Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking

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EMISSIONS AND INDOOR CONCENTRATIONS OF PARTICULATE MATTER AND ITS SPECIFIC CHEMICAL COMPONENTS FROM COOKING: A REVIEW

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ABSTRACT

It has long been known that cooking can create high concentrations of aerosol indoors. Increasingly, it is now being reported that cooking aerosol is also a significant component of outdoor particulate matter. As yet, the health consequences are unquantified, but the presence of well known chemical carcinogens is a clear indication that cooking aerosol cannot be benign. This review is concerned with current knowledge of the mass concentrations, size distribution and chemical composition of aerosol generated from typical styles of cooking as reported in the literature. It is found that cooking can generate both appreciable masses of aerosol at least within the area where the cooking takes place, that particle sizes are largely within the respirable size range and that major groups of chemical compounds which have been used to characterise cooking aerosol include alkanes, fatty acids, dicarboxyclic acids, lactones, polycyclic aromatic hydrocarbons, alkanones and sterols. Measured data, cooking emission profiles and source apportionment methods are briefly reviewed.

Keywords: Cooking; cooking aerosol; cooking emissions; cooking tracers

1. INTRODUCTION

Indoor air pollution is reported to be responsible for 2.7% of the global burden of disease (Fang et al., 1999). Worldwide more than 1 million people die from chronic obstructive pulmonary disease (COPD) annually due to indoor exposure to smoke which generally contains a range of health-damaging pollutants, such as fine particles and carbon monoxide (Hetland et al., 2000). The use of solid fuels (biomass and coal) for cooking and heating homes is practised by around 3 billion people in open fires and leaky stoves, especially by people with low and medium resources in developing countries. As such, poorly ventilated homes can have indoor smoke concentrations of respirable particles of more than 100 times the acceptable levels (Hetland et al., 2000) with mostly women and young children being exposed to these extremely high levels.

Indoor levels of particles in developed countries are much lower than in developing countries and this is generally attributable to the advancement in technology for general household activities and also the use of cleaner fuels (such as liquefied petroleum gas, electricity and natural gas) for cooking and heating. However, there are still observed risks to health in people exposed to indoor air in these locations. Legislation relating to air pollutant exposure in developed countries is normally based upon ambient outdoor concentrations, potentially leading to inadequate protection of the general public who spend the majority of their time at home, offices or other enclosed locations where the concentrations of some pollutants are often much higher than ambient levels (Marcazzan et al., 2001). Knowledge of the indoor environment is limited and is of great importance as the majority of people have been found to spend about 80-90% of their time indoors in many countries (Koistinen K.J., 2001; Scapellato et al., 2009; Delgado-Saborit et al., 2011). Also the indoor environments have been found to be affected by factors such as the design of the buildings, insulation and ventilation in order to ensure an adequately controlled environment for thermal comfort, which can also affect level of individual exposure (Tan et al., 2012).

This literature review deliberately omits those studies that report emissions from cooking using biomass and solid fuels. In such studies, the elevated concentrations reported derive largely from the combustion of the fuel used for cooking rather than from the cooking itself. This study focuses on studies of cooking emissions reported from the use of cleaner cooking fuels, such as electricity and gas. It is expected that the use of electricity and gas will also contribute to the cooking emissions. However, although such emissions will be included in the concentrations reported in the literature, the main contribution to those concentrations is expected to be from compounds deriving from the cooking of the ingredients itself.

1.1. Particulate Matter

Particulate matter (PM) is defined as the mass of a mixture of solid particles and liquid droplets of various sizes (range from a few nanometres to tens of micrometres) suspended in a volume of air which represent a broad class of chemically and physically diverse substances. Particulate matter is classified according to its size, thus PM_{10} is defined as the concentration of particulate matter with aerodynamic diameter of 10 micrometres or less, while $PM_{2.5}$ is defined as the concentration of particulate matter that has aerodynamic diameter of 2.5 micrometres or less.

Particulate matter consists of components that are released directly from a source (primary PM) or are formed by chemical reactions in the atmosphere (secondary PM). It comes from natural and man-made sources and consists of a range of chemical compounds which can be useful for the identification of the source. Primary particulate matter is released from sources which include road transport (tyres and brake wear, engine combustion, road dusts), industrial, commercial and domestic burning of fuels and also dust from these activities, and natural sources (sea spray and dust).

1.2. Cooking and PM

Several studies of indoor air have identified cooking as one of the most significant particle generating activities indoors (Kamens et al., 1991; Ozkaynak et al., 1996; Chao and Cheng, 2002; Lazaridis et al., 2006; Zhao et al., 2007a; Buonanno et al., 2009; Lai et al., 2010; Wan et al., 2011; Massey et al., 2012). The general population is exposed to cooking-related risk regardless of race, age, wealth and cultural food preferences as cooking is an important aspect of human culture (Kim et al., 2011). The processes used in cooking such as frying, roasting, grilling, boiling and broiling contribute to pollutant emissions and are affected by ingredients, recipes and procedures, fuel types, temperature and extraction/ventilation equipment (Zhang et al., 2010). Table 1 summarises the cooking styles, ingredients and oils used for some common cultural culinary techniques. The table shows that many of the ingredients and cooking methods are common to various culinary techniques. This is a reflection of the current intercultural exchange that represents an increasingly vague difference between the major styles of cooking.

Cooking contributes particles to outdoor as well as indoor air. Commercial cooking emissions may have contributed to the exceedence of the Federal $PM_{2.5}$ air quality standards in certain regions such as Pittsburgh, Pennsylvania, where meat charbroiling was shown to contribute to carbonaceous PM (Cabada et al., 2002). Large scale cooking has been identified to be an important contributor to organic carbon (OC) and elemental carbon (EC) in the urban environment including secondary organic aerosol (SOA) formed by condensation of reaction products of gaseous organic emissions following photochemical processes) (Roe et al., 2005).

Rogge et al. (1991) reported that 21% of the primary fine organic aerosol in the Los Angeles area in the 1980s was generated by charbroiling and meat cooking activities, which was in agreement with previous studies in the area (Hildemann et al., 1991b). A similar study in 1997 in Denver Colorado, the Northern Front Range Air Quality Study (NFRAQS), found that meat cooking contributed about 15% of $PM_{2.5}$ organic aerosol concentrations (Watson et al., 1998).

Recently a study in New York City (NYC) using a High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS) identified that cooking and traffic were two distinct and mass-equivalent Primary Organic Aerosol sources, contributing 30% of the total Organic Aerosol (OA) mass collectively during the period (Sun et al., 2011). The average mass concentration of Cooking OA was 1.02 $\mu g/m^3$, higher than the mass concentration of Hydrocarbon like OA (0.91 $\mu g/m^3$), which was surprising as the sampling site was actually close to two major highways (<1 mile), giving a clear indication that cooking activities were an important source of primary particles in NYC. An earlier air quality campaign in Beijing in 2008 using a HR-ToF-AMS found that 24.4% of total organic mass was similarly attributed to cooking related organic aerosols (Huang et al., 2010) .

Measurement of particle number and size distribution of particles generated during cooking has been carried out in various studies to provide a better understanding of characteristics of particles generated during cooking (Abt et al., 2000; Buonanno et al., 2009; Dennekamp et al., 2001; See and Balasubramanaian, 2006a; Wallace et al., 2004; He et al., 2004b).

Generally the risk associated with cooking is still poorly understood, although such awareness is necessary to ensure adequate protection of health for the general public. This review will provide an analysis of the sampling methods, data upon aerosols emitted from cooking, the source profiles identified and their usefulness in apportionment studies will also be considered.

2. EMISSIONS FROM COOKING

Studies of cooking emissions have been carried out in both real life kitchens and in controlled environments. It is assumed that in controlled experimental setups, the measurements are influenced mainly by the fuel used and the food being cooked while in actual real life kitchens measurement of emissions are influenced by many factors such as room arrangement, building materials, outdoor infiltration, other combustion devices, ventilation, and cooking methods (Huboyo et al., 2011).

Visible fumes are generated during the cooking process, which are usually due to submicrometer sized particles, which consist of oil droplets, combustion products, steam from water in the food being cooked and condensed organic pollutants. The particulate matter (PM) generated is generally within the ultrafine particle (UFP) - which represents particles of diameter less than100 nm - and fine PM ($PM_{2.5}$) size ranges. The physical stirring of food has been found to lead to the generation of large aerosols due to the process of splashing of the ingredients (Long et al., 2000). The combustion process associated with cooking can lead to the formation and direct emission of ultrafine particles (UFP) to the atmosphere, and hot vapours in the cooking fumes may also cool and nucleate to form more UFP (Sioutas et al., 2005; Lai and Ho, 2008). These particles may contain organic substances, such as polycyclic aromatic hydrocarbons (PAH) and heterocyclic amines, adsorbed on their surfaces (Ho et al., 2002).

There is a scarcity of national inventories of cooking activities, but an attempt was made by Roe et al. (2005) to compile a national emission inventory for commercial cooking in the United States as listed in Table 2. For comparison, data for highway vehicles extracted from the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data for the same year (Chappell et al., 2003), show that although traffic emits orders of magnitude more CO and VOC than cooking, particulate matter emissions from cooking are comparable with those emitted from highway vehicles. This is consistent with a study of Li et al. (2003), who found that the emission rates of total PAH from cooking sources in the study city (i.e. emissions from both restaurants and home kitchens), were slightly lower than those for traffic sources in a representative city of Taiwan (8,973 kg/year for cooking against 13,500 kg/year for traffic). Nonetheless, they observed that the emission rate for $B[a]P_{eq}$ toxic equivalent for cooking sources was much higher than that from traffic sources (675 kg/year from cooking and 61.4 kg/year emitted from traffic sources). This indicated that cooking PAH may cause much more serious problems than traffic sources in terms of carcinogenic potency (Li et al., 2003).

2.1. Particle mass concentration

The PTEAM Study (Particle Total Exposure Assessment Methodology) performed in the US, reported around 20 µg/m^3 higher particle concentrations in houses where cooking took place during their monitoring than those house where no cooking occurred (Wallace, 1989). They reported that the proportion of $PM_{2.5}$ and PM_{10} due to cooking represented 25% for both particle sizes. This proportion increased to 65% and 55%, respectively, when considering indoor sources alone (Ozkaynak et al., 1996). Source apportionment of PTEAM ambient and personal exposure samples using a combined receptor model found that cooking was the largest contributory source of PM indoors, responsible for about 52.5% of the personal exposure samples and 43.2% of residential indoor concentrations (Zhao et al., 2006). After 1,000 hours of cooking, they also found that the mean $PM_{2.5}$ personal exposure increased an average of 56 µg/m^3 while cooking activities took place, and that cooking increased the overall 24-hours personal exposure about 2.5 µg/m^3 in those persons that had cooked during the sampling day (Wallace et al., 2006).

A study to characterize indoor sources of particles conducted in Boston, USA, made measurements of particle size and volume concentration over 6 days in four non-smoking households equipped with gas and electric stoves (Abt et al., 2000). The monitoring equipment was placed in a single indoor location adjacent to the kitchen and living room and from the data obtained, it was found that the highest mean peak mass concentrations were for barbequing and sautéing for the $PM_{0.02-0.5}$ and $PM_{0.7-10}$ respectively, whilst the lower mean peak concentrations were found for frying and oven cooking or toasting for the same size ranges respectively (see Table 3) (Abt et al., 2000).

Another US study found that the average $PM_{2.5}$ concentration due to cooking over 195 cooking events was about 5.5 µg/m^3 with a standard error of 2.3 µg/m^3 (Allen et al., 2004). In Europe, a study made a comparison of elderly residents in Amsterdam (47) and Helsinki (37), and found that the estimated contribution from cooking ranged from 1.9 µg/m^3 for indoor $PM_{2.5}$ in Helsinki to 3.4 µg/m^3 for $PM_{2.5}$ personal exposure concentrations (Brunekreef et al., 2005).

Rates of emission of aerosol have been reported to vary based on type of appliance used, the cooking conditions used and fat content of meat (McDonald et al., 2003). In an experiment where hamburger, steak and chicken were grilled and charbroiled, McDonald et al. (2003) found that the $PM_{2.5}$ emission rate for charbroiling meats ranged between 4.4 to 15 g/kg. The largest quantity of $PM_{2.5}$ was emitted by hamburger (15 g/kg) which had higher fat content

(30%) and were cooked on a char broiler. These results are consistent with data reported by Hildemann et al. (1991a) . McDonald et al. (2003) reported that charbroiling produced higher concentrations than frying, 12-46 g/kg meat when charbroiling vs. 0.57 g/kg meat when frying. They also reported that charbroiling lean meat produced less concentrations of particles in the smaller size range (<20 nm) and in the larger size range (>100 nm) than regular meat.

Similarly, Buonanno et al. (2009) found that gas stoves emitted more particles than an electric stove when frying resulting in higher indoor concentrations when gas stoves were used (60-118 µg/m^3) than when electric stoves were employed (12-27 µg/m^3); and that emission rates were considerably affected by the type of food used (Table 3). Increased emissions measured at the source were reported to be a function of increased cooking temperature. Foods containing a higher percentage of fat generated higher emission rates than those with less fat percentage. They reported higher aerosol mass emission when cooking fatty foods resulting in higher indoor concentrations (280-389 µg/m^3) than when cooking vegetables (78 µg/m^3). Particle emission factor varied significantly also with type of oil used. Sunflower oil generated the lowest mass emission factors, whilst the highest emissions were from olive oil (Buonanno et al., 2009). Glytsos (2010) reported that frying of onions in olive oil in a controlled room emitted $PM_{2.5}$ increasing the indoor concentration in the range of 70 to 600 µg/m^3 (Glytsos et al., 2010).

See and Balasubramanian (2006b) investigated the physical and chemical properties of emissions from a Chinese food stall in Singapore while food was stir fried in a wok using a gas stove, and at two different and distinct times (See and Balasubramanian, 2006b). The mass concentration of particles ($PM_{2.5}$) measured in the food stall at the opposite site of a 4-

LPG burner stove increased from 26.7 μg/m^3 during non-cooking hours to 312.4 μg/m^3 during cooking hours (increased by a factor of 12).

Analysis of various cooking methods which included steaming, boiling, stir-frying, pan-frying and deep-frying revealed that the largest amount of particulate matter measured at 20 cm from the cooker was generated during deep frying ($PM_{2.5}$ 190 μg/m^3) and the lowest concentration was observed during steaming ($PM_{2.5}$ 72 μg/m^3) (See and Balasubramanian, 2008). Both studies have indicated that cooking with oil contributes to the production of more particles than cooking with water, which is consistent with the work of He et al. (2004a). In another study, See et al. (2006) made a comparison of emissions from Chinese, Indian and Malay food stalls and reported that the highest mass concentrations of $PM_{2.5}$ were found in the Malay stall (245.3 μg/m^3), whilst the lowest were measured in the Indian stall (186.9 μg/m^3) (See et al., 2006).

Several studies have found that Asian style cooking emits more particulate matter than Western cooking with concentrations of $PM_{2.5}$ ranging 30 to 1,400 and 20 to 535 μg/m^3 as reported by various groups (Lee et al., 2001; Levy et al., 2002; He et al., 2004b)

A summary of the main studies reporting aerosol concentration emitted from cooking and the reported concentrations can be found in Table 3.

2.2. Particle size distribution

The size distribution of aerosols emitted from cooking activities has been reported in several studies whose methodology and study description is summarised in Table 4 and results are compiled in Table 5. Generally some of these studies have shown that indoor particle concentrations are substantially affected by cooking activities, cleaning and the movement of people (Abt et al., 2000; He et al., 2004a; Diapouli et al., 2011). The largest percentage of the measured particles are ultrafine particles (UFP), with modes in the number distribution reported generally in the range of 20 to 100 nm (see Table 5).

He et al. (2004a) studied 15 homes in Australia while cooking was carried out under good and poor ventilation for 48 hours. They found that some indoor activities led to an increase in indoor particle number concentration of about 1.5-27 times concentrations in comparison with the particle number concentration when no indoor source was in operation. They also found an emission rate ranging 0.2-4x10^{12} particles/min and peak submicron number concentrations for cooking of 16,000 and 180,000 part/cm^3 (He et al., 2004a).

An investigation of the size distribution of particles emitted from cooking was carried out using a scanning mobility particle sizer (SMPS) in a domestic kitchen using five different cooking methods, such as steaming, boiling, stir-frying, pan-frying, and deep-frying. Deep-frying was found to have the highest particle number concentration, whilst steaming produced the lowest particle number concentration. Their observations found that cooking activities using oil produce higher concentrations than those using water (See and Balasubramanian, 2006a). They reported a 24-fold increase in particle concentration observed between deep frying and background concentrations (6.0×10^5 cm^{-3} compared to background concentrations which were 2.5×10^4 cm^{-3}) (See and Balasubramanian, 2006a). In another study, they characterised Chinese cooking emissions, and found that the average number concentration increased by factor a of 85 during the cooking periods (7.7x10^5 part/cm^3 compared to 9.1x10^3 part/cm^3 during non- cooking hours (See and Balasubramanian, 2006b).

Yeung and To (2008) examined aerosols generated by commercial food preparation and found a lognormal size distribution. Increased cooking temperature resulted in an increased modal diameter of aerosols. Higher cooking temperature also increased the normalized number concentration sub-micrometer aerosols (between 0.1 and 1.0 µm) (Yeung and To, 2008).

Siegmann and Sattler (1996) found that diameter and number concentrations of oil droplets increased with an increase in temperature. They analysed aerosols from different hot vegetable oils and obtained a size distribution with a mean droplet size range of 30 nm at 223^{o}C to 100 nm at 256^{o}C. Particle number concentration increased from 2.25 x 10^5 part/cm^3 to 4.5 x 10^5 part/cm^3 in the same range of temperatures (Siegmann and Sattler, 1996).

Dennekamp et al. (2001) studied the generation of ultrafine particles and nitrogen oxides using different cooking procedures comparing gas and electric stoves in a laboratory. They found higher concentrations of particles in the size range of 15-40nm (and also oxides of nitrogen) when cooking on gas (Dennekamp et al., 2001). The smaller particles generated were found to grow in size with time during the experiment. The high concentrations of pollutants observed were attributed to the absence of ventilation in their laboratory kitchen.

