, food ingredients, duration of cooking period, cooking temperature, cooking styles, ventilations, etc. The contribution of cooking emissions to the overall ambient aerosol was estimated to be between 12% and 20% (Zhu et al., 2014); (Healy et al., 2013). Cooking produces harmful substances including particulate matter (Gao et al., 2013), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAH) (Shen et al., 2012), carbonyl compounds (Cheng et al., 2015). Generally, these substances are present in the air in gaseous or particulate form, depending on environmental factors such as temperature and relative humidity. These compounds have been recognized as significant contributors to ambient haze pollution (Sun et al., 2014). Chinese cooking usually uses oil to scramble or fry food. During this high-temperature cooking process, over 300 types of reaction products are generated including fatty acids, alkanes, alkenes, aldehydes, ketones, alcohols, esters, aromatic compounds, heterocyclic compounds, etc. (Liang, 2004). It not only deteriorates the indoor and outdoor air quality through physicochemical reactions, but also has a considerable harmful impact on human health (Chafe et al., 2014).

Under certain conditions, the material attached to the surface of particles may be absorbed into the human body and consequently have adverse effect on health. Studies have shown that these chemicals exert a lung toxicity, immune-toxicity, genotoxicity and potential carcinogenicity on the body, etc. The potential health hazards often affect people who are subjected frequently to cooking emissions. Experimental studies and surveys found that cooking emission pollutants are likely to have mutagenic and carcinogenic effects, and cooking is regarded as one of the major factors in relation to non-smoking Asian women suffering from lung cancer (Zhao et al., 2007a, b, c; Lam, 2005a, b).

Considering the multiple effects of cooking emissions, Chinese cooking emissions has been a hot research topic for the last two decades. Therefore, this study aims to review the scientific publications published in Chinese and English related to emissions from Chinese cooking which provides a scientific and technological overview with an emphasis on factors impacting cooking emissions as well as the related influence on human health.

2. Research on cooking emissions in China

2.1. A brief research history

Both National Standard of cooking emission GB 18483–2001 and newly-published Shanghai Standard of cooking emission DB31/844–2014 set maximum concentrations allowed (GB 18483–2001_2.0 mg/m^3, DB31/844–2014_1.0 mg/m^3) for total cooking fume and odour as well as minimum removal efficiency of purification facilities.

Fig.1 provides the information of the annual numbers of new studies on Chinese cooking emission published in Chinese and English (the corresponding publication for each paper is written in SI).

Fig.2 summarizes the number of research papers on Chinese cooking emissions. There are numerous Chinese cooking styles which are categorised into eight major cuisines. As Chinese style cooking always produces intense smell and a lot of fume, most urban residents and restaurants use purification equipment in their kitchens (Sun et al., 2015). For that reason, there are more and more studies (Cheng and Hsieh, 2010; Pan et al., 2011) on efficiencies of these purification systems. Furthermore, other factors including oil type, restaurant scale, cooking time, ventilation, food material, temperature, utensils and fuel are regarded as important factors to be considered in the published studies.

Cooking emission studies are mainly conducted in Beijing and Shanghai, as presented in Fig.3. These two cities are the largest cities in China with plenty of catering business on one side and research institutes on the other side. Compared to some other regions in China, Beijing and Shanghai have better conditions to conduct relevant studies. Also, these two cities are under strict supervision of local governments, which set a strict regulation program to mitigate pollution in major Chinese cities. Hong Kong and Taipei conducted several studies in this area, mainly aiming to investigate chemical composition of aerosol and related health effects.

Majority of the studies were conducted in the field (e.g. restaurants, canteens and family kitchens) hence the sampled data are representative of real conditions (fig.4). In addition, there are measurements carried out in the laboratories or lab kitchens, where variables could be controlled and kept at relatively stable values. The emission characteristics can be quantified accurately in laboratory studies which is important for modelling.

The most commonly investigated pollutant components are given in fig.5. In addition, several studies were focused on the risk evaluation associated with pollutants. Each pollutant category presented in Fig. 5 is further discussed in section 2.2.

2.2. Cooking emission characteristics

2.2.1. PM

We conclude that PM concentrations for cooking emissions impacted by various factors were between 0.14 and 24.46 mg/cm^3. Wan et al. (2011) observed that cooking increased the average number concentrations of ultrafine particles (UFPs, particles smaller than 100 nm in diameter) and accumulation mode particles (AMPs) by 10-fold from the background level in the living room and by 20–40-fold in the kitchen. $PM_{2.5}$ mass concentrations increased to the maximum average of about 0.160 mg/m^3 and 0.06 mg/m^3 in the kitchen and living room respectively. Particles from cooking emissions were mainly in the ultrafine size range which contributed the most on particle number concentration. However, AMPs mainly contributed to the mass and surface area by 60% and 73% contribution to the surface area concentrations in the kitchen and living room.