Frying of onions in olive oil in a controlled room to characterise contributors of particle concentrations in indoor environments produced high particle concentrations, ranging between 9 - 15 × 10^4 particles cm^{-3} (Glytsos et al., 2010). High emission of nanoparticles were reported during frying (1.15 x 10^5 part/cm^3, mainly 20 nm). However, sometime after the frying stopped (i.e. 45 min later), the number concentration decreased down to 4 x 10^5 part/cm^3 and particles become larger leading to a bimodal size distribution indicating a strong coagulation effect (Glytsos et al., 2010), which is consistent with previous studies (Dennekamp et al., 2001; Sjaastad et al., 2008).

A study in an apartment in Taiwan found a range of mode diameters of particles concentrations between 30-50nm for domestic cooking processes of scrambling eggs, frying chicken, and cooking soup with higher mode diameter for frying chicken (Li et al., 1993).

Similarly, in an 18 month campaign in a four bedroom house consisting of three levels located near Washington DC, USA; particles generated from cooking were found to be mainly in the ultrafine range (about 90% of total particles), with frying being found to generate more particles than any other cooking method (Wallace et al., 2004), consistent with recent studies (Hussein et al., 2006; Buonanno et al., 2011; Huboyo et al., 2011).

Buonanno et al. (2009) sought to evaluate the influence of temperature, oil, food and stove type on particle number, surface area and mass emission factors consequence of cooking with different methods such as grilling and frying. They used a Scanning Mobility Particle Sizer (SMPS) and Aerodynamic Particle Sizer (APS). They found that frying food with oil using an electrical frying pan produced emission factors well below those observed for frying using a gas stove. The particle emission factor was also dependent upon the temperature of the stove, with values 9 and 4 times higher at the maximum stove power for gas and electric stoves respectively (Buonanno et al., 2009), consistent with previous studies of Siegmann and Sattler (1996), Dennekamp et al. (2001), Yeung and To (2008) and To and Yeung (2011). In another study by them, they reported high particle indoor concentrations (3×10^4–6×10^5 particles cm^{-3}) in 14 pizzerias and PM_1 concentrations of about 10–327 $\mu g\ m^{-3}$ during normal ventilation conditions (Buonanno et al., 2010). However most of the particles generated in this study are believed to be from the wood burning used to fire the oven, and highlights the high particle concentrations that can build up in such microenvironments. In another study, Buonanno and colleagues found that frying the same type of food consistently emitted more particles than grilling, with a factor of 1.4-1.5 (Buonanno et al., 2011).

3. ON-LINE CHEMICAL CHARACTERISATION – AEROSOL MASS SPECTROMETER

Atmospheric organic aerosol consists of many compounds with dissimilarities in properties making the characterisation of its chemical composition and mass concentration by analytical processes quite difficult (Seinfeld and Pankow, 2003; Kanakidou et al., 2005; Goldstein and Galbally, 2007; Zhang et al., 2011). It has been found that only about 10% of the Organic Aerosol (OA) mass can be easily speciated by techniques such as GC-MS and inconsistencies have been found to exist between different thermal-optical organic carbon (OC) quantification and artefact removal techniques (Schauer et al., 1996; Zhang et al., 2007). In order to obtain better understanding of submicron aerosols, on-line chemical characterisation can be performed. The Aerodyne Aerosol Mass Spectrometer (AMS) has the ability to quantify the mass concentration and mass spectrum of organic matter giving insights into the aerosol sources, chemistry and processes in the environment (Zhang et al. 2011).

Several studies have used an AMS for real-time measurement of particles and have identified organic aerosols from cooking, referred to as Cooking Organic Aerosol (COA) (Mohr et al., 2009; Allan et al., 2010; Huang et al., 2010; Mohr et al., 2011; Sun et al., 2011). Results from this instrument provide real-time, highly time-resolved measurements of the concentrations and size distributions of non-refractory submicron aerosol (NR-PM1) species (i.e., organics, sulphate, nitrate, ammonium, and chloride) with the capability to separate different organic ions at the same nominal mass-to-charge ratio (m/z). The mass spectra (MS) represent the linear superposition of the spectra of individual components weighted by their concentrations. The mass information of the functional nature of the organics can be acquired on inspection of the mass spectra obtained from the AMS after the removal of the inorganic contributions (Allan et al., 2004; Allan et al., 2010). Multivariate factor analysis of the MS matrix has been conducted in most studies and has provided OA factors that offer a quantitative generic description of thousands of individual organic species (Zhang et al, 2011). The individual factors typically correspond to a large group of OA constituents with similar chemical composition and temporal behaviour that characterise different sources and atmospheric processes. Nonetheless, the AMS provides limited molecular details of aerosols analysed because the molecules are fragmented during high temperature vaporization and ionization in the AMS (Canagaratna et al., 2007).

The main reference spectra of primary OA from cooking emissions (COA) derived from the AMS have been obtained in Barcelona (Mohr et al. 2009, Mohr et al.2011), London (Allan et al., 2010), New York and Beijing (Huang et al., 2010). A high resolution mass spectrum of COA obtained in 2006 by Sun et al. (2011) was different from that reported by Mohr et al. (2009), but similar to the one analysed in London and Beijing (Mohr et al., 2009; Allan et al., 2010; Huang et al., 2010; Sun et al., 2011).

Characterisation of primary emissions from simulations of different types of Chinese cooking and biomass burning was also done using a High Resolution Time of Flight AMS (HR-ToF-AMS) at Peking University Shenzhen (He et al., 2010). The MS for all the cooking were similar, with highest signals at *m/z* 41 and *m/z* 55 (dominated by $C_3H_5^+$and $C_4H_7^+$), whilst biomass burning MS showed the highest signals at *m/z* 29 and *m/z* 43. Therefore, there was a significant difference between cooking and biomass burning mass spectra. On the other hand, the MS of both cooking and biomass contained ions that demonstrated the presence of saturated alkanes, alkenes, and long chain fatty acids in their primary OA (He et al., 2010). The fragments that dominated Chinese cooking are believed to be fragments resulting from electron ionization of unsaturated fatty acids from frying. The O/C ratios of OA ranged from 0.08- 0.13 for the Chinese cooking and 0.18 to 0.26 for biomass burning (He et al., 2010).

Another difference between cooking and biomass burning MS was the presence of more mass fragments in the range of m/z>100 for biomass burning than in the cooking emission profile. He's study provides useful MS for the identification of individual components during factor analysis of ambient OA datasets measured using an AMS.

Huffman et al., (2009) used a modified fast temperature –stepping thermodenuder coupled with a HR-ToF-AMS to determine chemically resolved volatility of the OA emitted from various primary sources of ambient OA, including meat cooking. Meat cooking OA was found to have consistently lower volatility than ambient OA (Huffman et al., 2009). Meat cooking MS was hydrocarbon-like and dominated by reduced ions (C*x*H*y*), with the abundant ions being $C_3H_7^+$ (*m/z* 43) and $C_4H_7^+$ (*m/z* 55), whilst the contribution from oxygenated ions was low. The range of O/C ratios was between 0.11-0.14 similar to those of typical fatty acids like oleic acids, and much lower than for ambient urban Oxygenated OA (OOA) (Huffman et al., 2009).

Prominent peaks were also identified in the study of Sun et al. (2011), which further suggested that the suitable source spectral signature for cooking emissions and thus for use as spectral markers for COA is the *m/z* ratio 55/57. The COA spectrum was characterized by a high ratio of 2.9 and a high fraction of *m/z* 55 (f55 = 8%), which confirmed the presence of COA at urban locations (Sun et al., 2011). They also found that COA contributed 38% of $C_3H_3O^+$ and 29% $C_4H_7^+$ at *m/z* 55; 25% of $C_3H_5O^+$ and 20% of $C_4H_9^+$ at *m/z* 57; and had a significant correlation with a few $C_xH_yO^+$ ions (e.g., $C_5H_8O^+$, $C_6H_{10}O^+$, and $C_7H_{12}O^+$) (Sun et al., 2011).

Mohr et al. (2009) reported that meat cooking aerosol had an elevated *m/z* 60 and contained significant fractions of oxygenated organic compounds with similar mass spectral fractions than ambient hydrocarbon like OA (HOA) (Mohr et al., 2009). Allan et al. (2010) identified the largest peaks for COA at *m/z* 41 and *m/z* 55, similar to those identified by Lanz and colleagues (2007) (Lanz et al., 2007). They also observed a diurnal profile which had large peaks occurring in the late evening and smaller peak around at midday, which they ascribed to mealtimes in London and Manchester (Allan et al., 2010).

Zhang et al. (2007) identified meat cooking as a part of the HOA after analysing organic aerosol obtained in a field campaign using the AMS (Zhang et al., 2007). Combustion of fossil fuel was the other source of HOA. Aerosol mass contributions from HOA in the urban areas were strong, but smaller contributions were observed in rural areas attributed to atmospheric dilution. OOA components had higher concentrations than advected HOA indicating that oxidation of Secondary OA (SOA) was the strongest contributing source to OOA, whist HOA (and its various sources such as cooking) were less significant contributors to organic aerosol (Zhang et al., 2007).

In California food cooking was found to contribute to 10% of submicron OA mass in the summer periods, but due to high covariance, food cooking composition was not distinct from the SOA during the autumn (Williams et al., 2010). During the summer the SOA had four distinct components identified which accounted for about 88% of the total fine OA mass when all were combined. The components included three distinct oxygenated sources: SOA1 (oxygenated species with hydrocarbons), SOA2 (oxygenated species from photo-oxidation of gas-phase precursors), SOA3 (from advanced photochemical oxidation exist) and the fourth component was from biogenic SOA.

Similarly, He et al. (2011) deployed a HR-ToF-AMS at an urban site in Hong Kong – Schenzen metropolitan area and the data obtained indicated four OA components which included HOA, biomass burning (BBOA) and two oxygenated OA components with the

HOA contributing 29.5% of the total organic mass. Cooking emissions and fossil fuel combustion were the identified sources of HOA (He et al., 2011).

AMS and ^{14}C data from Mexico City identified that non-fossil fuel sources (such as food cooking and biogenic SOA) contributed to 38% of organic carbon and 28% total carbon during the low regional fire period of their sampling (Aiken et al., 2010), further illustrating the importance of cooking as a source contributing to aerosol concentrations in ambient air.

It is important to note the limitations of the AMS, which are that it only determines the non-refractory material and does not distinguish between anthropogenic and biogenic secondary organic aerosols (SOA) (Baltensperger and Prévôt, 2008). This can lead to both qualitative and quantitative uncertainty in the reporting of data.

4. SPECIFIC ORGANIC COMPOUNDS EMITTED DURING COOKING

Cooking involves a wide range of chemical reactions. For instance, many sugars (e.g. disaccharides or oligo-saccarides) or carbohydrates undergo hydrolysis when heated with water. The hydrolysis reaction breaks down the complex sugar into single ring sugars. If sugars are heated further, degradation reactions will occur and the sugar rings will open up to form new molecules such as acids and aldehydes. If the temperature is increased sufficiently, the degradation products may recombine to form chain-like molecules (Barham, 1950). In meat cooking, fat which occurs as triglyceride (i.e. fatty acids esterified to a glycerol backbone) in uncooked meat is hydrolysed or thermally oxidized and produces free glycerol, free fatty acids and mono and diglycerides as shown in Figure 1 (Nolte et al., 1999). The chemical reactions that occur between proteins and carbohydrates or sugars during cooking are known as the Maillard reactions. These involve initial degradation to amino acids and smaller sugars. The acids and aldehydes produced after the opening of the sugar rings react with the amino acids to produce a wide range of chemicals (e.g. furanones) (Barham, 1950).

The chemical properties of the aerosols generated during cooking can be measured to further provide useful information on the aerosol composition. In most of the studies aimed at performing chemical speciation of the cooking aerosol, samples are collected on filters for gravimetric determination and to allow subsequent chemical analysis. In some cases, denuders are used to collect the vapour phase of semi-volatile components for further analysis. Off-line chemical characterisation studies often employ sampling methods which have the potential to cause positive artefacts associated with the reaction of trace gases with particles on the filter or the filter itself. Negative artefacts may also arise from evaporative loss of semi-volatile components. Strict sampling procedures and guidelines should keep these artefacts to a minimum (Harrison and Yin, 2005).

Table 6 gives details of key studies that have sampled and subsequently analysed the chemical composition of aerosols from cooking. Most of the off-line chemical characterisation has been done using a GC-MS analytical stage for organic speciation of the cooking emissions, with many compounds of interest requiring derivatisation. A summary of specific groups of compounds emitted from cooking identified and characterised by these studies appear in Table 7, whilst Table 8 to Table 18 present a summary of concentrations of specific compounds emitted during cooking reported in the literature, as discussed below.

4.1. Effect of cooking styles and ingredients on organic compound emission profiles

Research has identified that different cooking styles emit different profiles of compounds. The differences have been attributed to factors such as cooking processes and ingredients

(Hildemann et al., 1991a; Rogge et al., 1997; Schauer et al., 1999a; He et al., 2004a). Western fast food cooking involves frying with beef and chicken as the main cooking method and meats consumed. Chinese cooking practice on the other hand generally involves the use of pork, poultry, seafood as well as vegetables during cooking as listed in Table 1. Chemical composition variations are thus expected to be observed for various different cooking operations. For instance, nonanedioic acid has been identified as the most abundant dicarboxylic acid in Chinese cooking and hexanedioic acid for meat cooking (Rogge et al., 1991; He et al., 2004c; Zhao et al., 2007c). Sitosterol and monosaccaride anhydrides have been attributed to vegetables used in Chinese cooking as they were not observed in meat cooking processes. These differences in chemical composition need to be considered for selection of molecular markers, which will be useful to assess the contribution of cooking to atmospheric particulate organic matter (POM) (Rogge et al., 1991; He et al., 2004b; Zhao et al., 2007c; Zhao et al., 2007b). Figure 2 shows Marker-to-OC ratios of meat cooking profiles using profiles from Rogge at al. (1991), Watson et al. (1998) and Schauer et al. (1999a; Schauer et al., 2002). These source profiles and species are usually included in models by normalising emissions with OC or $PM_{2.5}$.

Higher fat contents in cooking ingredients have been found to produce more fatty acids compared with the low fat content ingredients in the same cooking operation (Rogge et al., 1991; Zhao et al., 2007b; Zhao et al., 2007c). This is generally observed also when Chinese cooking is compared with Western style fast food; the latter having higher concentrations of fatty acids, indicating the high proportion of ingredients with higher fat content. Animal and vegetable fats are rich in high concentrations of normal fatty acids with even carbon numbers from C4 to C34 as triglycerides and phospholipids (Zhao et al., 2007a).

In a experiment comparing grilling and charbroiling different types of meat, grilling was found to emit less organic compounds than charbroiling, which yielded about 5 times more PAH (i.e. 30-50 mg/kg for charbroiling vs. <10 mg/kg for grilling), 10 times more lactones (i.e. 7-30 mg/kg for charbroiling vs. 2-4 mg/kg for grilling) and 20 times more cholesterol (i.e. 1-8 mg/kg for charbroiling vs. 0.04-0.2 mg/kg for grilling) (McDonald et al., 2003) .

When different types of meat were grilled in a shed, Mohr et al. (2009) reported large differences of emissions with increasing emissions as the fat content increased, even when the meats were cooked in the same manner. This is qualitatively consistent with earlier studies (Rogge et al., 1991; McDonald et al., 2003). Rogge et al. (1991) reported that generally grilling of meat led to the higher production of aerosols made of fatty acids. This was attributed to the oil and grease droplets falling into the gas flame or onto the heat source where they would vaporize and renucleate and grow into small particles.

Zhao et al. (2007a) investigated the chemical composition of particulate organic matter from Western fast food cooking and identified tetradecanoic acid, hexadecanoic acid, octadecanoic acid, 9-octadecanoic acid, nonanal, levoglucosan, hexanedioic acid and nonanedioic acid as potential tracers with saturated and unsaturated fatty acids accounting for 78% of total quantified compounds. When they analysed the chemical composition of aerosol from Chinese cooking, they identified also a dominant homologue of fatty acids with its concentration being about 73-85% of the quantified compounds. They also identified levoglucosan and β-sitosterol as well as a clear pattern of n-alkanes which were taken as an indication of vegetables consumed in the Chinese cooking process (Zhao, 2007b). The concentration of quantified compounds per unit of particulate organic matter in Western cooking was found to be much higher than that in Chinese cooking (Zhao, 2007a). The candidate organic tracers that they found to distinguish emissions of Western cooking from

Chinese cooking in Ghanzou (China) are tetradecanoic acid, hexadecanoic acid, octadecanoic acid, oleic acid, levoglucosan, mannosan, galactosan, nonanal and lactones (Zhao, 2007b). Table 8 shows clearly from their findings that the Chinese cooking made a much greater contribution of PAHs to particulate organic matter than Western fast food with 2,855 ng/mg of particulate organic matter in Chinese cooking as against 40 ng/mg in Western cooking.

Nolte et al. (1999) analysed meat cooking smoke and found that 1-palmitin and 2-palmitin were the most abundant compounds observed with significant emissions of 1-stearin and 1-olein monoglycerides and cholesterol (Nolte et al., 1999). Similar to what was observed with emissions of particulate number and particulate matter mass, higher concentrations of organic pollutants were observed to be emitted during oil-based cooking methods compared to steaming and boiling which were water-based (See and Balasubramanian, 2008). Also an analysis of commonly used cooking fuels in Hong Kong identified that gas cooking produced higher concentrations of PM_{10}, organic material and total volatile organic compounds during cooking by stir frying, pan frying and deep frying in domestic settings (To and Yeung, 2011). Higher concentrations of pollutants were observed in commercial kitchens compared to domestic kitchens probably due to the volume of food cooked or methods of cooking used. In the commercial restaurant, broiling of meat was found to produce higher concentrations of PM and VOC especially for electric broiling of meat compared to gas broiling. This was attributed to a larger contact area for the beef on the electric broiler compared to the gas broiler leading to more intense effect of the heat (To and Yeung, 2011).