Lin et al. (2014) reported that PM concentration in a cooking fume in typical Shanghai restaurants (Shao Yong, Hong Kong-style, Sichuan, etc.) and Western food, ranging between 0.69–2.60 mg/m^3, PM2.5 was within the range of 0.14–1.67 mg/m^3. The results of Wen and Hu (2007) showed that the sampled $PM_{2.5}$ from a restaurant fume was between 1.382 and 4.053 mg/m^3 in Beijing, which was 8–35 times higher than the ambient atmospheric $PM_{2.5}$ concentration. The highest

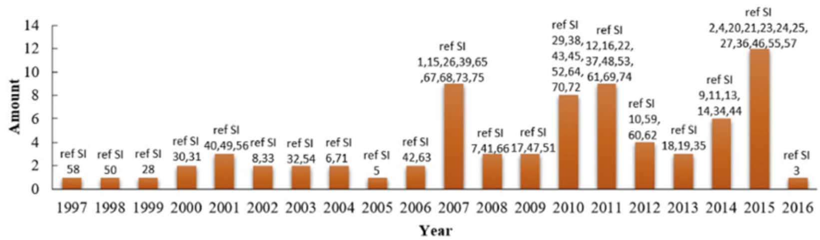

Fig. 1. Annual numbers of new studies on Chinese cooking emission.

concentration of $PM_{2.5}$ occurred in a restaurant with home style-cooking. Lee et al. (2001) observed that the highest concentration of PM was between 0.699 and 2.911 mg/m^3 in Korean barbecue restaurants using peanut oil.

Type of oil used for cooking is very important for physico-chemical properties of the emissions. Wu et al. (2016) found that PM emissions produced while using olive oil (1.50×10^5 μg/min) were significantly greater compared to lard (1.81×10^4 μg/min), peanut oil (1.13×10^4 μg/min) and soybean oil (7.78×10^4 μg/min). On the other hand, Gao et al. (2013) compared rapeseed oil, soybean, peanut, sunflower, olive and blended oil and they found that particle mass concentration was not only dependent on the type of cooking oil, but also the heating temperature. The temperature ranged from 45 to 198 °C during their experiment. Sunflower oil was used for cooking and the test lasted for 2 min. It was found that the volume frequency of fume particles in the range of 1.0–4.0 μm accounts for nearly 100% of PM 0.1–10 with the mode diameter 2.7 μm, median diameter 2.6 μm, Sauter mean diameter 3.0 μm, DeBroukere mean diameter 3.2 um, and distribution span 0.48.

In addition, different fuels also affect the concentration of PM. Wood, crop residues, electricity, liquefied petroleum gas, methane, coal are commonly used fuels in China. Chen et al. (2016) compared the PM emission produced from fuels with different calorific values. The emission factor of honeycomb was the lowest, 5.05 g/kg, while the wood had the highest emission factor, 12.71 g/kg. Guo et al. (2010) investigated $PM_{2.5}$ and PM_{10} emissions from three types of fuels including natural gas, liquefied gas as well as honeycomb briquette combustion and found that natural gas emitted the greatest $PM_{2.5}$ and PM_{10} exceeding the national indoor air quality standard for a factor of 117and 146 respectively. In the Chinese standard GB/T1 8883–2002,the hourly PM_{10} concentration is limited to 0.15 mg/m^3, while the $PM_{2.5}$ was based on the US EPA standard for daily average concentration, 0.065 mg/m^3. The metal composition analysis associated with $PM_{2.5}$ and PM_{10} generated from the catering fumes showed that manganese (6.037–27.745 μg/m^3), zinc (33.931–187.924 μg/m^3) and iron (56.096–397.878 μg/m^3) content was high, lead (0.226–9.064 μg/m^3) and copper (1.009–2.485 μg/m^3) were in within a mid-range, while chromium (0.872–109.352 ng/m^3), cadmium (9.649–113.910 ng/m^3) and mercury (15.007–93.067 ng/m^3) content were the lowest. Therefore, Baumgartner et al. (2011) stated that adoption of clean fuel in China is the most effective way to reduce PM.

Purification equipment is installed above the cooking area in most Chinese urban residential kitchens which removes most of the cooking emissions. Purification equipment also affects particulate matter emissions. Wu et al. (2002) showed that $PM_{2.5}$ concentration was within the range of 7.96–24.46 mg/m^3 and 1.92–2.10 mg/m^3 before and after installing the purifier respectively. Pan et al. (2011) also proved that purification equipment can remove PM with efficiency of 60%. Deng (2008) argued that the purification efficiency of different equipment varies between 54% and 85% and the most effective one is a combination of condensation via water film plus atomization, cyclone separation and activated carbon.

Cooking emissions can be a significant source of atmosphere in general (Zhu et al., 2014). Therefore, it is important to investigate the chemical composition of cooking emissions. Zhao et al. (2007a, b, c) investigated particulate organic matter (POM) in $PM_{2.5}$ emitted from four different Chinese cooking styles using gas chromatography–mass spectrometry (GC–MS). The identified species were consistent among all cooking styles and the quantified compounds accounted for 5%–10% of the total POM in $PM_{2.5}$. The most abundant chemical species identified in POM fraction were fatty acids, representing of 73%-85% of the quantified compounds in this fraction. Cantonese style cooking produces the lowest amount of saturated and unsaturated fatty acids, with only 39 μg of fatty acids/mg of POM. Hunan style and Dongbei style produced 50 and 51 μg of fatty acids/mg of POM. Sichuan style releases about 2-fold more fatty acids compared with Cantonese style. Cantonese style and Hunan style in Shenzhen release more fatty acids of per mg of POM than in Guangzhou. The pattern of n-alkanes and the presence of β-sitosterol and levoglucosan were attributed to usage of vegetables. He et al. (2004) also characterized POM from Hunan Cooking and Cantonese Cooking in Shenzhen. Comparatively, more than half of the $PM_{2.5}$ mass was classified as organic compounds, and over 90 organic species were identified and quantified, accounting for 26.1% of bulk organic particle mass and 20.7% of $PM_{2.5}$. Fatty acids, diacids and steroids were the major organic compounds emitted from both styles of cooking. 90% of the quantified organic mass were fatty acids. The mass of organic species and the molecular distribution of n-alkanes and PAHs indicated the dissimilarities between the two different cooking styles, but