4.2. Emissions of Polycyclic Aromatic Hydrocarbons

The incomplete combustion or pyrolysis of organic substances containing hydrogen and carbon, leads to the production of polycyclic aromatic hydrocarbons (PAH). They are stable organic molecules, some of which are known carcinogens (USEPA, 1999; IARC, 2010). Table 9 summarises the concentrations of PAH in fumes reported in the literature with different cooking styles, methods and ingredients; whilst Table 10 summarises the concentrations in fumes from different oils. The cooking method used has been identified as one of the influential factors affecting emission of some compounds, with deep frying found to produce more pollutants and an abundance of higher molecular weight PAHs.

Li et al. (2003) analysed fumes from the rooftop exhausts of ten restaurants producing Chinese, Western, fast food, and Japanese types of food in Taiwan and studied their PAH content. They found that Chinese cooking contributed higher levels of benzo[a]pyrene equivalents than all other styles of cooking, with Western food contributing about seven times less than the Chinese method. Japanese and Western fast food showed a negligible contribution to benzo[a]pyrene. This is consistent with later work by Zhao et al. (2007c), who did not detect any PAH in Western style fast food cooking.

Nonetheless, the percentage of PAH in Chinese cooking as a proportion of total quantified compounds is generally small in emissions from cooking. The compounds of highest concentration emitted from Chinese cooking are pyrene (He et al., 2004b) with traces of benzo[a]pyrene present (Zhao et al., 2007b). Meat and seed oil cooking were observed to release mainly chrysene (Rogge et al., 1991; Schauer et al., 1999a; Schauer et al., 2002). Samples collected in the breathing area of chefs working at Norwegian à la carte restaurants contained naphthalene within the range of 0.05-0.27 $\mu g/m^3$ with a total mean value for the restaurants being 0.18 $\mu g/m^3$ (Sjaastad and Svendsen, 2009).

The relatively low proportion PAH compounds in Chinese emissions was also observed by See et al. (2006) when they made a health risk assessment of occupational exposure to PAH associated with Chinese, Malay and Indian cooking. They found that Malay cooking emitted higher PAH concentrations and also a larger fraction of PAH in $PM_{2.5}$ (600 ng/m^3 and 0.25%, respectively) than the other methods (Chinese, 141 ng/m^3 and 0.07%; Indian, 37.9 ng/m^3 and 0.02%, respectively). This was attributed to extensive frying of snacks (See et al., 2006). Deep frying generated more PAH than other cooking methods due to the high temperature during cooking as well as the large amount of oil used for this method of cooking.

This trend was further observed when Chinese cooking and Indian cooking were compared: higher PAH concentrations were observed for Chinese cooking due to stir frying and higher cooking temperature, whilst the Indian cooking style generated the lower PAH concentrations. Indian cooking emitted large amounts of volatile PAH with lower molecular weight like naphthalene, fluoranthene and phenanthrene attributed to low temperature cooking, such as simmering (See et al., 2006). Chinese cooking, on the other hand, was found to emit higher molecular weight PAHs such as benzo[b]fluoranthene, indeno[1,2,3-cd]pyrene and benzo[g,h,i]perylene. These trends were attributed to the cooking methods employed in each type of cooking from the amount of food cooked, the amount and type of oil used, to the temperatures reached during cooking, and cooking time (See et al., 2006).

The effect of the cooking method was also examined by See and Balasubramanian (2008), who found that techniques that involve the use of oil at high temperatures, such as stir frying, pan-frying and deep-frying, released higher amount of PAH compared with those that involve the use of water, such as boiling and steaming. This is consistent with work of Schauer et al. (2002). Higher quantities of oil are generally used in stir frying, commonly used in Malay and Chinese cooking, than simmering which is the most common technique used for preparation of Indian dishes (Table 1). In addition, high temperature frying was found to lead to production of higher molecular weight PAHs, while low temperature cooking results in formation of more low molecular weight PAHs (See et al., 2006). McDonald et al. (2003)

compared the PAH emissions from charbroiling and grilling meat and found that PAH emissions from charbroiling were about 3–5 times more than when food was grilled. This was attributed to the contact of the lipid material dripping from the meat (during cooking) onto the cooking appliance. Thus, the higher PAH concentrations observed during charbroiling were due to the direct access of lipids onto the hot flame compared to the cooler griddle surface used in grilling (McDonald et al., 2003).

The emission of PAHs in cooking fumes, not only is related to the cooking method, but also to the cooking ingredients. Schauer et al. (1999a; 2002) studied the emissions of cooking fumes for charbroiling hamburger meat (1999a) and frying vegetables (2002). They found that cooking meat produced far greater PAH concentrations than frying vegetables. Zhu and Wang (2003) studied the emissions of low and high fat food using different cooking methods. The frying of low fat foods was observed to lead to the generation of more PAH than the broiling. This was not the case for high fat food which exhibited the reverse with higher concentration of PAH detected when the food was broiled (Zhu and Wang, 2003). This was illustrated when low fat fish produced a higher level of PAH when fried than when broiled, and pork chops produced higher PAH when broiled than when fried.

In another study of cooking in domestic and commercial kitchens it was observed that PAH concentrations were higher for increased cooking temperatures with mean measured benzo[a]pyrene concentrations of 6-24 ng/m^3 in domestic kitchens and 150-440 ng/m^3 in commercial kitchens (Zhu and Wang, 2003). The difference was attributed to the large amount of food cooked in the commercial kitchen.

The type of oil used for cooking will also affect the composition of cooking fumes and its PAH content as summarised in Table 10. Fortmann et al. (2001) analysed five untreated (i.e. raw and uncooked) cooking oils (canola, olive, corn, peanut and vegetable oils) for PAH in a controlled environment. Olive oil and peanut oil were found to contain higher concentrations of PAH than the other oils analysed (Fortmann et al., 2001). Chiang et al. (1999) carried out analysis on the fumes emitted from lard oil, peanut oil and soya bean oil by and found that fumes from these commonly used commercial cooking oils in Taiwan contained dibenzo[a,h]anthracene and benzo[a]anthracene. Benzo[a]pyrene was also found in fumes in peanut oil and soya bean oil. Chiang et al. (1999) found that extracts of fumes from sunflower, vegetable and corn oils contained all the above PAHs as well as benzo[b]fluoranthene with sunflower oil fumes having high concentrations of benzo[a]pyrene of about 22.7 $\mu g/m^3$ and corn oil the least, 18.7 $\mu g/m^3$ (Chiang et al., 1999).

Wu et al. (1998) analysed the fumes from three different commercial cooking oils (lard oil, soya bean oil and peanut oil) frequently used in Chinese cooking and found that fumes contained PAHs, nitro-PAHs such as 1-nitropyrene and 1,3-dinitropyrene (Wu et al., 1998). In another study it was observed that cooking with lard emitted higher concentrations of PAHs, followed by soya bean oil and rapeseed oil (Zhu and Wang, 2003). Chen and Chen (2001) analysed the polycyclic aromatic hydrocarbon (PAH) contents of smoke emitted from selected cooking oils and they observed that soybean oil generated a larger amount of PAH than canola oil or sunflower oil. In a subsequent study where they examined the smoke emitted during the cooking of chicken legs they found that canola oil emitted the greatest content of PAHs, followed by soybean and sunflower oil (Chen and Chen, 2001; Chen and Chen, 2003). This contradictory observation of soybean oil or canola oil releasing more PAH contents in the two studies was attributed to the heating of oil with or without food ingredients as well as possible difference in smoke collection device used in the different experiments. Chen and Chen (2003) also found that a much greater content of smoke was generated when the oils were heated with chicken leg than when heated with glass beads alone.

4.3. Emissions of n-Alkanes

Normal alkanes have been found to range from C_{14} to C_{33} for the various cooking techniques (He et al., 2004b; Zhao et al., 2007c) as summarised in Table 11. The distribution of n-alkanes emitted from Chinese restaurants have generally been observed to be substantially different from the distribution from meat cooking (Rogge et al., 1991; Schauer et al., 1999a; He et al., 2004b) and similar to alkane patterns from frying vegetables in seed oils (Schauer et al., 1999a; Schauer et al., 2002). Emission of n-alkanes from cooking consisted of a negligible fraction of the total quantified organic mass emitted and is dependent on the cooking conditions (Rogge et al., 1991; He at al., 2004b). Hildemann et al., (1991a) reported that the n-alkane concentration release rate increased from frying to charbroiling of meat with extra lean meat releasing less compounds than regular meat (Hildemann et al., 1991a). This was similar to observations by Rogge et al., (1991), where charbroiling was found to produce three times the mass of n-alkanes than frying of meat (16 mg/kg of charbroiling meat as against 5.5 mg/kg of frying meat). Rogge et al. (1991) also observed that charbroiling regular meat released four times the mass compared to extra lean meat (thus affected by fat content of meat).

Western style fast food cooking has been observed by Zhao and co-workers to emit double the concentration of n-alkanes per mg particulate organic matter (POM) compared to Chinese cooking. They also observed that Chinese cooking has an odd to even carbon preference when carbon number is greater than 23, whilst Western style fast food does not (Zhao et al., 2007a). This is taken as an indication of the high plant wax content of Chinese cooking (Zhao et al., 2007b). The n-alkanes have a C_{max} at C_{25} for western fast food (Zhao et al., 2007a) and meat cooking (Rogge et al., 1991). Chinese cooking exhibits a C_{max} at C_{29} or C_{31} taken as an indication of the presence of vegetables during cooking operations.

4.4. Emissions of Fatty Acids

Meat and oils used in cooking contain fats made up of saturated and unsaturated fatty acid esters of glycerol. The chemical processes that typically occur during high temperature treatment of food are the degradation of sugars, pyrolysis of proteins and amino acids and the degradation of fats (Svendsen et al., 2002). The cooking process leads to production of free fatty acids, free glycerol and mono- and diglycerides (Nolte et al., 1999). Table 12 summarises the concentrations of fatty acids reported in the literature.

In Western fast food cooking, the quantified saturated fatty acids observed range from C_6 to C_{20} with distinct even to odd carbon preference and a predominance of palmitic acid (Zhao et al., 2007a). Chinese cooking was found to emit C_6-C_{24} fatty acids with a similar even to odd carbon preference and palmitic acid preference similar to meat cooking (Rogge et al., 1991; He et al., 2004b) and seed oil cooking (Schauer et al., 2002). The most common unsaturated fatty acids observed were oleic acid and linoleic acid for Chinese cooking (Zhao et al., 2007b; He et al., 2004b). The most prominent organic compound released from American cooking is oleic acid (Rogge et al., 1991; Schauer et al., 1999a; Schauer et al., 2002; He et al., 2004b).

The concentration of emitted saturated fatty acids in western fast food was found to be 13 times higher than in Chinese cooking while unsaturated fatty acid concentrations were only two times higher, attributed to ingredients and cooking temperature. The ratio of oleic acid to stearic acid in western style fast food cooking is less than one, but greater than one in Chinese cooking. This was attributed to the high temperature in fast food which favours degradation of triglyceride and phospholipids to release and evaporate fatty acids and reduce the production of unsaturated acids (Rogge et al., 1991; Zhao et al., 2007a). High concentrations of nonanoic acid emissions are observed in both Chinese and Western style fast food cooking with a higher ratio of nonanoic acid to other acids (C_8-C_{10}) in Western style fast food. Schauer et al. (1999a; Schauer et al., 2002) compared the emissions of fatty acids from different ingredients, such as meat and vegetables. They found that charbroiling hamburger meat released more fatty acids than frying vegetables. They also found that stir frying released more fatty acids than deep frying.

Peanut oil, commonly used in Chinese cooking, was heated in a wok and heated to a temperature of 260°C. Gas phase organic emissions were found to contain several n-alkanoic acids as methyl esters of hexadecanoic acid (palmitic acid), oleic acid (octadecenoic acid) acid and dicarboxylic acid- linoleic acid (octadecadienoic acid). It was concluded that the fatty acids were derived from the tri-acylglycerides and di-acylglycerides of peanut oil (To et al., 2000). These further highlighted the importance of temperature in cooking as the temperature used in the study (260°C) was not sufficient to lead to the complete breakdown of the fatty acid components (To et al., 2000).

4.5. Emissions of Dicarboxylic Acids

Dicarboxylic acids are released from the oxidation of dialdehydes during autoxidation of unsaturated lipids and are generally measured in the range of C_4-C_{11} (Rogge et al., 1991; He et al., 2004b). Hexanedioic acid followed by nonanedoic acid, have been identified as the predominant acids in Western fast food cooking (Zhao et al., 2007a). Nonanedioic acid is the predominant dicarboxylic acid identified from Chinese cooking (He et al., 2004b; Zhao et al., 2007b). Meat cooking showed highest concentration for hexanedioic acid (Rogge et al., 1991, Schauer et al., 1999a) and the study of cooking with seed oil showed a predominance of hexanedioic acid and octanedioic acids (Schauer et al., 2002). A higher concentration of this acid has been observed in western fast food with the amount of dicarboxylic acid per mg of

POM in Chinese cooking being about nearly 30 times less than in Western cooking (Zhao et al., 2007a). This has been attributed to the breakdown of unsaturated fatty acids and unsaturated lipids (Zhao et al., 2007a). A summary of the concentrations of dicarboxylic acids reported in the literature is found in Table 13.

4.6. Emissions of Aldehydes

A recent IARC monograph reported that cooking, in particular frying, generates substantial amounts of certain gaseous pollutants such as formaldehyde (IARC, 2006), acetaldehyde (IARC, 1999), acrylamide (IARC, 1994) and acrolein (IARC, 1995).

Concentration distributions have been found to be similar for Western and Chinese style cooking for most of the aldehydes (Table 14), except for nonanal, which is one order of magnitude higher in Western cooking (Zhao et al., 2007b).

Similar to what was observed for other organic species, the type of ingredient cooked is also key in the release of aldehyde emissions during cooking. The studies of Schauer et al. (1999a; Schauer et al., 2002) show that charbroiling hamburger meat emits more aldehydes than frying vegetables.

Sjaastad et al. (2010) used a model kitchen similar to a Western European restaurant to assess if higher mutagenic aldehydes were emitted during the frying of beefsteak on an electric or gas stove with margarine or soya bean oil as the frying fat oil. It was found that mutagenic aldehydes were detected in the breathing zone of cooks in the range of non-detectable to 61.80 $\mu g/m^3$ (Sjaastad et al., 2010). They also found that higher exposures to these components were more pronounced when frying on a gas stove instead of an electric stove which may cause adverse health effects especially for people occupationally exposed to these fumes (Sjaastad et al., 2010). An earlier study of Sjaastad and Svendsen (2008) had involved the frying of beef steak using margarine, rapeseed oil, soybean oil or virgin olive oil as frying fat in similar conditions as a regular Norwegian home (in terms of ventilation conditions and frying procedure).They recorded mutagenic aldehyde concentrations ranging from non-detectable to 25.33 µg/m^3 (Sjaastad and Svendsen, 2008). They also observed statistically significantly higher levels of mutagenic aldehydes and particles when margarine was used as the cooking fat compared to the other oil.

Amides are formed during cooking (Stadler et al., 2002). N-glycosides formed by reaction of reducing sugars with asparagines - one of the common natural amino acids- when heated, resulted in significant levels of acrylamide (Figueroa et al., 2006). Rogge et al. (1991) reported the presence of several amides in smoke released during charbroiling hamburger meat, such as palmitamide, stearamide, and oleamide. Another nitrogen-containing compound found was N,N-dibutylformamide. Frying hamburgers emits 2.8 mg of amides/kg of meat, whereas gas broiling extra-lean meat increases the amount released by 13-fold (36 mg/kg of meat); doubling the fat content (regular meat) further doubles the amount emitted (70 mg/kg of meat) (Rogge et al., 1991). Zhao et al. (2007c) compared the emissions of several amides in the smoke released during Western and Chinese cooking, and found that Western style fast food cooking released larger quantities of amide compounds.

4.7. Emission of N-alkanones and Lactones and Organic Ions

N-Alkanones (Table 15) are also detected from cooking, with 2-pentadecanone the most prominent alkanone. Concentration distributions have been found to be similar for western and Chinese style cooking (Zhao et al., 2007b) for most ketones, although 2-pentadecanone, 2-hexadecanone and 2-heptadecanone are orders of magnitude higher in Western style cooking.

Lactones (Table 15) are detected from emissions of Western style fast food, meat charbroiling, seed oil and Chinese cooking operations (Zhao et al., 2007a; Zhao et al., 2007b; Schauer et al., 2002; Rogge et al., 1991). They are not emitted in large quantities, but can serve as good cooking tracers. The Western cooking style releases more lactones than Chinese cooking. For both n-alkanones and lactones, and similar to previous trends observed for other organics, temperature during cooking has also been shown to have an influence on their release, with emissions from stir frying higher than those from deep frying (Schauer et al., 2002).

See and Balasubramanian (2008) reported the content of organic ions in the smoke produced when using several cooking techniques. Consistent to the trend observed for other organics, techniques that involve the use of water, such as steaming and boiling, released lower amount of organic ions than those which involve the use of hot oils. Nonetheless, for organic ions, deep-frying releases the highest amount of organic ions (Table 16).

4.8. Emissions of Molecular Markers

These are organic compounds occurring naturally in food which can be used as tracers. Some major biomarkers for food are cholesterol, sterols and monosaccharide anhydrides, as summarised in Table 17. Sterols are widely present in animal and vegetable body tissues with plant lipid waxes and membranes generally comprised of C_{28} and C_{29} pythosterol compounds such as β–sitosterol. Cholesterol is biosynthesised by higher animals and found in body tissues such as animal fats and oils (Rogge et al., 1991; Zhao et al., 2007b).

Molecular markers identified for Chinese and Western cooking are levoglucosan, galactosan and cholesterol (Zhao et al., 2007a; Zhao et al., 2007b; He at al., 2004b) while only cholesterol has been detected for meat cooking (Schauer et al., 1999a; Rogge et al., 1991). Schauer et al. (1996), Schauer and Cass (2000) and Schauer et al. (2002) have also identified cholesterol as a tracer for activities of meat cooking.

Combinations of molecular biomarker compounds may be useful in distinguishing cooking source type. Zhao et al. (2007a) combined concentrations of cholesterol and levoglucosan with other compounds such as β–sitosterol, hexanoic acid and nonanedioic acid and were able to differentiate emissions from western style fast food from Chinese cooking. This was done by considering the ratio of meat to vegetable in both cooking styles as well as the differences in concentration ratios of different chemical species.

The percentages of levoglucosan and cholesterol to total quantified compounds in Western style fast food were observed to be lower than in Chinese cooking indicating that cooking oil may have an effect on the total emission of compounds (Zhao et al., 2007a).

4.9. Emissions of Elemental Carbon and Inorganic Compounds

Cooking fumes contain carbonaceous particles (containing elemental carbon (EC) as well as organic carbon (OC)) mainly within the fine particle fraction of the emission (See and Balasubramanian, 2008). Organic carbon is the major constituent found in cooking fumes (Kleeman et al., 1999; Schauer et al., 1999a; Chow et al., 2004; Kleeman et al., 2008; See and Balasubramanian, 2008). Comparison of different culinary methods (Table 18) showed that those using oil released higher concentrations of EC and OC than those using boiling (i.e. boiling and steaming). EC and OC follow a similar trend to that observed with the release of organic ions, with the highest emissions attributed to deep frying (See and Balasubramanian, 2008).

Particle bound water soluble ions have also been identified in cooking fume exhaust Na^+, K^+, NO_2^-, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-} (Hsieh et al., 2011). See and Balasubramanian (2008) found that no major differences were observed between different cooking techniques (Table 18).

The metal content of the aerosol emitted during cooking was analysed by See and Balasubramanian (2008) during steaming, boiling, stir-frying, pan-frying and deep frying. They found that generally, the higher concentrations were observed in those techniques that used mainly oil, and frequently the highest concentrations were found in the smoke released during deep-frying (Table 18).

5. APPORTIONMENT STUDIES

Source apportionment studies are conducted to identify sources of pollution and the contributions from the various sources to total pollution; eliminating the tendency to emphasize certain sources while ignoring others. Source apportionment aids in the identification of major sources which can be useful in the development of best possible control practices to ensure adequate reduction of pollution.

Early source apportionment studies used mainly data for elements such as Fe, Zn, Pb, Cr, Al and Ni together with inorganic ions as tracers for source identification and as there are usually various sources of the same element it often has proved difficult to identify pollution sources with confidence (Pant and Harrison, 2012). This problem has been reduced with the use of organic compound markers (Lin et al., 2010). Organic compounds are generally representative of their particular pollution sources and their selection for use in receptor models depends on a) the chemical species selected to characterise the source should not be reactive and should be conserved in the atmosphere; b) the source profiles should be linearly independent and c) the uncertainties of measurement should be random, uncorrelated, and normally distributed (Lin et al., 2010).

Receptor modelling of airborne particulate matter involves the application of multi-component chemical composition data to attribute the mass measured in the atmosphere to specific sources of emission. Ambient pollutant measurements are collected at sampling sites to deduce the information on the sources of pollution and how it affects concentrations in the location. Measurements of well as chemical species generated during cooking processes provide a profile for the cooking emissions which in combination with the profile of other sources such as traffic are a useful tool in source profile identification.

The most commonly used receptor model to apportion cooking sources is the Chemical Mass Balance (CMB) model. Other source apportionment studies on cooking emissions have used statistical techniques such as the Diagnostic Ratio, Principal Component Analysis (PCA) and Positive Matrix Factorisation (PMF) for understanding the sources of PM emitted to the atmosphere (Hopke et al., 2003; Robinson et al., 2006; See and Balasubramanian, 2006b; Zhao et al., 2006; Kleeman et al., 2008; Brinkman et al., 2009; Allan et al., 2010; Clougherty et al., 2011).

5.1. Chemical Mass Balance (CMB) Model

This model requires chemical source profiles which describe the specific chemical composition of emitted particles as input in order to quantify those sources within the data and apportion for the sources in the atmosphere. Source profile and fitting specie selection for CMB analysis is a sensitive process which requires careful consideration as the profiles must be adequately different for all the sources included in the model to ensure proper apportionment at the receptor. The source emissions in the profile should not interact with each other during transport and also their chemical and physical properties should be practically constant during their transport from source to receptor (Chow and Watson, 2002). Some sources do not have existing source signatures or ones specific to the location being studied. In such cases profiles are borrowed from other cities with similar pollution sources, which may not represent the source of emissions in the sampling area of interest perfectly (Lee et al., 2008b; Pant and Harrison, 2012). Similarly when source profiles are too similar, the CMB model yields large uncertainties in source contributions (Chow and Watson, 2002). Generally the species used in most CMB models are from the source profiles available through the USEPA Speciate database. The source profiles consist of both organic and inorganic aerosol constituents (Schauer and Cass, 2000). The source profiles generally used for charbroiled meat cooking, gasoline vehicle emissions, diesel truck emissions and paved road dust (Hildemann et al., 1991a; Schauer et al., 1999a; Schauer et al., 1999b; Fraser et al., 2002) and for vegetative detritus and natural gas combustion (Rogge et al., 1993a; Rogge et al., 1993b) are mainly obtained from studies in the United states such as Texas and Los Angeles (Zheng et al., 2002; Fraser et al., 2003). However, the use of source profiles from locations other than the area of study might introduce uncertainty in the apportionment of some source contributions (e.g. road dust; soil).

A review by Lin et al., 2010 identified the need for a more specified organic compound markers for some particle sources such as non-meat cooking particle emissions, paved roads, fugitive dust, biogenic, and agriculture emissions as well as a source contributions library for particular locations, for use in CMB models.

Mass balance models that have been applied in indoor environments have usually taken into consideration various combustion related activities like home heating and cooking; and also activities such as cleaning and infiltration of outdoor air resulting in a contribution from outdoor sources (Millar et al., 2010). CMB analyses have made use of different combinations of source profiles for the estimation of the contribution of food cooking emissions to ambient particle concentrations. Several food cooking source profiles have been published (Rogge et al., 1991; Nolte et al., 1999; Schauer et al., 1999a; Rogge, 2000; Schauer and Cass, 2000; Chow et al., 2004; Robinson et al., 2006). These cooking profiles contain speciated organic data with a range of emission composition and rates mainly dependent on cooking technique and food type. The use of source profiles and fitting species require that the model must include all major sources and the species should be conserved during transport from source to receptor (Watson et al., 1998; Robinson et al., 2006). Organic molecular markers such as oleic acid, cholesterol and palmitic acids are used to estimate the contribution of food cooking emission to primary organic aerosol (Rogge et al., 1991; Schauer et al., 1999a; Robinson et al., 2006). Cooking has in some cases been classified with agricultural burning and wood smoke due to emissions of similar organic compounds from the processes (e.g. levoglucosan and cholesterol) (Chow and Watson, 2002).

Using the chemical mass balance model to apportion for the sources of $PM_{2.5}$ in a city has been exemplified by Schauer et al. (1996). They found that the organic carbon mass contribution of PM due to meat cooking was about 23% in Los Angeles, which was comparable to findings by Hildemann et al. (1991b) and Rogge et al. (1991) in earlier studies. The CMB approach was also used to find that meat cooking contributed between 20% and 75% to ambient concentrations of PAHs in residential areas (Venkataraman and Friedlander, 1994).

Robinson et al. (2006) made use of the basic set of source classes and compounds developed by Schauer et al. (1996) and Schauer and Cass (2000). The CMB analysis included source profiles of eight source classes: diesel vehicles, gasoline vehicles, road dust, biomass combustion, cooking emissions, coke production, vegetative detritus and cigarettes. However, Robinson et al. (2006) reported that a large systematic bias was generally observed in CMB models due to differences in species and source profile marker to organic carbon ratios. The ambient ratio of palmitic acid to oleic acid was higher than expected from other published literature, reflecting problems presented by source profile variability. This signified that the CMB could not fit both the acids simultaneously, even though ambient concentrations showed a strong correlation indicating they were from the same source. The use of the two alkanoic acids as fitting species in the model in addition to other cooking markers however provided a better model for source contribution estimates, further highlighting the importance of molecular markers in source apportionment analysis. The model apportioned 320 ± 140 ng C/m^3 (10% of the study average ambient organic carbon) to food cooking emissions.

In the south-eastern United States, particle phase organic compounds were used in a CMB model to understand how the primary source contributions of particulate matter and fine particulate organic carbon concentrations varied with seasons (Zheng et al., 2002). The results indicated that wood smoke, meat cooking and gasoline powered motor vehicles contributed to $PM_{2.5}$ organic carbon concentrations in the range of 25-66%, 5-12% and 0-10% respectively, with minor contributions from paved road dust and vegetative debris. Between 2003 and 2004, Zheng et al. (2002) sampled again four sites of the Carbonaceous Aerosol Characterization Experiment (CACHE) and used CMB and carbon isotope analysis to further understand variability of organic components and source contributions to fine organic carbon and $PM_{2.5}$ in the south-eastern United States. Meat cooking was again identified as a primary emission source of OC along with eight other sources including wood combustion (which was the most dominant source, 14-23%), gasoline engine exhaust, diesel engine exhaust, vegetative debris, cigarette smoke, road dust and natural gas exhaust (Zheng et al., 2006). The carbon isotope analysis showed results consistent with the CMB analysis, with both identifying that urban areas had a high fossil fraction of carbon.

Meat cooking operations were also identified as one of the sources of ambient fine particulate matter in Houston Texas with a contribution of between 0.9-1.3 $\mu g/m^3$ at urban sites and 0.7 $\mu g/m^3$ at background sites (Fraser et al., 2003). Other important sources identified were diesel exhaust (1.6- 3.7 $\mu g/m^3$ at the urban site), gasoline powered vehicles, paved road dusts and wood combustion. These sources were identified using eight source profiles in the model which used 24 molecular markers.

CMB analysis of organic molecular marker data in Pittsburgh Pennsylvania also identified cooking as an anthropogenic source of organic aerosol and $PM_{2.5}$ and found that secondary organic aerosols were actually the major components of organic carbon (OC) in Pittsburgh in all seasons, whilst primary sources affected ambient concentrations only occasionally (Subramanian et al., 2007). This is unlike other locations where the contributions of meat cooking and traffic are unaffected by season and show no seasonal variation (Fraser et al., 2003).

In Atlanta meat cooking was among the major contributors of fine OC identified with a range of 7-68% (average 36%) in summer periods and 1-14% (average 5%) during the winter months. Gasoline and diesel exhaust contributed 21% and 20% respectively to OC during the summer and 33% to 4% during the winter, with wood combustion being an additional source during that period contributing an average of 50% of OC probably due to use of wood for heating of houses in winter and the festive period.

Lee et al. (2008a) used CMB and UNMIX receptor models to apportion sources of $PM_{2.5}$ aerosols collected between March 2001 and February 2001 in Korea. The CMB results identified diesel vehicle exhaust as the major contributor to PM (33%), with meat cooking contributing 12% of the $PM_{2.5}$ mass measured. Other sources identified were secondary sulphate (15%), secondary organic carbon (9%), urban dust, Asian dust, biomass burning, sea salt, residual oil combustion, gasoline vehicle exhaust, automobile lead and unknown components (Lee et al., 2008a). The UNMIX on the other hand only identified seven $PM_{2.5}$ sources and apportioned 30% of the mass to diesel vehicles, 17% to secondary sulphate, 15% from biomass burning, secondary nitrate (13%), gasoline vehicle, secondary organic carbon and Asian dust, but not cooking sources.

In Beijing (China), cooking was among the seven emission sources of particulate organic matter identified (Wang et al., 2009). Like other studies, the other sources included gasoline /diesel vehicles and vegetative burning in addition to coal burning in this case. The CMB model established that contribution from cooking was actually higher during the summer, whilst the biomass burning contribution was the highest during the winter (Wang et al., 2009).

At a heavily polluted urban site in central California, molecular marker CMB was carried out on ultrafine airborne particulate matter. Meat cooking was identified to account for 33-67% of the $PM_{0.1}$ at the urban site compared to diesel engines which accounted for 15-21%. At a rural site meat cooking contributed 22-26% of the $PM_{0.1}$ OC, and diesel engines accounted for 8-9% (Ham and Kleeman, 2011). As regards the organic carbon of the larger $PM_{1.8}$ particles, meat cooking contributed less to the PM at the rural site than diesel engines; while at the urban site the contribution from meat was still higher than from diesel engines. Lower OC contributions were estimated compared to the measured concentrations, which implies an unidentified contribution of either secondary organic aerosol (SOA) or oxidized primary organic aerosol (POA). They estimated that meat cooking led to 0.01-0.025 $\mu g/m^3$ of $PM_{0.1}$ (Ham and Kleeman, 2011).

The above studies have illustrated the importance that cooking has as a source contributing to organic aerosol. The studies have also identified that in order to reduce particle pollution, especially in populated metropolitan areas, efforts should focus on controlling cooking as well as other particle sources such as traffic emissions.

5.2. Diagnostic Ratio and Ratio:Ratio Plots

Diagnostic ratio is a binary ratio method for source identification which involves comparing ratios of pairs of frequently found compounds emitted to distinguish between different known sources. It is usually used with caution as a) it is often difficult to discriminate between some sources; b) its interpretation depends on the ratio considered; and c) the profile chosen can vary in the presence of highly reactive compounds and thus can introduce bias.

Similarly, plots of concentrations of different markers against each other has been a useful tool to examine correlations among different markers. Robinson et al. (2006) made plots of various ambient species, focussing on only five important markers for cooking; n-hexadecanoic (palmitic) acid, n-octadecanoic (stearic) acid, 9-hexadecenoic (palmitoleic) acid, 9-octadecenoic (oleic) acid, and cholesterol. Oleic and palmitoleic acid concentrations as well as stearic and palmitic acid concentrations were well correlated with a slope of one implying a single dominant source for the alkenoic acids. Only a slight correlation was observed between cholesterol and palmitic acid but the scatter was comparable to measurement uncertainty, so the sources could have been the same. Saturated and unsaturated acids however, when plotted against one another showed no correlation (e.g. palmitic acid against palmitoleic acid) (Robinson et al., 2006). Assuming they are chemically stable, it was concluded that these acids have different dominant sources. Ratio–ratio plots aid in the inference of potential source profiles. These plots should be examined using different ratio species and different combinations of source specific markers to develop a good understanding of ambient data and source profiles. Robinson et al. (2006) made use of such plots of acids (two alkanonic and alkenoic) normalised by cholesterol and observed a good correlation in ambient data by displaying well organised ratio to ratio plots.

Normalisation is a general approach to reduce the anomalies in large data sets. Scatters along the diagonals of the plots can be attributed to measurement uncertainty or the variability of emissions of species. The reference specie used to normalise the concentrations of the two target species affects the exact organisation of data in a ratio-ratio plot. Changing the reference specie should not alter the likely conclusion about the source profile combination (Robinson et al., 2006) as illustrated in Figure 2. The change however causes the location of both the source profiles and ambient data in the plots to shift. Cholesterol has been found to be a good reference for food cooking markers and so has been generally used.

Diagnostic ratios for PAHs, such as BeP/(BeP + BaP), IND/(IND + BghiP), Cor/BeP and BghiP/BeP have been widely used in the investigation of their origins and to aid in the identification of the possible emission sources in air samples. See et al. (2006) used this technique in combination with other statistical methods. The ratios were calculated to provide insight into the origins as well as markers or tracers of pollution sources. The ratios of Phe/(ant + Phe) (structural isomers of molecular weight MW = 178), Flt/(Flt + Pyr) (MW = 202), BaA/(BaA + Chr) (MW = 228) and Ind/(Ind + BPe) (MW = 276) were evaluated based on mean concentrations (See et al., 2006).

ANT/(ANT + PHE) ratios were used by Gu et al. (2010) to indicate combustion sources while FLU/(FLU+PYR) ratio < 0.2 was taken as an indication of PAHs from petroleum sources, 0.4–0.5 for combustion of fuel and > 0.5 for grass combustion (Miguel and Pereira, 1989; Gu et al., 2010).

Table 19 shows some diagnostic ratios obtained for culinary techniques and from vehicle emissions as a comparison. The ratios from See et al. (2006) and See and Balasubramanian (2008) are relatively unaffected by type of cooking and there is some overlap in cooking ratios with those from traffic, making quantitative differentiation impossible.

Some size resolved source apportionment studies have used molecular marker to organic carbon ratios as chemical signatures for source contribution identification and good tracers have been identified for molecular markers with similar size distribution for EC and OC (Kleeman et al., 2008). Kleeman et al. (2008) found that the size distribution for cholesterol was highly correlated ($R^2 > 0.9$) with both OC and EC size distributions further suggesting that cholesterol can serve as an appropriate tracer for meat cooking contributions, as suggested by previous authors (Robinson et al., 2006). The most abundant PAH measured in emissions from meat cooking was phenanthrene, with smaller concentrations of fluoranthene and pyrene. Higher ambient concentrations of these compounds were observed from other sources such as diesel engines (Kleeman et al, 2008).

In Xiamen, China, diagnostic ratios and PCA were used to identify that cooking sources, gasoline and diesel vehicle exhaust, industry emissions and coal combustion were the sources of particle bound PAH (Hong et al., 2007).

Ho et al. (2010) used the ratio of octadecanoic acid to hexadecanoic acid to identify cooking emissions as a source of pollution from a set of organic species measured during the air quality sampling campaign in Beijing in 2006. The ratio for cooking was between 0.39 and 0.85 with an average value of 0.36 (Ho et al., 2010).