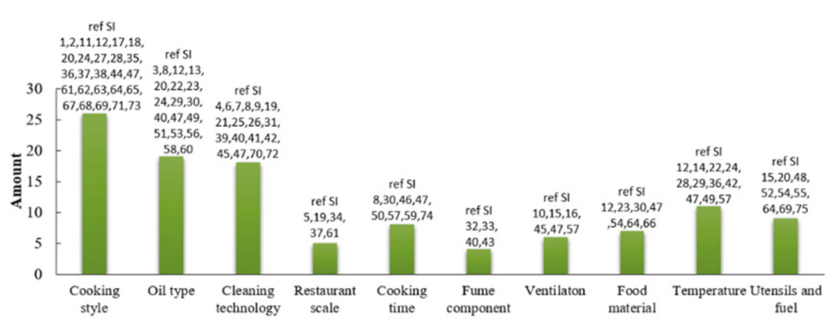

Fig. 2. The number of studies for different research topics.

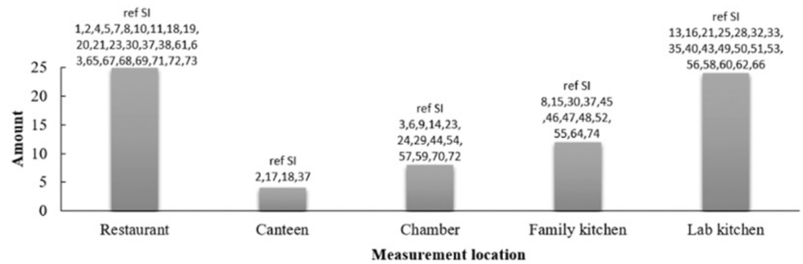

Fig. 3. The number of studies in different cities.

generally the major part of the organic particulate emissions of the two restaurants were similar. Zhao et al. (2007a, b, c) reported that the total amount of quantified compounds of per mg POM in western-style fast food cooking was much higher than that in Chinese cooking. The most abundant identified compounds in POM fraction were fatty acids, accounting for 78% of total quantified POM, with the predominant one being palmitic acid. Dicarboxylic acids displayed the second highest concentration among quantified homologues with hexanedioic acid being predominant, followed by nonanedioic acid. Cmax of n-alkanes occurs at C25, but the significant concentrations appeared at C29 and C31. In addition, both levoglucosan and cholesterol were quantified.

In Zhao et al. (2015), total suspended particles (TSP) samples from residential cooking emissions in an urban site of Guangzhou, south China were collected and the organic compositions of these samples were analysed. The average mass concentration of TSP emitted from the Chinese residential cooking monitored in rooftop exhausts was 138 μg/m^3. This result was lower than those monitored in residential kitchen and in rooftop exhausts of Chinese restaurant. Organic matter (OM), as the major component, accounted for 66.9% of TSP mass in Chinese residential cooking emissions.

2.2.2. VOCs

Cooking is regarded as one of the most important contributor to ambient VOC levels in China, which significantly affects both air quality and human health (Jiang et al., 2014). Main components of VOCs include alkanes, olefines and aromatic hydrocarbon, aldehydes and ketones. Wang et al. (2011) investigated a typical city in the northeast area of China, Shenyang. Shenyang is the largest city in Northeast China with >10 million residents living and working there. 81 types of VOCs were detected from cooking fumes, mainly saturated alkanes (40.0%) and alkenes (10.4%). The total average VOCs concentration was 3.407 ± 0.900 mg/m^3. The obtained VOC emission factor of cooking emissions was 5.03 g/kg, and the total volume of discharged VOCs into the atmosphere was 994.5 t in 2007. The concentration of aromatic hydrocarbons such as benzene and toluene also increased during the cooking periods (Lin et al., 2014).

VOCs can also be photochemically active, making them important precursors of tropospheric ozone (O_3) and secondary organic aerosol (SOA), hence vital for regional ozone formation and haze. Therefore, investigation of atmospheric reactive VOCs is a basis of other relevant research topics.

For example, Wang et al. (2011) detected 39 toxic compounds from cooking which were found the main contributors on the produced VOCs. Major components were benzene and chlorinated hydrocarbons. The equivalent propylene concentration (EPC) of VOCs activity was of 622.5 μg/m^3. It is a parameter for evaluating VOCs chemical reactivity. In addition, Wang et al. (2011) examined the ozone formation potential from VOCs produced Sichuan restaurant was 1667.5 t and SOA formation potential total was 2.17 t. The greatest contributor was m-xylene. Table 1 gives the information of VOCs concentration from all studies. We concluded that VOC concentrations varied from 0.35 to 3.41 mg/m^3. Barbeque produced the greatest mass concentrations compared to Sichuan cuisine, canteen and other restaurants.

2.2.3. Carbonyl compounds

Carbonyl compounds, as major substances in cooking fume emissions, have strong chemical reactivity among VOCs. Cheng et al. (2015) measured concentrations of carbonyl compounds from 8 different cooking styles in chosen restaurants in Beijing. The concentrations were decreasing in this fashion: Roast duck > Chinese BBQ > Home dishes > Western-style fast food > school canteen > Chinese fast food > Sichuan Cuisine > Huaiyang Cuisine. Huaiyang cuisine is a type of cuisine not exclusive to any city. The range of the concentration of carbonyl compounds was between 0.115 mg/m^3 and 1.036 mg/m^3.

Shi et al. (2015) investigated the influence of cooking procedures and ingredients on carbonyl compounds emission. They observed a noticeable difference between different ingredients such as 1.349 mg/m^3, 1.3 mg/m^3, 0.385 mg/m^3 and 0.108 mg/m^3 corresponding to fried chicken, fried potatoes, fried octopus and fried eggs, respectively. Frying process with more oil and high oil temperature released much more carbonyl compounds (3.4–12.5 time higher) than that with less oil and low oil temperature. They also found that frying chicken nuggets using olive oil released the highest carbonyl compound emissions (1.913 mg/m^3), while soybean oil released the lowest (0.699 mg/m^3). When frying potatoes, it was observed that rapeseed oil discharged highest carbonyl compounds (1.853 mg/m^3), while peanut oil discharged the lowest (0.699 mg/m^3).

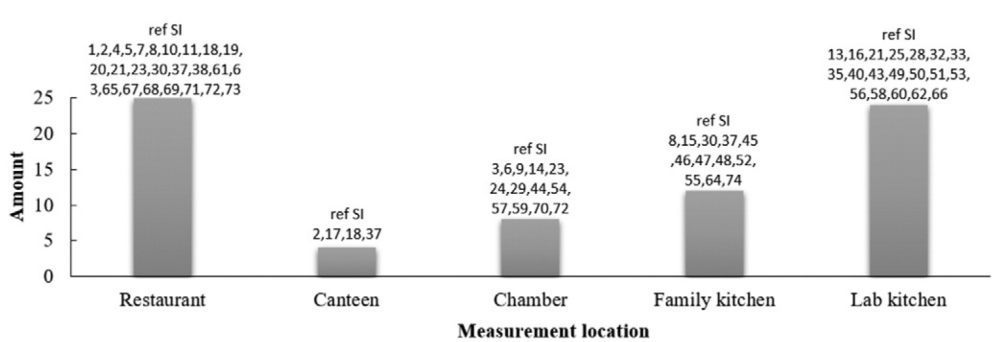

Fig. 4. The number of studies conducted in various locations.

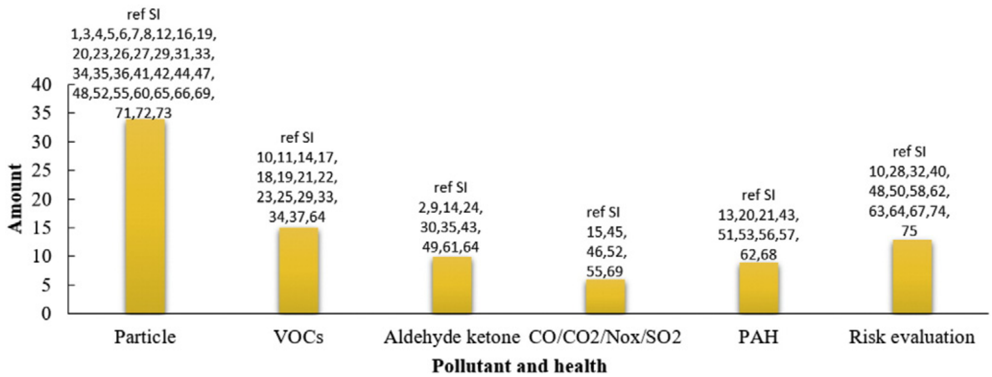

Fig. 5. The number of studies investigating various pollutants.

Ho et al. (2006) investigated exhaust from Hong Kong restaurants with different cooking styles. Generally, the component of carbonyl compounds with the highest concentration was formaldehyde, which accounted for 12%–60% of the total amount. Acrolein was also abundant in the gas phase of the cooking exhaust due to it being a volatile liquid, and accounting for 30% of the total amount. It was concluded that formaldehyde, acetaldehyde, acrolein and nonanal contributed to 72% of the total amount.

Formaldehyde is regarded as one of the main indicators of indoor air pollution. Wang et al. (2010a, b) monitored the formaldehyde concentration in a residential kitchen and concluded it exceeds 17–200% of the standards (the national standard of GB/T1 8883–2002 for indoor air quality limits the hourly average concentration of formaldehyde to 0.10 mg/m^3). Wu et al. (2016) indicated that the highest formaldehyde concentration in smoke from frying was 0.270 mg/m^3, 35% over the formaldehyde emission limitation in China's Pollutant emission standards (0.20 mg/m^3).

The fuel type has also significant influence on the carbonyl emissions. Huang et al. (2011) found that the total amount of carbonyls emitted from cooking using town gas was three times higher than when using LPG, with acetaldehyde being the most abundant carbonyl at the town gas dwelling, but with insignificant emission at the LPG dwelling.