5.3. Multivariate Statistical Methods

Principal Component Analysis is multivariate statistical technique which reduces the number of variables and groups into factor variables with similar characteristics. The set variables are transformed into a smaller set of linear combinations to analyse the variance of the original set. The selection of compounds and elements used in the model are based on their signal to noise ratio, their suitability for use as definite source markers and their percentage of values above the quantification limit (Brinkman et al., 2009).

PCA has been found to assist effectively in identification of factors affecting personal exposure to PM using organic tracers by Brinkman et al. (2009). They measured a broad distribution of organic tracer compounds in PM personal samples and found that multiple organic marker species for the same source loaded the same factor, with meat cooking being observed to have high correlation with organic carbon concentrations ($r = 0.84$) (Brinkman et al., 2009).

As most primary tracers are emitted from multiple sources, an assemblage of compounds as a group, rather than an individual tracer is used for indicating the quantity of cooking aerosol in the atmosphere. Cholesterol supplemented with monoglycerides, oleic acid and nonanal have been identified as potential primary tracers for meat cooking (Nolte et al., 1999).

PCA was also used to analyse sources of PM_{10} using concentrations of ambient air polycyclic aromatic hydrocarbons bound to PM at various sites consisting of a garden site, industrial-traffic intersection, a residential site and an island site in the city of Xiamen in China. In the summer period, five components were identified by the model, with 12% of the variance attributed to cooking fuels, which was indicated by high loadings of Chry and moderate loadings of BaA, Acen and An (Hong et al., 2007). The highest contributions were actually seen from gasoline and diesel vehicles exhausts throughout the study period.

$PM_{2.5}$ measurements from some sites in California (N=23) were analysed using Unmix and PMF. Eight factors were obtained for both models, which included cooking, marine sea salt, fugitive dust, agriculture-dairy, secondary aerosol motor vehicle and residential wood combustion (Chen et al., 2007).

6. CONCLUSION

Cooking has been shown to be a source of particulate matter both indoors and outdoors in cities around the world. Apportionment studies that have identified this source have made use of source profiles mainly derived in the United States as the earlier studies were carried out in that region.

The composition of cooking aerosol is highly diverse, depending upon factors such as the raw food composition, cooking oil (if used), cooking temperature and cooking style. This diversity implies that identification and quantification of cooking aerosol in the atmosphere is very difficult unless the source characteristics at the measurement location are well known. While further knowledge of source-related chemical composition would be beneficial, quantitative source apportionment will remain imprecise and potentially inaccurate in situations with mixed cooking source types contributing to atmospheric concentrations. This provides a considerable challenge to Chemical Mass Balance models where it is necessary to input a source profile. It is less problematic for the now common studies in which PMF is used to disaggregate mass spectral data from AMS instruments. However, as yet such studies are unable to identify specific cooking styles and considerable skill is needed to achieve an optimal separation of the cooking organic aerosol (COA) factor from other factors contributing to organic carbon concentrations.

There is a need for an enhanced understanding of cooking emissions around the world and of the effects upon human health. This review has found that Chinese cooking can lead to a much greater contribution of PAHs to particulate organic matter relative to western-style fast food cooking. The studies reviewed identified potential candidates of tracers for cooking emissions as tetradecanoic, hexadecanoic and octadecanoic acids, nonanal, lactones and levoglucosan. Western-style fast food cooking tracers were 9-octadecenoic, hexanedioic and nonanedioic acids; whilst Chinese cooking tracers were oleic acid, mannosan and galactosan. Further studies will go a long way to provide further insight to verify these choices and to determine whether these choices vary with geographical location and other culinary techniques.

This review also shows that cooking aerosol comprises particles largely generated in the ultrafine size region. These particles have an associated large surface area and are capable of deposition in the respiratory system with high efficiency. Improved capture of cooking emissions above the stove by fume extraction and filtration would contribute substantially to improvements in both indoor and outdoor air quality, and hence a reduction in human exposure.

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TABLE LEGENDS

Table 1. General cultural styles of cooking. Common ingredients, oils and spices used

Table 2. National emissions rate (tonnes/year) of criteria pollutants from commercial cooking in the USA (Roe et al., 2005) and for highway vehicles (Chappell et al., 2003)

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Table 9. Polycyclic aromatic hydrocarbons emitted from cooking food – indoor concentrations and emission factors (see columns for units)

Table 10. Polycyclic aromatic hydrocarbons in fumes from heated oils - indoor concentrations and emission factors (see columns for units) - and in uncooked oil

Table 11. N-alkanes emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 12. Fatty acids emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 13. Dicarboxylic acids emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 14. Aldehydes emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 15. Ketones and lactones emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 16. Concentrations of organic ions emitted from cooking food

Table 17. Molecular markers, amides and other organic compounds emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 18. EC/OC, metals and inorganic ions emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Table 19. Comparison of diagnostic ratios of PAHs

FIGURE LEGENDS

Figure 1. Break down products of triglycerides (Nolte et al., 1999)

Figure 2. Marker to OC ratio for meat cooking profiles (Robinson et al., 2006)

Table 1. General cultural styles of cooking. Common ingredients, oils and spices used

COOKING STYLE	METHOD	INGREDIENTS	OIL	SPICES
Chinese	Stir fry, simmer, steam roast stew	MAIN- Meat type- Pork, sea food, poultry, beef, Vegetable-cabbage, carrots, cucumber, broccoli OTHERS- Eggs, ginger, hot pepper, scallion, garlic, rice, flour, peanuts, fruits	Soy beans Peanut oil Canola oil	essence of chicken, salt, peanut oil, light soy source, sugar
Western	Grill, broil, roast, deep fry, stew,	MAIN -Meat type-beef, chicken Vegetables-carrots, broccoli, OTHERS - milk, flour	Corn oil, vegetable oil olive oil,	Salt, black pepper, garlic, basil, parsley
Fast Food	Deep fry, stew	MAIN - Meat type- beef, chicken, Potatoes	Vegetable, butter, corn oil	Salt
African	Deep fry, boiling, stew	MAIN- Meat- beef, chicken, fish Vegetables-spinach OTHERS- yam, rice, plantain, banana.	Ground nut oil, palm oil, vegetable oil	Thyme, curry
Indian	Deep fry, boiling, stew	MAIN- Meat- fish and chicken OTHERS- rice, flour, beans, lentils, pearl millet, wheat flour, milk, yoghurt, plantain. .	Vegetable oil, peanut oil, mustard oil, coconut oil, sesame oil,	Chilli pepper, black pepper, mustard seed, cumin, turmeric, ginger, cardamom, cinnamon, clove, garam masala, coriander, garlic, mustard seeds, nutmeg, mint
Malay	Deep fry, boiling, stew	MAIN- Meat-Fish, squids, prawns, crabs , chicken, beef and mutton. OTHERS-rice, noodles, yoghurt, coconut milk.	Vegetable oil, coconut oil, sesame oil,	Lemongrass, shallots, ginger, chillies, garlic, turmeric, lime leaves, laksa leaves, wild ginger flower buds or torch ginger and screwpine leaves, fennel, cumin, coriander, cardamom, cloves, star anise, mustard seeds, and nutmeg

Table 2. National emissions rate (tonnes/year) of criteria pollutants from commercial cooking in the USA (Roe et al., 2005) and for highway vehicles (Chappell et al., 2003)

Pollutant	Total charbroiling	Deep frying	Flat griddle frying	Clamshell griddle frying	Under-fired charbroiling	Conveyorized charbroiling	Highway vehicles
VOC	115	1,170	39	940	7,200	2,100	4,400,000
CO	33,000		1,900		23,700	7,400	48,400,000
$PM_{2.5}$	79,300		11,900	910	58,300	8,200	135,000
PM_{10}	85,500		15,700	1,100	60,300	8,500	192,000
PAH total	206		41		122	43	

Table 3. Particle mass and number concentration measured in indoor environments close to cooking activities

Reference	Location	Comment	Concentration (µg/m^3)	Particle Number concentration (part/cm^3)
Li et al., 1993	Taiwan	Chicken		1.2-2.6 x10^5
Siegmann and Sattler, 1996	Switzerland	Rapeseed Oil		2.5-4.5 x10^5
Abt et al. 2000	US	Frying - $PM_{0.02-0.5}$	29	
		Frying – $PM_{0.7-10}$	19	
		Barbequing - $PM_{0.02-0.5}$	57	
		Barbequing - $PM_{0.7-10}$	12	
		Oven cooking - $PM_{0.02-0.5}$	50	
		Oven cooking – $PM_{0.7-10}$	8	
		Sauteing - $PM_{0.02-0.5}$	42	
		Sauteing – $PM_{0.7-10}$	294	
		Toasting - $PM_{0.02-0.5}$	45	
		Toasting – $PM_{0.7-10}$	8	
Dennekamp et al., 2001	UK	Frying vegetables (500 g) – gas stove		1.4 x10^5
		Frying bacon (4 racers) – gas stove		5.9 x10^5
		Frying vegetables (500 g) – electric stove		0.11 x10^5
		Frying bacon (4 racers) – electric stove		1.6 x10^5
		Bake cake – gas oven		0.9 x10^5
		Bake cake – electric oven		0.3 x10^5
		Roast meat and potatoes – gas oven		1.2 x10^5
		Roast meat and potatoes – electric oven		0.2 x10^5
		Toast –gas grill		1.4 x10^5
		Toast – electric grill		1.4 x10^5
Lee et al. 2001	China	$PM_{2.5}$ Chinese hot pot restaurant	81	
		$PM_{2.5}$ Chinese dim sum restaurant	28.7	
	Hong Kong	$PM_{2.5}$ Western Canteen	21.9	
Levy et al. 2002	USA	$PM_{2.5}$ food court	200	1.4 x 10^5
Wallace et al., 2004	USA	Cooking dinner		1.3 x10^4
		Cooking breakfast		5.7 x10^3

Table 3 Cont. Particle mass and number concentration measured in indoor environments close to cooking activities

Reference	Location	Comment	Concentration (μg/m^3)	Particle Number concentration (part/cm^3)
He et al., 2004a	Australia	$PM_{2.5}$ (48h) cooking	37	1.27 x 10^5
		$PM_{2.5}$ (48h) cooking pizza	735	1.37 x 10^5
		$PM_{2.5}$ (48h) frying	745	1.54 x 10^5
		$PM_{2.5}$ (48h) grilling	718	1.61 x 10^5
		$PM_{2.5}$ (48h) kettle	13	1.56 x 10^4
		$PM_{2.5}$ (48h) microwave	16	1.63 x 10^4
		$PM_{2.5}$ (48h) oven	24	6.15 x 10^4
		$PM_{2.5}$ (48h) stove	57	1.79 x 10^5
		$PM_{2.5}$ (48h) toasting	35	1.14 x 10^5
		$PM_{2.5}$ residential kitchen	535.4	2.86 x 10^4
He et al., 2004c	China	$PM_{2.5}$ Hunan restaurant	1406	
	China	$PM_{2.5}$ Cantonese restaurant	672	
See and Balasubramanian, 2006a, See and Balasubramanian, 2008	Singapore	$PM_{2.5}$ Steaming	66 ± 7.6	5.4 x10^4
		$PM_{2.5}$ Boiling	81 ± 9.3	6.9 x10^4
		$PM_{2.5}$ Stir-Frying	120 ± 13	9.3 x10^4
		$PM_{2.5}$ Pan-Frying	130 ± 15	11 x10^4
		$PM_{2.5}$ Deep-Frying	190 ± 20	59 x10^4
See and Balasubramanian, 2006b	Singapore	Stir-fry in a wok typical Chinese food commercial food stall $PM_{2.5}$	286	7.7 x 10^5
See et al., 2006	Singapore	$PM_{2.5}$ Chinese stall	202 ± 141	
		$PM_{2.5}$ Malay stall	245 ± 77	
		$PM_{2.5}$ Indian stall	187 ± 44	
		$PM_{2.5}$ Background	29 ± 8	
Hussein et al., 2006	Czech Republic	Cooking in a stove, frying, oven		0.6-1.8 x10^5
Sjaastad et al., 2008	Norway	Frying Beefsteak		1.2 x10^3 [(a)]
Yeung and To, 2008	Hong Kong	Frying vermicelli with beef		89 x10^5
		Pan-frying steaks		8.5 x10^5
		Pan-frying chicken fillets		8.5 x10^5
		Pan –frying pork chops		8.8 x10^5
		Hot oil test		6.4 x10^5

Table 3 Cont. Particle mass and number concentration measured in indoor environments close to cooking activities

Reference	**Location**	**Comment**	**Concentration (µg/m^3)**	**Particle Number concentration (part/cm^3)**
Buonanno et al., 2009	Italy	Grilling in a gas stove at maximum power Cheese	283	1.1×10^5
		Wurstel sausage	352	1.3×10^5
		Bacon	389	1.0×10^5
		Eggplant	78	1.2×10^5
		Frying 50 g of chips in a gas stove at maximum power with Olive oil	118	1.2×10^5
		Peanut Oil	68	1.2×10^5
		Sunflower Oil	60	1.1×10^5
		Frying 50 g of chips using an electrical pan with sunflower oil	12	1.4×10^4
		olive Oil	27	2.6×10^4
		peanut Oil	13	1.5×10^4
Buonanno et al., 2010	Italy	PM_1 range	10-327	$1.1\text{-}9.8 \times 10^5$
		$PM_{2.5}$	12-368	
		PM_{10}	15-482	
Buonanno et al., 2011	Italy	Grilling 100 g cheese		1.8×10^5
		Frying 100 g cheese		2.8×10^5
		Grilling 100 g bacon		2.0×10^5
		Frying 100 g bacon		2.8×10^5
		Grilling 100 g pork meat		1.6×10^5
		Frying 100 g pork meat		2.3×10^5
		Grilling 100 g eggplant		1.6×10^5
		Frying 100 g eggplant		2.3×10^5
		Grilling 100 g chips		1.5×10^5
		Frying 100 g chips		2.3×10^5
		Grilling 100 g onion		1.6×10^5
		Frying 100 g onion		2.4×10^5
Glytsos et al. 2010	Czech Republic	Frying a slice of onion with olive oil – electric griddle		1.2×10^5

Table 3 Cont. Particle mass and number concentration measured in indoor environments close to cooking activities

Reference	Location	Comment	Concentration (μg/m^3)	Particle Number concentration (part/cm^3)
Huboyo et al., 2011	Japan	Tofu boiling	22.8 (1.21-294)	6.8 x10^{2} [(a)]
		Tofu frying	41.2 (1.76-707)	3.0 x10^{2} [(a)]
		Chicken boiling	30.8 (5.36-1,082)	2.5 x10^{2} [(a)]
		Chicken frying	101.6 (1.67-1,366)	1.1 x10^{2} [(a)]
To and Yeung, 2011	Hong Kong	Frying vermicelli with beef – gas cooking (Domestic kitchen) – PM_{10}	1,330	
		Frying vermicelli with beef – electric cooking (Domestic kitchen) – PM_{10}	1,030	
		Pan Frying of meat – gas cooking (Domestic kitchen) – PM_{10}	1,020	
		Pan Frying of meat – electric cooking (Domestic kitchen) – PM_{10}	520	
		Deep frying of chicken wings – gas cooking (Domestic kitchen) – PM_{10}	890	
		Deep frying of chicken wings – electric cooking (Domestic kitchen) – PM_{10}	680	
		Deep frying of tofu – gas cooking (Commercial kitchen) – PM_{10}	4,720	
		Deep frying of tofu – electric cooking (Commercial kitchen) – PM_{10}	3,980	
		Griddle frying of meat – gas cooking (Commercial kitchen) – PM_{10}	2,260	
		Griddle frying of meat – electric cooking (Commercial kitchen) – PM_{10}	2,600	

(a) Particles with diameter 0.3 μm <Dp<0.5 μm

Table 4. Size distribution studies for cooking aerosols

Study and Country	Location and duration	Sampling method (a)	Food	Environmental condition
Hildemann et al., 1991a USA	Commercial scale kitchen Sampling port located above the cooking surface, below the extractor fan.	Electrical Aerosol Analyser TSI 3030	Meat cooking during frying and charbroiling extra-lean and regular hamburger meat	Mechanical ventilation
Li et al., 1993 Taiwan	Domestic kitchen with a gas stove Sampling ports 3m away from the gas stove	DMA TSI 3932; CPC TSI 3022	scrambling eggs, frying chicken, and cooking soup	Windows and doors were closed during measurements
Siegmann and Sattler, 1996 Switzerland	Laboratory kitchen Hot oil at 223, 236 and 256°C.	SMPS	Rapeseed oil	Closed window
Abt et al., 2000 USA	Domestic kitchen with gas and electric stoves. Samples collected over 6-day periods Equipment located in an indoor location adjacent to the kitchen.	SMPS TSI 3934; Electrostatic classifier TSI 3071A; CPC TSI 3022a; APS TSI 3310A	Frying, sautéing, barbequing, oven cooking and toasting	Open doors
Dennekamp et al., 2001 UK	Laboratory kitchen with gas and electric stoves Sampling inlet at face level in front of the cooker	SMPS TSI 3934; CPC TSI 3022A	Vegetable oil used to stir-fry 500 g of vegetables and also 5 rashers of bacon	No ventilation. All windows and doors were closed.
Wallace et al., 2004 USA	Domestic kitchen using gas stove Measurements performed in the duct of the ventilation system.	DMA Electrostatic classifier TSI 3071; CPC TSI 3010; APS TSI 3320; Optical particle counter model 500-I Climet Instruments	Deep frying (peanut oil) of flour tortillas; stir fry (peanut oil) vegetables and frying eggs with butter.	No ventilation. Forced ventilation (recirculation of air)

(a) DMA - Differential Mobility Analyser; SMPS - Scanning mobility particle sizer; APS - Aerodynamic particle sizer; CPC - Condenser Particle Counter

Table 4 Cont. Size distribution studies for cooking aerosols

Study and Country	Location and duration	Sampling method (a)	Food	Environmental condition
Wallace et al., 2006 USA	Personal and indoor (living room) measurements for 7 days in free-style living conditions.	Real time concentrations: Personal and indoor sampling using optical particle counter (personal MIE DataRAM) Integrated exposure: Personal – PEM gravimetric monitor Indoor – Harvard impactor monitor	Normal cooking activities	No control on ventilation
Hussein et al., 2006 Czech Republic	Domestic kitchen using an electrical stove and adjacent living room. Continuous measurement for 15 days at 3 min intervals Sampling ports at 1.5m from the ground and 1m (kitchen) and 5m (adjacent room) from the stove.	SMPS TSI 3934C;	Normal cooking activities (e.g. boiling potatoes, soup, rice, pasta, frying potatoes or pancakes, toasting and baking chicken in the oven.	Natural ventilation
See and Balasubramanian, 2006a, b Singapore	Domestic kitchen Inlets located 0.5 m above the gas stove	SMPS TSI 3034	Steaming, boiling, pan-frying, stir-frying, and deep-frying a pack of 150 g plain tofu (soybean curd) using corn oil.	No ventilation. All windows and doors were closed.
Yeung and To, 2008 China	Commercial kitchen with 2 gas stoves, and an electric griddle	SMPS TSI 3934; electrostatic classifier TSI 3071A; CPC TSI 3022,	Stir frying Chinese food and frying western food	No ventilation. All windows and doors were closed.
Sjaastad et al., 2008 Norway	Laboratory kitchen ($19m^2$) with electric stove in the middle of the floor with kitchen hood and adjoining room. Sampling ports 1m above the floor (all location) and 1.3 away from the stove (in the kitchen).	Kitchen: Particle counter Met One Model 237B; SMPS TSI-3936 Adjoining room : Electrostatic classifier TSI-3080 Ultrafine CPC TSI-2025A	Frying a beef steak with margarine at maximum power.	Mechanical ventilation.