2.2.4. PAHs

Polycyclic aromatic hydrocarbons (PAHs) have attracted widespread attention, due to their high toxicity, biodegradability and being able to bio-accumulate. PAHs in atmosphere can be transported over long distances, which will not only affect the area in the proximity of the source but will also have a wider range of influence on the air quality. Most importantly, they can enter the body through breathing and ingestion which can harm human health.

Chen et al. (2012) measured 21 PAH congeners from the exhaust of 3 types of restaurants: 9 Chinese, 7 Western-style, and 4 barbeques. The total PAH concentration measured at BBQ restaurants (58.81 $\pm$ 23.89 μg/m^3) was significantly higher than that of Chinese (20.99 $\pm$ 13.67 μg/m^3) and Western (21.47 $\pm$ 11.44 μg/m^3) restaurants. However, the total benzo[*a*]pyrene potency equivalent (B[*a*]Peq) concentration was the highest in Chinese restaurants (1.82 $\pm$ 2.24 μg/m^3), followed by Western (0.86 $\pm$ 1.43 μg/m^3, $p < 0.01$) and BBQ-type restaurants (0.59 $\pm$ 0.55 μg/m3, $p < 0.01$). Chen et al. (2007a, b) quantified 8 gaseous and 22 particulate PAHs from exhaust samples collected in six representative commercial kitchens in Hong Kong during peak lunch hours, including Chinese restaurants, Western restaurants, and Western fast-food restaurants. Among gaseous phase, naphthalene (67–89%) was the most abundant PAH in all the exhaust samples. The contribution of acenaphthylene in the gaseous phase was significantly higher in Chinese restaurants, whereas fluorene was the greatest in emissions from the Western restaurants and Western fast-food restaurants. Pyrene was the most abundant particulate PAH in the Chinese restaurants, accounting to 14%–49% (from 29.2 to 103.3 ng/m^3). Comparatively, its contribution was much lower in the Western cooking style restaurants, where it contributed from 10% to 22% (from 5.2 to17.5 ng/m^3). In addition, cooking styles were compared including deep frying, steaming, and mixed cooking styles (combination of steaming and frying). Deep frying produced the highest amount of total gaseous PAHs, 4041.7 ng/m^3, 6 times higher than the steaming (661.0 ng/m^3). The estimated annual gaseous PAH emissions for Chinese restaurants, Western restaurants, and Western fast-food restaurants were 255, 173, and 20.2 t y^{-1} and 252, 1.9, and 0.4 t y^{-1} were estimated for particulate phase PAH emissions respectively.

PAHs emitted by restaurants in Lanzhou, including home cooking, Sichuan, Hunan and barbeque restaurants were monitored by Zhu et al. (2014). It was observed that the PAHs concentration from the indoors of the kitchen and exhaust of cooking fume was ranging from

Table 1
VOCs concentration information.

	Wang et al. (2011) μg/m^3	Lin et al., (2014) μg/m^3			Cheng and Ji, 2001 μg/m^3	Shi et al. 2015 μg/m^3	Ho et al. 2006 mg/m^3	Huang et al. (2011) μg/m^3	
		Sichuan cuisine	canteen	BBQ				Town gas	LPG
Aromatic hydrocarbon	68.14	126.57	93.11	171.17					
Carbonyl	105.61	53.69	72.32	28.85	0.115–1.036	0.108–1.913	55–967	241	185
Alkane	1362.80	39.04		45.78					
Esters		24.27		27.69					
Alkene	354.33	23.13		35.29					
Alcohol	1454.8	8.77		5.53					
Total VOC concentration	3407.06 $\pm$ 889.5		247.15	314.32					
EPC (μg/m^3)	622.5								
Annual VOCs (t)	994.5								

0.171 to 0.500 mg/m^3 and from 0.220 to 0.836 mg/m^3, respectively. Most of them were 4–5 ring PAH's, accounting for 61.36% and 62.29% of the total PAHs, respectively. Fine particulate matter produced from BBQ restaurants have higher level of PAHs, that reached up to 616.71 ng/m^3. The lowest concentration of 0.171 mg/m^3 occurred in Hunan cuisine. Cooking using salad oil produced the highest concentrations of PAHs, which was 0.526 mg/m^3. Chen et al. (2012) observed the PAHs concentrations were 0.7, 0.2 and 0.4 mg/m^3 during heating of soybean oil, sunflower oil, and canola oil, respectively. However, there is no maximum allowable concentration limit for PAHs in the atmosphere in Taiwan. Gao et al. (2015) heated oil for 3 min and cooked for 7 min, and found that PAH in particulate matter ranged from 0.2258 to 0.6578 mg/m3 upon heating 40 to 85 g of edible oil. The sampling flowrate was 1 L/min and the sampling period was 10 min.

The influence of the cooking fuel was studied by Shen et al. (2012). They measured EFs of PAHs, per kg of fuel burned, for nine commonly used crop residues burnt in a typical Chinese rural cooking stove. The measured EFs of total PAHs averaged at 63 ± 37 mg/kg, ranging from 27 to 142 mg/kg, which were higher than those measured in chamber experiments. EFs of gaseous and particulate phase PAHs were 27 ± 13 and 35 ± 23 mg/kg, respectively. 80 ± 6% of PAHs were associated with $PM_{2.5}$. Stepwise regressions found that modified combustion efficiency and fuel moisture were the most important factors affecting the emissions.

Hou et al. (2008) investigated the characteristics of the charcoal broiling source and its impact on the fine organic aerosols in the atmosphere in Beijing. The total PAHs and fatty acids in emitted $PM_{2.5}$ were 8.97 and 87,000 ng mg $^{-1}$, respectively. The concentrations of the light molecular weight (LMW) 3 and 4-ring PAHs were much higher than those of the high molecular weight (HMW) 5 and 6-ring PAHs. Table 2 provides PAH information from all studies. We concluded that PAHs concentration emitted from the exhaust stacks, dining area and kitchen ranged from 0.0175 μg/m^3 to 83 μg/m^3.

2.2.5. $CO/CO_2/SO_2/NO_X$

The largest amount of gaseous pollutants emitted was recorded during incomplete combustion of fuel or when a low combustion efficiency (CO2/(CO + CO2) < 0.5) was observed. The variation range was 6.27–228.89 mg/m^3, 0.16–0.80 mg/m^3, 0.69–4.33 mg/m3, 0.70–21.70 mg/m^3 for CO, CO_2, NO_2 and SO_2 respectively, owning to combustion of gas fuel. Upper limit values for CO, CO_2, SO_2 and NO_2 in Chinese standard GB/T 18883–2002 are 10 mg/m^3, 0.10%, 0.50 mg/m^3 and 0.24 mg/m^3, respectively. Out of these CO, SO_2 and NO_2 are for the hourly averaged values, and CO_2 is for the daily averaged value. Liu (2007) investigated 400 residential kitchens to obtain the comprehensive index per CO, CO_2 and NO_2. Results showed that the ratio belonging to clean kitchens was 4.8%. It is an index considering both the real measured pollutant concentration and the limits of pollutant concentration in national standard, as presented in Table 1. While the proportions of un-contaminated and light contaminated kitchens were 33.5% and 21.7%, respectively, the proportion of moderate and severe contaminated kitchen were 14.0% and 26.0%, respectively. The evaluation index is given in Table 3.

Wang et al. (2010a, b) conducted measurements in kitchens in Shenyang during the winter seasons. Results showed that both CO and SO_2 were within indoor air quality health standards. The volume fraction of CO_2 exceeded 10% - 130% of the national standard, while NO_2 concentration exceeded over 40% of the limit set for CO_2 and NO_2 that are 0.10% and 0.24 mg/m^3 respectively.

The average concentrations of CO and CO_2 in Hong Kong, Korean, Chinese hot pot, Western-style dim sum restaurants and canteens were monitored by Lee et al. (2001). The monitored average CO_2 concentration ranged between 636 and 2344 ppm. The CO_2 concentration in the dining area exceeded the standard Hong Kong Indoor Air Quality Objective (HKIAQO) of 1000 ppm. As for CO, the process of making barbecue and boiling food produced large amounts of CO, which were 4 to 6

Table 2
PAH information.

	Chen et al. 2012 μg/m^3			Chen et al., 2007a, b ng/m^3			Zhou and Zhao, 2015 mg/m^3		Chen et al., 2012 mg/m^3			Gao et al. 2015 mg/m^3
	Chinese	Western-style	barbeques	Chinese	Western	Western Fast-food	Indoor	Kitchen		sunflower oil	canola oil	
Gas PAHs				2816.7–3025.3	1067.1–7823.8	1521.7–2593.3						
PPAHs				30.0–748.7	19.1–74.2	17.9–70.5	0.171–0.500	0.220–0.836	0.2258–0.6578			0.2258–0.6578
B[a]Peq	1.82 ± 2.24	0.86 ± 1.43	0.59 ± 0.55									
Total PAHs	20.99 ± 13.67	21.47 ± 11.44	58.81 ± 23.89	2846.6–3774.0	1141.3–7842.9	1539.7–2663.8				0.2	0.4	

times greater compared to Western-style dim sum restaurants as well as canteens.

CO, CO_2 and SO_2 emissions from different fuels were further investigated by Chen et al. (2016). They found that honeycomb produced the minimum CO, CO_2 and SO_2. The corresponding emission factors were 123, 1446, and 1.31 g/kg. Geng et al. (2012) also obtained emission factors for CO, SO_2 and NO_x, which were 53.30, 0.41 and 1.45 g/kg from burning domestic coal. Guo et al. (2010) studied three types of domestic fuels (natural gas, liquefied petroleum gas and coal briquettes), and found the gaseous pollutants (SO_2, NO_2, CO, CO_2) all exceed the limits regulated by indoor air quality standards.

2.2.6. Toxicity and exposure

Detailed investigations into toxicity and exposure haven't been achieved so far. A small number of studies sampled the exposure concentrations to several toxic components, with a few focussed on the evaluation of exposure risk by using models. Considering the significant cooking emissions, following aspects need to be conducted in future: short-term prospective cohort effect research, long-term observation studies, toxicological mechanism research including both in vitro and in vivo, molecular and protein levels.

Baumgartner et al. (2011) tested 280 adult females and 240 children in 44 rural Yunnan kitchens who were exposed to particulate matter. They found the exposure of female adults in winter was twice higher than that for summer (117 μg/m^3, 55 μg/m^3). Comparatively, the particle exposure of children in summer reached up to 53 μg/m^3. It was concluded that kitchen ventilation and kitchen structure were the main factors affecting the exposure values.