(a) DMA - Differential Mobility Analyser; SMPS - Scanning mobility particle sizer; APS - Aerodynamic particle sizer; CPC - Condenser Particle Counter

Table 4 Cont. Size distribution studies for cooking aerosols

Study and Country	Location and duration	Sampling method (a)	Food	Environmental condition
Yeung and To, 2008 Hong Kong	Laboratory kitchen (168m^3) with gas stove and electric griddle. Fume hood installed above cooking area.	SMPS TSI 3734; Electrostatic classifier TSI 3071A; CPC TSI 3022A	Chinese style – frying vermicelli with beef- in gas stove; Western style – pan-frying steaks, chicken fillets or pork chops - in electric griddle and hot oil in electric griddle.	No ventilation
Buonanno et al., 2009 Buonanno et al., 2011 Italy	Open plan laboratory kitchen (80m^2) using gas and electrical stoves. Sampling 2 meters away from the stove for 8-10 mins.	SMPS TSI 3936 APS TSI 3321 CPC TSI 3775 Nanometer Aerosol sampler (TSI 3089)	Fry and grill different ingredients: pork meat, eggplant, chips and cheese, bacon and oils (olive oil, peanut oil and sunflower oil)	Minimum ventilation - doors and windows closed. Normal ventilation -doors and windows closed with mechanical ventilation in operation.
Buonanno et al., 2010 Italy	15 pizzerias Sampling 2 meters away from the stove for 8-10 mins.	SMPS TSI 3936 APS TSI 3321 CPC TSI 3775 Nanoparticle surface area monitor TSI 3550 ; PM_{10}, $PM_{2.5}$ and PM_1 measured using a DustTrak DRX Aerosol Monitor TSI 8534	Baking pizza	Normal commercial kitchen ventilation.
Glytsos et al., 2010 Czech Republic	Laboratory room (60m^3) Electric stove Sampling ports 0.9 m above the floor.	DustTrak Aerosol Monitor TSI 8520; P-Trak Ultrafine particle counter TSI 8525 ; GRIMM SMPS+C system - GRIMM, CPC Model 5.403 and Long Vienna DMA.	Frying half of an onion diced in hot olive oil (15 mL).	Mechanical ventilation using the air conditioning system.
Huboyo et al., 2011 Japan	In a kitchen (8.5 m^2) with fumehood and adjoining room (3 m^2). Cooking with single gas stove at medium setting. Sampling ports 1.1m away from the stove (in the kitchen) and 5 m away in the adjoining room.	Sioutas cascade Impactor (SKC); $PM_{2.5}$ UCB optical particle counter (Barkeley Air Monitoring Group	Frying in sunflower oil and boiling 400 g of soybean curd (tofu) and 400 g of chicken	Ventilation system (standard exhaust fan); Natural ventilation (windows opened)

(a) DMA - Differential Mobility Analyser; SMPS - Scanning mobility particle sizer; APS - Aerodynamic particle sizer; CPC - Condenser Particle Counter

Table 5. Particle diameter mode (i.e. diameter representing highest particle number concentration) of particle number size fraction distribution from cooking activities

Reference	Location	Comment	Diameter (nm)
Li et al., 1993	Taiwan	Frying Chicken	30-50
Siegmann and Sattler, 1996	Switzerland	Rapeseed Oil	30-100
Kleeman et al., 1999	USA	Meat charbroiling	180-320
Abt et al., 2000	US	Size range Increasing diameter during cooking Oven cooking event	20-70
Wallace et al., 2004	USA	Cooking dinner	18-50
		Cooking breakfast	10-50
Yeung and To, 2008	Hong Kong	Frying vermicelli with beef	140
		Pan-frying steaks	150
		Pan-frying chicken fillets	115
		Pan –frying pork chops	102
		Hot oil test	107
Buonanno et al., 2009	Italy	Grilling in a gas stove at maximum power Bacon	50
		Cheese	40
		Eggplant	20
		Wurstel sausage	40
		50 g of chips fried with sunflower oil	50
		50 g of chips fried with olive Oil	61
		50 g of chips fried with peanut Oil	50
		50 g bacon grilled on a gas stove	60
Glytsos et al., 2010	Czech Republic	Frying a slice of onion with olive oil	20 – 45
Buonanno et al., 2011	Italy	Frying 100 g mozzarella	80
		Frying 100 g chips	60
		Grilling 100 g bacon	90
		Grilling 100 g eggplant	40

Table 6. Sampling, extraction and analysis of emissions from cooking

STUDY & RESEARCH OBJECTIVES	SAMPLING CONDITIONS	SAMPLE SUBSTRATE PRE-TREATMENT	EXTRACTION PROCEDURE	ANALYTICAL METHODOLOGY	COMPOUNDS ANALYSED
Rogge et al., 1991 Characterise organic compound composition emitted during meat charbroiling	1.8 µm cyclone upstream of 3 pumps Flow rate 9.0-9.6 L/min Sampling duration: 70-80 min	47mm teflon and quartz fiber	Samples were a composite of 15 quartz filters Extraction: Hexane (two times) and with benzene:2- propanol (2:l; three times) Extraction method: mild sonication Final volume reduced to 200-500 µL . Derivatization: one aliquot of the extract was derivatized with diazomethane to convert organic acids to their methyl ester analogues	GC/MS 30-m column	N-alkanes, branched alkanes, alkenes, alkynes, ketones,carbonyls,aromatic hydrocarbons, lactones, amides, saturated and unsaturated fatty acids, dicarboxylic acids, furans amides, steroids.
Wu et al., 1998 Determination of mutagenic PAH emitted from cooking oils	Personal sampling pump Flow rate: 2 l/min Sampling duration: 30 min.	37-mm Grade AA glass fiber filter paper	Extraction with a 200 ml acetone then concentrated to 10 ml in a vacuum rotary evaporator and evaporated to dryness under nitrogen stream. Residue was redissolved in 2ml for analysyis.	HPLC system (LH-20 column 15 mm id=190 mm) for PAHS. For detection of aminopyrenes a HPLC Hewlett Packard 1050 was used equipped with a 25-cm Nucleosil C column and spectrofluorimeter.	polycyclic aromatic hydrocarbons; nitro-polycyclic aromatic hydrocarbons
Schauer et al., 1999a Characterise organic compound composition emitted during meat charbroiling **Schauer et al., 2002** Characterise organic compound composition emitted during oil cooking	Emissions sampled in the ventilation system of a commercial kitchen downstream of the filter and grease extractor. Sampling time was 85 min. Dilution tunnel: mix exhaust emissions with 25- to 180-fold excess of HEPA filtered air. 1.8 µm AIHL-design cyclone separators upstream of samplers. Flow rate in each sampling train was 10 L/min, except sampling train a) at 30 L/min and sampling train g) at 0.2 L/min. Organic compounds collected using: a) 1 XAD coated denuder upstream of 3 quartz filters in parallel followed by 2 PUFs in series. b) 3 quartz filters followed each by 2 PUFs in series. EC/OC collected using: c) 2 quartz filters in series Mass emissions, trace metals and organic acids collected using: d) Teflon filter upstream of two KOH impregnated quartz fibre filters Mass emissions & soluble ions collected using: e) Teflon filter VOC collected using: f) 6-L SUMA canister downstream of teflon filter e) Carbonyls collected using: g) DNPH-impregnated C18 cartridges	Quartz fibre filters prebaked at 550ºC for 12 h Denuders coated following protocol described in Gundel et al. (1995) (Gundel et al., 1995) PUF plugs were pre-cleaned with 4 successive extractions of Dichloromethane/acetone/hexane (2:3:5). Solvent was removed by compressing the PUFs. Plugs were air dried in a dark organic free room, and stored in pre-cleaned glass jars at -20ºC.	*Quartz fibre filters:* Extraction: Hexane (two times) followed by benzene/2- propanol (2:l; three times) Extraction method: mild sonication *Denuders and PUFs:* Extraction: Dichloromethane/acetone/hexane (2:3:5) (4 times) Extraction method: Manual shaking In all cases, extracts from each aliquot were combined and concentrated to 250 µL Concentrated extract was split in two. Derivatisation: one aliquot of the extract was derivatised with diazomethane to convert organic acids to their methyl ester analogues. C18 cartridges were extracted as described in Grosjean et al. (1996) (Grosjean et al., 1996) Teflon filters were extracted in water for water-soluble ions.	Organic compounds: Denuder, filter and PUF extracts (derivatized and underivatized aliquots) were analysed by GC/MS Hewlett Packard 5890 series fitted with a 30m, 0.25 mm inner diameter, 0.25 µm film thickness HP-1701 capillary column. Total non-methane organic gases and individual VOCs (C1-C10) were analysed from the SUMA canisters by GC/FID as described in Fraser et al. (1997) (Fraser et al., 1997) Carbonyl collected in the C18 cartridges were eluted with 2 mL acetonitrile analysed by LC/UV as described by Grosjean et al. (1996). Organic and elemental carbon (EC/OC) as described by Birch and Cary (1996) (Birch and Cary, 1996) Trace metals were analysed by XRF. Soluble ions were analysed by AA and IC.	N-alkanes, branched alkanes, alkenes, alkynes, ketones, carbonyls, aromatic hydrocarbons, lactones, amides, saturated and unsaturated fatty acids, dicarboxylic acids.

Table 6 Cont. Sampling, extraction and analysis of organic emissions from cooking

STUDY & RESEARCH OBJECTIVES	SAMPLING CONDITIONS	SAMPLE SUBSTRATE PRE-TREATMENT	EXTRACTION PROCEDURE	ANALYTICAL METHODOLOGY	COMPOUNDS ANALYSED
Svendsen et al., 2002 Characterise aldehydes and fat aerosol collected in the breathing zone of the cook in fumes from commercial restaurants.	Personal exposure sampler with inlets located in the shoulder of the cook of 19 commercial kitchens using deep frying devices equipped with ventilation hoods. Aldehydes were collected a sampling device containing silica impregnated with 2,4-dinitrophenyl hydrazine. Flow rate was 1.5 L/min during 1.5-2.5 hours. Fat aerosol collected onto pre-weighted one glass fibre filter (Nucleopore AAA). Flow rate, 2 L/min during 65 to 200 mL. Total number concentration was measured with TSI 3936 SMPS used to measure the PAHs were collected onto glass fibre filters in a filter holder and 2 XAD-2 tubes downstream. Flow rate, 1 L/min during 200 min.	None	Fat aerosol extracted with 5 mL of 1,1,2-trichloro-1,2,2-trifluoroetahne. The aldehydes were reacted with 2,4-dinitropheynlhydrazin (DNPH) to form the corresponding stable hydrazone derivatives. The derivatives were eluted with HPLC grade acetonitrile.	Fat aerosol was determined using a FT-IR (Perkin Elmer 1605). The eluate was injected onto a C18 reverse phase column and detected using a UV detector operating at 360 nm.	Aldehydes, fat aerosol
McDonald et al., 2003 Characterise organic compound emission composition emitted during charbroiling and grilling of chicken and beef	University lab kitchen following commercial standard procedures. Emissions collected at the end of a residence chamber to allow the gas/particle equilibrium. 2.5 µm cyclone separators upstream of samplers. Flow rate in each sampling train was 113 L/min. Samples collected on Teflon filter for $PM_{2.5}$ and elements. Samples collected on quartz filters for carbon and ion analysis Samples collected on Teflon-impregnated glass fibre (TIGF) filter followed by a PUF/XAD-4/PUF sandwich cartridge for speciated particle-phase and semi-VOCs. CO was measured using non-dispersive infrared analyser.	Quartz fibre filters were baked at 900ºC for several hours. XAD-4 was solvent extracted in a Soxhlet with methanol followed by dichloromethane. TIGF filters were cleaned by sonication in CH_2Cl_2 for 30 min followed by another 30 min sonication in methanol. PUFs were rinsed with distilled water and Soxhlet extracted with hexane/ether (90:10), followed by acetone.	Half of the quart fibre filter was extracted with 10 mL of distilled-deionised water. TIGD filters and PUF/XAD-4/PUF sorbent were solvent extracted and combined for analysis.	$PM_{2.5}$ mass determined by gravimetric analysis. Ionic species determined by ionic chromatography. NH_4^+ was analysed by indolphenol automated colorimetry. Water-soluble K^+ was analysed by atomic absorption spectrometry. Carbon by thermal/optical reflectance. 0.56 cm^2 punch waa analysed for OC/EC by the TOR method. Elements by X-ray fluorescence. Organics determined with an Agilent GCMS (GC Model 6890plus, MSD Model 5973N) equipped with a 60m x 0.25mm x 0.25 um DB5-MS capillary column.	$PM_{2.5}$, CO, OC/EC, inorganic species, elements, lactones, sterols, PAHs, biphenyls,
Zhu and Wang, 2003 Characterise PAH emitted in commercial and domestic Chinese kitchens	A sampler was located in a new kitchen 0.5 m from the pan (cooking methods) and in the centre of the kitchen (domestic and commercial kitchens). In all cases, the sampler was 1.5 m above the ground level. All doors and windows were closed during cooking. Electric hobs were used for cooking. Samples were collected over 100 mins to test different cooking methods, and over 2 consecutive days for 12-h (8:00 – 20:00) in domestic and commercial kitchens. Low noise small samplers (MP-15CF) operated at 1.0 l/min equipped with a Whatman glass filter (GFF, 25 mm) collected particle bound PAHs and a XAD-2.5 g cartridge collected the gaseous PAHs.	Filters were combusted overnight and sealed in aluminium foil. XAD-2 cartridges were pre-extracted in dichloromethane and methanol for 48 h, vacuum-dried in desiccators and stored in solvent rinsed glass jars.	Extraction by sonication for 30-min with a 20 ml mixture of DCM and acetonitrile (3:2). The extract was concentrated to 10 ml and 30 µl of dimethyl sulfoxide was added. The mixture was concentrated under nitrogen and 1ml of methanol was added. 100 µl were injected for analysis.	HPLC (Hitachi L-7000 series) consisting of a precolumn (Supelco, 5C-18, 4.6x 50 mm) for PAH condensation and cleanup, a main column (Wakosoil, 5C-18, U4:6 250 mm) for separation and a fluorescence detector.	PAHs

Table 6 Cont. Sampling, extraction and analysis of organic emissions from cooking