Yang et al. (1998) showed that cooking aerosols contain significant amounts of MeIQx (2-amino-3,8-dimethylimidazo[4,5-*f*]quinoxaline). MeIQx has been shown to be carcinogenic in rodents by oral ingestion, causing leukemia, and liver tumours, clitoral gland, zymbal gland and lung. An amount of 0.25 ng MeIQx per 1 g of meat per min was estimated based on the mutagenic response, indicating significant amounts of MeIQx (268.1 ng/g Chinese dish of frying fish) present in cooking emissions in a short period.

Epidemiological studies have shown that women exposure to cooking fumes appears to be an important risk factor for lung cancer. Chang et al. (1997) collected fume samples from cooking using three type of common commercial oils in Taiwan and analysed for mutagenicity in the Salmonella/microsome assay. PAHs were extracted from the samples and identified by HPLC chromatography. All samples contained dibenz[*a*, *h*] anthracene (DB[*a*, *h*] A) and benz[*a*, *h*] anthracene (B[*a*] A). Concentration of DB[*a*, *h*]A and B[*a*] A were 1.9 and 2.2 μg/m^3 in fumes from lard oil, 2.1 and 2.3 μg/m^3 in soybean oil, 1.8 and 1.3 μg/m^3 in peanut oil, respectively. In addition, Benzo[*a*]pyrene (B[*a*]P) was identified in fume samples of soybean and peanut oil, with concentrations of 19.6 and 18.3 mg/m^3. These results provide experimental evidence, supported by epidemiological observations for women exposed to fumes from cooking oils, of the risk of contracting lung cancer.

It has been shown that trans, trans-2, 4-decadienal (tt-DDE) is an important toxic compound in cooking oil fumes (COF). Yang et al. (2007) quantified emissions of tt-DDE in both gaseous and particulate phases of three kinds of restaurant exhausts (Chinese, western and barbecue), per the criteria of US EPA Modified Method 5. The results indicate that the emission factors of tt-DDE in terms of μg $customer^{-1}$ were in sequence: barbecue (1990) > Chinese (570) > Western (63.8). The average proportion of tt-DDE in the particulate phase of the exhausts was 83% for the 16 investigated restaurants. Evidently, the majority of tt-DDE in the exhausts was in the particulate phase. There was no evident correlation found between phase distribution of tt-DDE and exhaust temperature in the restaurants investigated. In addition, the efficiencies of removal of particulate tt-DDE by air pollution control devices (APCDs) were assessed. The removal efficiencies of electrostatic precipitator (ESP), ESP and activated carbon in series, and wet scrubber were 64.2%, 86.3% and 71.3% respectively.

Chen et al. (2012) developed a probabilistic risk model to assess the incremental lifetime cancer risk (ILCR) for people exposed to carcinogenic PAHs and suggested that the maximum acceptable exposure time to the exhaust stack outlet area for Chinese, Western, and BBQ restaurants ranges between 5 and 19, 17–42, and 18–56 h $month^{-1}$,-respectively, based on an ILCR of $<10^{-6}$.

To et al. (2007) reported a territorial wide survey on the quantification of cooking fumes discharged from commercial kitchens of Chinese restaurants, Western restaurants and exotic food servicing areas. Results show that cooking fumes contain a wide spectrum of organic compounds including n-alkanes, PAHs, fatty acids (FAs) and aromatic amines (AAs). Their analytical results indicate that there is no statistically significant difference on the composition of their discharge in terms of carcinogenic elements such as PAHs, but at the 5% significance level, the mean concentrations of n-alkanes at the discharge points of exotic food servicing areas are higher than at the discharges of Chinese or Western restaurants.

Huang et al. (2011) assessed the emission of formaldehyde and showed that it accounts for nearly 68% and 100% of lifetime cancer risks when the fuel was towngas and LPG, respectively.

Mestl et al. (2007) developed a method to estimate exposure to PM_{10} from indoor cooking fuels for large populations. Average exposure was estimated at 340 μg/m^3 (SD 55) in southern cities, and 440 μg/m^3 (SD 40) in northern cities. For the rural population, the average exposure was 750 μg/m^3 (SD 100) and 680 μg/m^3 (SD 65) in the south and north, respectively.

Based on the average respiration rate (6 L/min) of humans, Chen et al. (2012) evaluated the average absorption of PAHs per min and estimated that they may be 4.2, 1.2, and 2.4 μg for cooked soybean oil, sunflower oil and canola oil respectively.

Kim et al. (2015) reported the association of cooking conditions, fuel use, oil use, and risk of lung cancer in a developed urban population in female cohort in Shanghai. A total of 71,320 non-smoking women were observed from 1996 through 2009 during which 429 incident lung cancer cases were identified. Questionnaires collected information on household living and cooking practices for the three most recent residences, the utilization of cooking fuel and oil, and ventilation conditions. Cox proportional hazards regression estimated the association for kitchen ventilation conditions, cooking fuels, and use of cooking oils for the risk of lung cancer by hazard ratios (HR) with 95% confidence intervals (CI). Ever poor kitchen ventilation was associated with a 49% increase in lung cancer risk (HR: 1.49; 95% CI: 1.15–1.95) compared to good ventilation. Just the use of coal as a fuel was not significantly associated with the cancer risk. However, residents who used coal in addition to poor ventilation (HR: 1.69; 95% CI: 1.22–2.35) for 20 or more years (HR: 2.03; 95% CI: 1.35–3.05) were significantly associated compared to no exposure to coal or poor ventilation only. These results demonstrate that indoor air pollution (IAP) from poor ventilation of coal combustion increases the risk of lung cancer. This is an important public health issue in cities across China where many people may have lived in homes with inadequate kitchen ventilation.