STUDY & RESEARCH OBJECTIVES	SAMPLING CONDITIONS	SAMPLE SUBSTRATE PRE-TREATMENT	EXTRACTION PROCEDURE	ANALYTICAL METHODOLOGY	COMPOUNDS ANALYSED
Chen and Chen, 2003 Characterise PAHs in fumes during frying of chicken.	Emissions collected on adsorption wool fitted on the cover of frying tank (closely tight during sampling)	Adsorption wool	Soxhlet extraction for 20hrs using acetone to 1ml then evaporated to dryness then residue dissolved in 10 ml acetone and stored for GCMS analysis.	GC/MS equipped with an HP-5MS (30 m x 0.25 mm i.d., 0.25 um film thickness)	PAHs
Li et al., 2003 Characterise PAHs in fumes during cooking of different styles	Emissions collected isokinetically from the exhaust vent in commercial kitchens. Three consecutive samples were collected at 10L/min for 45 min during the cooking time. Particle bound PAHs were collected on a tube-type glass fibre thimble (25x90 mm). Gaseous PAHs were collected onto a 5-cm polyurethane foam (PUF) followed by a 2.5 cm Xad-16 resin cartridge supported by a 2.5 cm PUF.	Samples were kept prior and after sampling in cleaned screw-capped glass bottles and jars.	Samples were extracted in a Soxhlet extractor with 1L of mixed solvent n-hexane/dichloromethane (1:1) for 24 hours. The extract was concentrated, cleaned and re-concentrated to 1 or 1.5 mL.	Hewlet-Packard GC HP 5890A with a Mass Spectrometer dector HP 59H72 equipped with a HP Ultra 2 50m x 0.32 mm x 0.17 um column.	PAHs
He et al., 2004b Characterise fumes emitted during Chinese style cooking	Samples collected at the exit of the exhaust vent of two commercial kitchens. Sampling times were 90-120min at lunchtime and dinner. Samples collected onto two honeycomb sampler and a three stage cascade impactor to collect $PM_{2.5}$ at 25 L/min. One honeycomb contained PTFE filters for particle mass determination and and ionic species analysis. The second honeycomb and the cascade impactor were loaded with quartz filters (Pallflex 2500QAT-UP) for the determination of EC/OC and organic speciation.	Quartz fiber filters were baked for 4 hours at 500ºC. Pre- and post-sampling filters were stored in pre-cleaned 250 mL glass jars with 3-5 mL of methylene chloride to prevent microbial growth. Sampled filters stored in the freezer.	Samples extracted with dichloromethane (3 times) and methanol (2 times) for 20 min using a mild ultrasound bath. Reduced to 5 mL with rotary evaporation and further concentrated to 1ml under a N_2 stream and split into three fractions. Two fractions were derivatised with BF_3/CH_3OH and bis-(trimethylsilyl) trifluoroacetamide (BSTFA) plus 1% trimethylchlorosilane (TMCS) to convert organic acids and unmethylated compounds to their methyl ester and trimethylsilyl derivatives respectively. Derivatisation temperatures and times were 80oC for 30 min and 85oC for 40 min respectively.	$PM_{2.5}$ mass determined by gravimetric analysis. Ionic species determined by ionic chromatography (DX-600, Dionex Corp). EC/OC determined with the Sunset analyser. Organics determined with an Agilent GCMS (GC Model 6890plus, MSD Model 5973N) equipped with a 60m x 0.25mm x 0.25 um DB5-MS capillary column.	N-alkanes, n-fatty acids and dicarboxilic acids; PAHs and other compounds including cholesterol and levoglucosan.
He et al., 2004c Characterise fumes emitted during Chinese style cooking	Samples collected at 40-60 cm at leeway from the exhaust vent of two commercial kitchens. Sampling times were 100-120min at lunchtime, and 45 minutes at dinner. Samples collected onto quartz fibre filters with a three stage cascade impactor (<10um, 10-2.5 um and <2.5 um) at 25 L/min.	Quartz fiber filters were baked for 2 hours at 500ºC. Pre- and post-sampling filters were stored in pre-cleaned 250 mL glass jars with 3-5 mL of methylene chloride to prevent microbial growth. Sampled filters were stored in the freezer.	Samples extracted with methylene chloride (3 times) for 20 min using a mild ultrasound bath. Reduced to 5 mL with rotary evaporation and further concentrated to 1ml under a N_2 stream.	GC/MS Autosystem XL Gas Chromatography coupled with a TurboMass Mass spectrometry (Perkin Elmer) equipped with a 60m x 0.32mm x 0.25 um fused silica capillary column (PE-35MS)	N-alkanes, n-alkenes, n-fatty acids; n-alkanal; n-alkenals; PAHs

Table 6 Cont. Sampling, extraction and analysis of organic emissions from cooking

STUDY & RESEARCH OBJECTIVES	SAMPLING CONDITIONS	SAMPLE SUBSTRATE PRE-TREATMENT	EXTRACTION PROCEDURE	ANALYTICAL METHODOLOGY	COMPOUNDS ANALYSED
See et al., 2006; See and Balasubrabramanian, 2006b Characterise PAH and metal composition emitted during Chinese, Malay and Indian style commercial cooking **See and Balasubrabramanian, 2006a, 2008** Characterise emissions from 5 types of cooking methods (steaming, boiling, stir-frying, pan-frying and deep- frying)	Sample collected at 1.5m above ground level at the opposite site of a 4 LPG burners stove in commercial food stalls.(See et al., 2006; See and Balasubrabramanian, 2006b) Sample collected at 1.5m above ground level and 0.2 m from a 2-burner domestic stove with no ventilation. Samples collected during cooking activities. (See and Balasubrabramanian, 2006a, 2008). Samples collected for 12 hours during cooking and non-cooking activities. A MiniVol portable air sampler (Airmetrics) collected $PM_{2.5}$ at a flow rate of 5 L/min onto: - 47mm 2 µm PTFE Teflon filter for gravimetric, metals and ion analysis. - 47mm QMA quartz filters for PAH	QMA filter was pre-combusted at 400ºC for 24h prior to sampling. No pre-treatment of Teflon filter	*PAH* Microwave extraction using 20mL acetone:hexane (1:1) for 20 min at 150W. Extracts concentrated to 3 mL using a rotary evaporator. Further concentration to almost dryness with N_2 stream and reconstituted with 1 mL of extraction solvent. *Metals* Microwave extraction as described by Swami et al. (2001) (Swami et al., 2001) *EC/OC* 2 6mm punches of a quartz fibre filter. One punch was combusted at 350ºC for 24h to remove the OC.	*PAHs* Hewlett Packard 6890 series GC/MS fitted with a DB-5MS 5%-phenyl-methylpolysiloxane 30m x 0.2 mm internal diameter x 0.25 µm film thickness. *Metals* Perkin Elmer ELAN 6100 ICP/MS *EC/OC:* Both combusted and uncombusted punches were analysed for carbon using a 2400 Series II CHNS/O analyser (Perkin Elmer) operated at the CHN mode with acetanilide as calibration standard.	PAHs Metals EC/OC
Zhao et al., 2007a, b Characterise organic compound emission composition emitted during Chinese and Western style cooking	Emissions sampled at the exhaust vent of the ventilation system of commercial kitchens downstream of the filter treatment methods. Samples collected during rush hour at lunch and dinner times. Sampling time was 120 min. 2 medium-volume samplers at a flow rate of 78 L/min collected samples in 90mm quartz fibre filter. 2 Dustraks (TSI) monitored the relative concentrations of $PM_{2.5}$ and PM_{10}. Background $PM_{2.5}$ was collected in the city using a hi-volume sampler (Andersen).	Quartz fiber filters were baked at 450ºC for 4.5 hours. Prior to sampling, filters were stored in a freezer.	Extraction with three successive portions of dichoromethane and methanol (3:1) for three 15-min in the ultrasound bath at room temperature. Extracts were filtered and destilled under negative pressure to 3-5 mL, subsequently concentrated to 1 mL under N_2 gas stream, and divided in three portions: Portion 1 – analysed directly in GCMS for non polar organic compounds. Portion 2 - Derivatized with BSTFA plus 1% TMCS at 70ºC for 2 h. This was analysed for polar organic compounds. Third portion – stored at 4oC as a backup.	Organics Agilent 6890plus / MSD model 5973N GC/MS using a DB-5MS 60m x 0.25 mm internal diameter x 0.25 µm film thickness column EC/OC: Carbon analyser Sunset Lab.	N-alkanes, PAHs, N-alkanals, N-alkanones, lactones, amides, saturated and unsaturated fatty acids, dicarboxylic acids, anhydrides, sterols
Sjaastad and Svendsen, 2008; Sjaastad et al., 2010; Sjaastad and Svendsen, 2009 Characterise PAHs, aldehydes and particulate matter collected in the breathing zone of the cook in fumes from frying a beefsteak.	Model kitchen (19 m2) containing gas or electric hobs and a canopy fume hood. Personal exposure sampler with inlets located in the shoulder of the cook. PAHs were collected onto glass fibre filters in a filter holder and 2 XAD-2 tubes downstream. Flow rate, 1 L/min during 200 min. Aldehydes were collected into stainless steel sorbent tubes filled with 220 mg Tenax TA. Flow rate, 100 mL/min for 10-200 min. Total particles collected onto pre-weighted double Gelman glass fibre filters. Flow rate, 2 L/min during 65 to 200 mL. Total number concentration was measured with TSI 3936 SMPS.	None	PAH were desorbed in dichloromethane.	PAH measured by a commercial laboratory following a modified version of AMI L5, NIOSH 5515, ISO/CD 12884 and VDI 3873. Aldehydes measured using an automatic thermic desorption unit ATD 400 (Perkin Elmer) connected to a GCMS (Focus GC-DSQ, Thermo Electron Corporation).	PAH; aldehydes

Table 7. Main identified cooking marker species in the literature

COMPOUND ANALYSED	SOURCE IN FOOD	OTHER SOURCES IN THE ENVIRONMENT
Unsaturated fatty acids Oleic acid- 9-octadecenoic acid-meat tracer, canola oil (Schauer et al, 2002) Linoleic acid- 9,12-octadecadienoic acid Palmitoleic acid- 9-hexadecenoic acid meat cooking (Zhao, 2007a; Robinson et al, 2006)	Combustion of triglycerides and phospholipids from seed oil, vegetable oil, fats of animals and meet cooking (Robinson et al, 2006)	Biomass smoke, motor vehicle exhaust and road dust (Robinson et al., 2006)
Saturated Fatty Acids hexanoic acid octanoic acid nonanoic acid-from seed oil (Schauer et al, 2002) hexadecanoic acid, palmitic acid, (Robinson et al, 2006)	Combustion of triglycerides and phospholipids from seed oil, vegetable oil and fats of animals. The acids are formed directly from the pyrolysis of their glycerol ester precursor analogues (nonanoic acid formed from the breakdown of oleic acid present in seed oil (Schauer et al, 2002)	Palmitic acid are emitted also from biomass smoke, motor vehicle exhaust, road tire dust (Robinson et al, 2006), tyre dust cigarette smoke, roofing asphalts and fuel combustion (Nolte et al., 1999)
Dicarboxylic Acids-C4-C8 hexanedioic acid – from meat cooking and seed oil octanedioic acid – from seed oil nonanedioic acid, tetradecanoic acid, octadecadienoic acid from soybeans oil (Schauer et al, 2002)	Products of dialdehydes formed during auto oxidation of unsaturated lipids. Produced from meat cooking (C_4-C_8 high concentrations for hexaneoic acid) and heating of seed oil (C_8 higher concentrations) (Zhao, 2007a).	
Polycyclic Aromatic Hydrocarbons pyrene chrysene –seed oil and meat cooking (Zhao, 2007a) benzo[a]pyrene	Incomplete combustion of organic substance (cooking materials such as meat, vegetables, oil)	House heating Cigarette smoking (Kleeman et al., 2008). Heavier PAH (coronene, benzo[ghi]perylene, indeno[1,2,3-cd]pyrene) are emitted from motor vehicles and retene from biomass burning (Brinkman et al., 2009)
Molecular bio markers • **Monosaccharide Anhydrides-** from breakdown of cellulose during cooking (Zhao, 2007a) Galactosan Mannosan levoglucosan • **Sterols** *B*-sitosterol –present in animal and vegetable body tissue (Zhao, 2007a). Cholesterol – from meat cooking (Zhao, 2007a; Robinson et al, 2006) stigmasterol	From the organic compounds of biological origin which have restricted occurrence and molecular stability so can be detected in body tissues. Plant lipid membranes and waxes. For Chinese food the average ratio of levoglucosan/(mannosan+galactosan) is 12 (Zhao, 2007a).	Levoglucosan is released from wood burning. (Kleeman et al., 2008; Zhao et al., 2007a Cholesterol produced from cigarette, debris of plant and road dust (Zhao et al., 2007a; Robinson et al., 2006; Nolte et al., 1999).
N Alkanes C_{23}-C_{31} C_{23}-C_{31} from cooking material/contents (Zhao, 2007a)	From cooking material/contents (Zhao, 2007a)	From motor vehicles (Brinkman et al., 2009)
Lactones C_7-C_{18} From food cooking (Zhao, 2007a; Schauer et al., 2002). 5-propyldihydro-2(3H) furanone (Schauer et al, 2002) 5-dodecyldihydro-2(3H) furanone (Schauer et al, 2002)	Meat charbroiling and food cooking (Schauer et al, 2002)	
Alkanals and alkanones C_9-C_{15} from cooking oil Nonanal (Zhao, 2007a) 2-pentadecanone- from soybean oil and seed oil (Schauer et al, 2002) 2-nonanone 2-undecanone 2-pentadecanone	Combustion of triglycerides in oil (Zhao, 2007a). From the decomposition of unsaturated fatty acids (oleic acid) (Schauer et al, 2002)	
Inorganic elements and ions From meat cooking Aluminium (Schauer et al, 1999a) Silicon (Schauer et al, 1999a) Phosphorus (Schauer et al, 1999a) Sulphur (Schauer et al, 2002; Schauer et al, 1999a) Chlorine (Schauer et al, 1999a) Potassium (Schauer et al, 1999a) Sodium (Schauer et al, 2002; Schauer et al, 1999a) Nitrate (Schauer et al, 2002; Schauer et al, 1999a)	From meat, vegetables and sauces (Schauer et al, 2002)	From soil, motor vehicles, cigarettes and biomass burning (Brinkman et al., 2009)

Table 8. Concentrations of organic compounds from western-style fast food and from Chinese cooking (ng/mg of particulate organic matter) (Zhao et al., 2007b,c)

Organic compounds	Western-style fast food cooking	Chinese cooking
n-Alkanes	3860	1880
Polycyclic aromatic hydrocarbons	40	2860
n-Alkanones	22700	2440
n-Alkanals	29200	3440
Lactones	13300	2140
Amides	4690	531
Saturated fatty acids	374700	26800
Unsaturated fatty acids	93300	29030
Dicarboxylic acids	57900	2050
Monosaccharide anhydrides	97	314
Sterols	487	1680

Table 9. Polycyclic aromatic hydrocarbons emitted from cooking food – indoor concentrations and emission factors (see columns for units)

	Rogge et al, 1991		Schauer et al, 1999a	Schauer et al, 2002						Zhu and Wang, 2003								McDonald et al, 2003					
PAH	frying hamburger	charbroiling hamburger	Hamburger meat charbroiled	stir fry in soybean oil		stir fry in canola oil		deep frying of potatoes in hydrogenated oil		Boiling Fish	Frying Fish	Broiling Fish	Boiling short pork chops	Frying short pork chops	Broiling short pork chops	Commercial Kitchen	Domestic Kitchen	Hamburger Auto-Char	Hamburger Under-Char	Steak Under-Char	Chicken Under-Char	Hamburger Griddle	Chicken Griddle
Units	mg/kg		µg/kg of cooked meat	µg/kg of cooked vegetables		µg/kg ofcooked vegetables		µg/kg of cooked potatoes		$\mu g/m^3/kg$						$\mu g/m^3$		mg/kg					
	particle	particle	gas+particle	gas	particle	gas	particle	gas	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle
Naphthalene			8990	645		588		338		0.028	0.25	1.1	0.045	0.53	1.3	2.33	1.84	23.04	19.11	14.8	8.75	0.61	1
Acenaphthene																		0.28	0.15	0.15	0.1	0.02	0.05
Acenaphthylene				38		37		19		nd	0.08	0.1	0.0013	0.57	2.4	4.20	1.24	4.89	4.24	4.28	2.06	0.16	0.13
Fluorene										nd	0.042	0.13	nd	0.071	0.34	0.94	0.07	1.09	1.26	1.17	0.72	0.21	0.18
Phenanthrene			1220	138	7	120	8	83	2	0.0021	0.045	0.043	0.0031	0.069	0.18	0.36	0.63	4.88	4.88	5.31	3.46	2.07	1.87
Anthracene			160	11	1	8	2	6	2	0.003	0.048	0.043	0.0022	0.033	0.13	0.43	0.28	0.91	0.94	1.03	0.88	0.17	0.44
Fluoranthene	0.13	0.35	520	40	7	24	5	19	1	0.011	0.25	0.15	0.015	0.31	0.43	1.08	0.94	0.88	1.4	1.28	1.28	0.86	0.62
Pyrene	0.09	0.74	670	28	4	15	5	19	1	0.009	0.25	0.15	0.013	0.17	0.55	4.20	0.63	1.15	1.9	1.56	1.8	1.15	0.82
Retene																		0.01	0.02	0.01	0.03	0.02	0.02
Benzo[ghi]fluoranthene										0.0082	0.18	nd	0.012	0.39	1.4	0.39	0.27						
Benz[a]anthrancene	0.02	0.29								0.0022	0.033	0.028	0.0031	0.049	0.14	0.76	0.23	0.22	0.22	0.11	0.34	0.07	0.12
Chrysene	0.11	0.95	600 (b)	5 (b)	9(b)		13(b)	5(b)	9(b)									0.24(b)	0.26(b)	0.12(b)	0.29(b)	0.06(b)	0.12(b)
Benzo[b]fluoranthene	nd	0.21								nd	0.082	0.037	0.0011	0.14	0.26	0.90	0.01	0.4(c)	0.34(c)	0.17(c)	0.24(c)	0	0.01(c)
Benzo[kl]fluoranthene	0.004	0.27								0.0021	0.011	0.01	0.0031	0.079	0.08	2.16	0.04						
Benzo[*a*]fluoranthene																							
Benzo[*b*]pyrene																							
Benzo[e]pyrene	nd	0.19								nd	0.055	0.04	nd	0.075	0.089	0.28	0.02	0.14	0.1	0.04	0.06	0.01	0
Benzo[a]pyrene	nd	0.19																0.17	0.15	0.07	0.1	0.02	0.01
Perylene	nd	0.03																					
Indeno[1,2,3-cd]pyrene																		0.1	0.09	0.05	0.06	0	0
dibenz(a,h)anthracene																		0.02	0.01	0.01	0.01	0	0
Benzo[ghi]perylene	nd	0.24																0.16	0.17	0.09	0.09	0	0
Coronene																		0.08	0.1	0.05	0.05	0.01	0.02

Table 9 Cont. Polycyclic aromatic hydrocarbons emitted from cooking food – indoor concentrations and emission factors (see columns for units)