Zhong et al. (1999) confirmed that exposure to Chinese-style cooking, especially cooking unrefined rapeseed oil at high temperatures in woks, may increase the risk of lung cancer. 504 incidents of primary lung cancer cases diagnosed from February 1992 through to January 1994 were identified through the population-based Shanghai Cancer

Table 3
Comprehensive index.

Comprehensive Index	Level	Evaluation
≤0.49	I	Clean
0.50–0.99	II	Un-contaminated
1.00–1.49	III	Light contaminated
1.50–1.99	IV	Medium contaminated
≥2.00	V	Severely contaminated

Registry. A control group of 601 non-smoking women were randomly selected from the Shanghai Residential Registry and they were frequency-matched to the expected age distribution of the cases. Exposure to indoor air pollutants from Chinese-style cooking was ascertained through in-person interviews. They estimated adjusted odds ratios (OR) and 95% CI by unconditional logistic regression. There were similar patterns of excess risk for exposure to indoor air pollutants from Chinese-style cooking across different histological types of lung cancer. Women who did not have a separate kitchen experienced a 28% increased risk of lung cancer (OR = 1.28; 95% CI = 0.98–1.68). They found little association with the window area of the apartment where subjects had lived for the longest period. Heating cooking oils to high temperatures was associated with a 1.64-fold increased risk of lung cancer (95% CI = 1.24–2.17). An 84% increased risk was found among women who most often cooked with rape-seed oil (OR = 1.84; 95% CI = 1.12–3.02). Lung cancer risks were also related to "considerable" smokiness of the kitchen during cooking (OR = 2.38; 95% CI = 1.58–3.57), frequent eye irritation during cooking (OR = 1.68; 95% CI = 1.02–2.78), to a more than weekly use of frying (OR = 2.09; 95% CI = 1.14–3.84) and deep-frying (OR = 1.88; 95% CI = 1.06–3.32).

Seow et al. (2000) conducted a case-control study of 303 Chinese women with pathologically confirmed, primary carcinomas of the lung and 765 controls. This was performed to examine the association between exposure to cooking meat and lung cancer risk. Their results suggest that inhalation of carcinogens during the frying of meat, may increase the risk of lung cancer among smokers. The proportion of smokers (current or ex-smokers) among cases and controls was 41.7 and 13.1%, respectively. Adenocarcinomas comprised 31.5% of cancers among smokers and 71.6% among non-smokers. Among smokers, women who reported that they stir-fried daily in the past had a significantly increased risk of lung cancer (adjusted OR, 2.0; 95% CI, 1.0–3.8) and among these women, risk was enhanced for those who stir-fried meat daily (OR, 2.7; 95% CI, 1.3–5.5). Women who stir-fried daily but cooked meat less often than daily did not show an elevated risk (OR, 1.0. 95% CI, 0.5–2.4). Risk was further increased among women stir-frying meat daily who reported that their kitchen was filled with oily fumes during cooking (OR, 3.7; 95% CI, 1.8–7.5). Therefore, both the dose and exposure time are significant factors to be considered

3. Conclusion

Considerable progress has been made in extending the knowledge of cooking emissions in China in the last 20 years. Research papers in this field have been published with increasing frequency by institutions in mainland China, Taiwan and Hong Kong. Studies were aimed at gaining a full understanding of Chinese cooking emissions, with investigations into both particulate and gaseous pollutants influenced by choice of food, oil, cooking methodologies, fuels and ventilation. The study of cooking emissions was found to be technically challenging due to the large concentrations of PM and VOCs and their inherent variations in physicochemical properties. Compounds studied by one institution were often not investigated by other groups which made it difficult to compare and validate the results. Therefore, it is necessary to conduct comprehensive studies which include influence of all the variables to fully evaluate cooking emissions.

Chinahas many unique characteristics which makes direct comparisons of its cooking emissions with American and European ones difficult. These differences include: dietary and living habits; the pollutants produced during Chinese-style cooking (including $PM_{2.5}$ concentration, composition, etc); racial differences and genetic characteristics and age structure. These variations lead to very different susceptibilities in the Chinese population to the contaminants released during cooking. Therefore, it is necessary to establish specific and systematic research into the health impacts and characteristics of cooking emissions based around the cooking habits and population features of China.

Chinese scholars can use the methodology used in Europe and the United States when conducting the study of air pollution and health impact of cooking emissions. However, the focus should be on understanding of emissions in China and their corresponding health effects, rather than simply adopting the results of other countries. Potential research topics include the investigation of pollutant formation, transportation and fate of pollutants, pollutant emission characteristics and dynamic processes, prospective cohort study plan, and threshold values of pollutants for various health effects. These studies will be used as the basis of atmospheric environmental health standards in China to improve its air quality.

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Appendix A. Supplementary data

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