	Li et al, 2003				He et al 2004b				See et al, 2006			Zhao et al, 2007c		Zhao et al, 2007b				See and Balasubramanian, 2008				
PAH	Chinese	Western	Fast Food	Japanese	Hunan cooking	Cantonese cooking	Hunan cooking	Cantonese cooking	Chinese	Malay	Indian	Western-stylefastfoodcooking	Chinese cooking (average)	Cantonese style	Sichuan style	Dongbei style	Hunan style	Steaming	Boiling	Stir-frying	Pan-frying	Deep-frying
Units	µg/m³				ng/m³		ng/mg of particles emitted		ng/m³			ng/mg of POM		ng/mg of POM				ng/m3				
	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle	particle
Naphthalene	36.1	61.3	46.8	39.5					1.9	2.8	3.9							0.17 ± 0.01	0.19 ± 0.01	0.30 ± 0.03	0.37 ± 0.04	0.50 ± 0.04
Acenaphthene	1.65	0.89	0.36	0.285					1	3.1	1.1							0.13 ± 0.03	0.42 ± 0.05	0.57 ± 0.07	0.98 ± 0.10	1.17 ± 0.14
Acenaphthylene	11.7	4.21	1.55	1.25					2.4	5.6	2.7							0.56 ± 0.06	0.75 ± 0.09	1.55 ± 0.13	1.73 ± 0.18	1.80 ± 0.26
Fluorene	2.32	1.44	1.92	2.38					3.8	9.2	3.9							0.84 ± 0.07	0.89 ± 0.07	1.53 ± 0.14	1.68 ± 0.12	2.62 ± 0.33
Phenanthrene	6.38	7.15	5.62	7.41			6.2	6.4	11.5	15.7	9.5	2±1	5.5	7 ± 3	6 ± 2	5 ± 1	4 ± 1	3.18 ± 0.23	3.97 ± 0.32	5.11 ± 0.86	5.87 ± 0.87	8.98 ± 0.68
Anthracene	1.03	1.15	0.225	0.225			0.27	ND	3	6.1	2.6							0.12 ± 0.01	0.16 ± 0.03	0.31 ± 0.03	0.36 ± 0.05	0.43 ± 0.07
Fluoranthene	1.32	1.35	0.72	0.635	8.8	10.4	6.2	15.5	6.9	30.7	1.6	nd	110.7	121±36	238 ± 97	56 ± 10	28 ± 16	0.86 ± 0.10	1.05 ± 0.14	1.61 ± 0.16	1.64 ± 0.18	1.64 ± 0.13
Pyrene	1.33	1.59	0.485	0.325	11	18.7	7.8	27.8	10.9	18.1	2.9	14±14	208.3	243 ± 71	466 ± 191	76 ± 19	49 ± 12	0.80 ± 0.10	0.96 ± 0.14	1.30 ± 0.18	1.35 ± 0.13	1.45 ± 0.16
Retene												nd	6.2	24 ± 14	1±3	nd	nd					
Benzo[ghi]fluoranthene							1.3	6.1				18±10	77.9	160±30	119±49	20 ± 4	13±3					
Benz[a]anthrancene	0.814	0.15	0.276	0.015			0.86	2.5	3.8	23.1	1							0.21 ± 0.03	0.30 ± 0.02	0.38 ± 0.07	0.40 ± 0.06	0.44 ± 0.07
Chrysene	0.502	0.247	0.596	0.104			0.81	2.8	5.8	48.7	1	7±7	26	59 ± 24	23 ± 8	12±3	10±2	0.56 ± 0.04	0.70 ± 0.09	1.05 ± 0.11	1.07 ± 0.11	1.19 ± 0.15
Benzo[b]fluoranthene	0.873	1.2	0.752	0.403	2.4 (a)	6.5 (a)	1.7(a)	9.7(a)	21.8	122.4	1.9	nd	18.4	48 ± 30	10±3	9 ± 4	7 ± 2	0.29 ± 0.04	0.70 ± 0.06	1.30 ± 0.10	1.30 ± 0.12	1.38 ± 0.13
Benzo[kl]fluoranthene	0.814	1.29	0.528	0.352					3.7	23.1	0.5	nd	14.6	40 ± 35	8 ± 3	6 ± 4	5 ± 3	0.29 ± 0.02	0.37 ± 0.04	0.48 ± 0.04	0.78 ± 0.10	0.94 ± 0.07
Benzo[*a*]fluoranthene												nd	2.8	11±17	nd	1±2	nd					
Benzo[*b*]pyrene												nd	17.5	52 ± 30	7 ± 4	5 ± 6	6 ± 2					
Benzo[e]pyrene	0.977	1.8	0.256	0.351	1	2.8	0.71	4.2														
Benzo[a]pyrene	1.22	1.59	0.296	0.28	0.7	1.4	0.51	2.1	5.6	16	0.9	nd	11.9	39 ± 42	1±2	3 ± 4	4 ± 2	0.20 ± 0.03	0.23 ± 0.02	0.38 ± 0.05	0.49 ± 0.05	0.56 ± 0.05
Perylene	1.69	1.48	0.216	0.232								nd	0.4	1± 4	nd	nd	nd					
Indeno[1,2,3-cd]pyrene	2.81	1.08	0.177	0.736			ND	3.9	24.4	105.9	1.3	nd	19.6	65 ± 58	4 ± 7	6 ± 6	3 ± 6	0.42 ± 0.04	0.87 ± 0.07	1.09 ± 0.14	1.38 ± 0.19	3.47 ± 0.30
dibenz(a,h)anthracene	1.91	1.35	0.069	ND					2.7	8.3	1.1							0.046 ± 0.008	0.21 ± 0.02	0.52 ± 0.05	0.62 ± 0.06	1.18 ± 0.15
Benzo[ghi]perylene	1.65	0.648	0.16	0.152			ND	16.7	31.9	170.1	2.1	nd	65.1	196±116	27 ± 11	18±9	19±8	0.36 ± 0.05	0.79 ± 0.06	1.29 ± 0.17	1.62 ± 0.19	4.33 ± 0.47
Coronene	0.737	0.448	0.504	0.4			ND	16.5				40	2855									

Note: Sjaastad and Svendsen (2009) reported naphthalene concetrations in the breathing area of chefs working at Norwegian à la carte restaurants in the range of 0.05-0.27 µg/m³.

Table 10. Polycyclic aromatic hydrocarbons in fumes from heated oils - indoor concentrations and emission factors (see columns for units) - and in uncooked oil

Reference	Siegmann and Sattler, 1996			Wu et al., 1998			Chiang et al., 1999			Fortmann et al., 2001					Chen and Chen,2001			Chen and Chen, 2003			Zhu and Wang, 2003		
Cooking conditions	250ºC (oil heated in iron pot)			250°C for 30 min (oil heated in iron pot)			250°C ± 10 for 30 min (oil heated in iron pot)			Uncooked					220°C for 2 h (oil heated in reaction tubes with adsorption tubes placed on them)			frying time 1hr			180-270°C for 2h (oil heated in iron pot)		
PAH	Rape seed	Corn	Peanut	Lard	Soy bean	Peanut	Lard	Soy bean	Peanut	Olive	Peanut	Canola	Corn	Vegetable	Soy bean	sunflower	canola	fried chicken legs in			Rape-seed	Soy bean	Lard
																		soya beans	sunflower	canola			
Units	mg/kg oil			$\mu g/m^3$			$\mu g/m^3$			ng/g					µg/g of Smoke			µg/m3 of smoke			ng/m^3		
naphthalene										31.7	13.9	15.5	13.3	17.6	ND	ND	ND	nd	nd	nd	12.08	13.67	15.5
acenaphthylene										ND	ND	ND	ND	ND	ND	21.1 ± 1.4	12.9 ± 1.2	16.06	5.68	6.79			
acenaphthene										19.9	ND	ND	ND	ND	72.5 ± 2.2	14.5 ± 0.2	62.2 ± 3.1	2.08	4.49	3.29	51.26	20.67	73.5
fluorene										1.73	ND	0.21	0.28	0.3	84.9 ± 0.8	21.7 ± 1.7	59.5 ± 2.5	22.71	nd	nd	2.2	2.27	1.55
phenanthrene	14.4	6.92	37.1							10.7	ND	ND	ND	ND	83.2 ± 4.5	33.0 ± 6.6	60.4 ± 4.3	10.44	4.86	19.17	0.22	0.18	0.26
anthracene										1.12	2.6	1.12	1.54	0.56	31.2 ± 2.6	10.3 ± 1.8	61.1 ± 2.6	14.91	3.57	18.13	0.2	0.13	0.44
fluoranthene	4.2	1.14	15.5							4.07	1.28	0.71	0.65	1.64	98.2 ± 6.3	44.0 ± 2.4	78.1 ± 5.4	10.48	7.42	19.86	0.51	0.31	0.67
pyrene	3.77	1.88	0.66							7.1	10.2	1.79	ND	ND	87.5 ± 3.4	40.1 ± 4.6	68.6 ± 3.6	nd	5.43	nd	0.56	0.42	0.66
benzo[a] anthracene	2.4	0.36	8.75	2.3 ± 0.22	2.1 ± 0.5	21.1 ± 0.8	2.2	2.3	1.3	4.49	13.6	6.51	ND	2.22	46.8 ± 1.2	21.5 ± 1.0	39.0 ± 1.0	5.96	3.97	7.11	1.01	1.57	2.25
chrysene	2.6	0.46	8.5							3.29	14.7	ND	ND	2.22	58.0 ± 6.6	24.6 ± 3.1	44.5 ± 5.2	2.98	3.5	nd	0.13	0.2	0.14
benzo[b] fluoranthene	1	0.47	0.32							77.3	72.8	ND	4.68	5.28	29.8 ± 3.1	13.3 ± 1.8	ND	nd	nd	nd			
benzo[k] fluoranthene															30.6 ± 1.1	15.5 ± 1.5	ND	nd	nd	nd	0.49	0.6	0.94
benzo[a] pyrene	7	0.8	0.1	ND	21.1 ± 0.8	19.6 ± 0.5	n.d	19.6	18.3	8.32	24.5	ND	11	4.22	16.1 ± 1.1	5.9 ± 0.9	10.1 ± 0.3	nd	nd	nd	3.06	2.37	3.2
dibenzo[a,h] anthracene				2.0 ± 0.3	2.4 ± 0.4	1.9 ± 0.1	1.9	2.1	1.8	9.26	27.1	ND	0.59	9.2	15.4 ± 1.2	5.8 ± 0.5	8.8 ± 1.3	23.44	nd		0.7	1.22	1.15
benzo[g,h,i] perylene							8.4				5.31	26.6	18.7	3.2	ND	ND	ND						
indeno[1,2,3-c,d]pyrene							9.84				16.2	30.3	2.67	2.03	8.2 ± 2.4	1.6 ± 0.2	9.9 ± 0.8	nd	nd	nd			

Table 11. N-alkanes emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	Schauer et al, 1999a	Schauer et al, 2002						He et al 2004		Zhao et al, 2007b				Zhao et al, 2007c	
Compound class	Hamburger meat charbroiled	stir fry in soybean oil		stir fry in canola oil		deep frying of potatoes in hydrogenated oil		Hunan cooking	Cantonese cooking	Cantonese style	Sichuan style	Dongbei style	Hunan style	Western-style fast food cooking	Chinese cooking
Units	µg/kg of meat cooked	µg/kg of vegetables cooked		µg/kg of vegetables cooked		µg/kg of potatoes cooked		ng/mg of particles emitted		(ng/mg of POM				ng/mg of POM	
n -alkanes	gas+particle	gas	particle	gas	particle	gas	particle	particle	particle	particle	particle	particle	particle	particle	particle
n-Tetradecane	5,000	930		530	25	340	5	8.2	3.8	19 ± 17	23 ± 9	24 ± 6	12 ± 3	46±8	19
n-Pentadecane	6,240	690		660	35	430	37	18	13	70 ± 11	75 ± 11	93 ± 13	46 ± 9	146±48	71
n-Hexadance	3,240	720	150	450	33	230	18	27.8	32.4	128 ± 33	43 ± 10	44 ± 25	21 ± 15	161±26	59
n-Heptandecane	400	170	34	650	95	310	33	58	45.7	139 ± 44	50 ± 12	45 ± 13	29 ± 6	234±61	66
n-Octadecane	1,450	77	28	180	16	96	11	55	34.1	71 ± 24	55 ± 19	57 ± 33	23 ± 6	137±77	51
n-Nonadecane	720	82	14	97	22	49	9	53.7	30.9	72 ± 14	75 ± 35	69 ± 17	39 ± 8	167±94	64
n-Eicosane	1,190	38	26	100	14	37	6	58.1	33.7	97 ± 25	65 ± 19	36 ± 30	39 ± 17	nd	59
n-Heneicosane	880	26	38	46	15	26	3	49.9	46.8	167 ± 80	104 ± 61	91 ± 35	75 ± 22	252±53	110
n-Docosane	610	19	10	36	10	20	1	42.8	49.2	192 ± 64	143 ± 76	34 ± 41	65 ± 59	73±118	109
n-Tricosane	560	25	18	36	5	19	1	54	54.5	214 ± 71	161 ± 71	80 ± 13	91 ± 26	394±67	137
n-Tetracosane	690	18	18	15	18	12		22.1	31.5	135 ± 33	102 ± 54	54 ± 20	66 ± 18	251±140	89
n-Pentacosane	780			7	13	9		22	29.1	292 ± 102	303 ± 105	102 ± 89	205 ± 46	549±124	225
n-Hexacosane	260		18		17			17.2	24.3	81 ± 22	59 ± 43	12 ± 20	25 ± 21	289±109	44
n-Heptacosane	650		340		470			13.2	32.1	181 ± 60	116 ± 41	59 ± 19	74 ± 13	366±135	107
n-Octacosane	1,140							11	17.1	62 ± 69	45 ± 69	nd	nd	242±114	27
n-Nonacosane	770							23.9	324.2	552 ± 223	212 ± 79	63 ± 43	207 ± 68	278±77	258
n-Triacontane								14.1	19.2	16 ± 25	31 ± 23	nd	nd	131±66	12
n-Hentriacontane								47.9	99	560 ± 197	367 ± 149	96 ± 51	346 ± 45	121±44	342
n-Dotriacontane								ND	10.1					28±67	Nd
n-Tritriacontane								ND	19.7	26 ± 41	90 ± 55	20 ± 32	nd	nd	34
Total class								596.9	950.3					3863	1883

Table 12. Fatty acids emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	Schauer et al., 1999a	Schauer et al., 2002						He et al., 2004b		Zhao et al., 2007b			
Compound class	Burger meat charbroiled	stir fry in soybean oil		stir fry in canola oil		deep frying of potatoes in hydrogenated oil		Hunan cooking	Cantonese cooking	Cantonese style	Sichuan style	Dongbei style	Hunan style
Units	µg/kg of meat cooked	µg/kg of vegetables cooked		µg/kg of vegetables cooked		µg/kg of potatoes cooked		ng/mg of particles emitted		ng/mg of POM			
Compound class	gas+particle	gas	particle	gas	particle	gas	particle	particle	particle	particle	particle	particle	particle
n - alkanoic acids													
Hexanoic acid								1,999	1,337	85 ± 74	159± 45	144± 112	103± 39
Heptanoic acid	32,200	5,940		530	162	370	2	2,295	1,688	13± 20	59 ± 11	67 ± 29	50 ± 18
Octanoic acid	38,700	5,930	160	4,330	170	640	27	3,202	2,444	32 ± 32	130± 32	137± 87	96 ± 27
Nonanoic acid	48,400	11,890	180	12,200	180	3,270	51	850	687	60 ± 46	208 ± 35	417± 243	154± 38
Decanoic acid	11,100	780	28	700		190	9	593	246	14± 16	60 ± 18	81± 27	44 ± 14
Undecanoic acid								390	90	3 ± 7	37 ± 11	73 ± 26	30 ± 7
Dodecanoic acid	6,460	320	59	210	20	100	4	2,462	463	116± 60	247 ± 86	208 ± 79	305 ± 113
Tridecanoic acid	21,700							422	92	25 ± 28	108± 47	113± 34	61± 15
Tetradecanoic acid		130	93	87	42	60	52	7,359	1,211	341± 114	1635± 809	801± 113	730 ± 188
Pentadecanoic acid	5,970		58		59		12	774	316	102± 27	437 ± 200	283 ± 43	224 ± 80
Hexadecanoic acid	17,400	238	2,980	690	2,280	800	1,760	57,892	26,621	10,608 ± 2,238	30,121± 7,982	23,344 ± 3,547	14,757 ± 2,947
Heptadecanoic acid	10,300				50		23	839	464	118± 41	285 ± 121	151± 28	162± 37
Octadecanoic acid	96,100	15	1,250	65	1,040	37	848	21,412	11,166	4,209 ± 996	6,084 ± 1,608	2,876 ± 533	3,975 ± 799
Nonadecanoic acid	600				7			47	50	5 ± 8	43 ± 10	29 ± 16	23 ± 7
Eicosanoic acid	860		38		65		48	1,959	2,462	257 ± 74	400 ± 119	191± 33	235 ± 54
Heneicosanoic acid								46	71				
Docosanoic acid	350		29		35		7	677	1,229	355 ± 94	490 ± 189	52 ± 52	268 ± 55
Tricosanoic acid								81	82				
Tetracosanoic acid								269	431	22 ± 35	86 ± 80	10± 24	71± 29
Pentacosanoic acid								23	20				
Hexacosanoic acid								22	29				
n - alkenoic acids													
9-hexadecenoic acid (palmitoleic acid)	18,400		174		36		18	3,638	2,101	101± 39	255 ± 96	108± 37	196± 60
9,12-octadecadienoic acid (Linoleic acid)	214,000		4,190		3,030		1,750	85,635	64,756	8,677 ± 2,233	13,547 ± 5,345	3,077 ± 904	10,132± 2,498
9-octadecenoic acid (oleic acid)	32,000		3,250		6,310		1,940	33,584	39,806	13,775 ± 2,663	29,375 ± 8,307	18,828 ± 3256	18,044 ± 2,723
Eicosenoic acid								782	3,435				
13-Docosenoic acid								307	670				
9,12,15-octadecatrienoic acid (linolenic acid)			310		270		77						

Table 13. Dicarboxylic acids emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	Schauer et al., 1999a	Schauer et al., 2002			He et al., 2004b		Zhao et al., 2007b			
Compound class	Hamburger meat charbroiled	stir fry in soybean oil	stir fry in canola oil	deep frying of potatoes in hydrogenated oil	Hunan cooking	Cantonese cooking	Cantonese style	Sichuan style	Dongbei style	Hunan style
Units	µg/kg of meat cooked	µg/kg of vegetables cooked	µg/kg of vegetables cooked	µg/kg of potatoes cooked	ng/mg of particles emitted		ng/mg of POM			
butanedioic acid (Succinic acid)							49 ± 47	225 ± 64	262 ± 159	166 ± 43
pentanedioic acid (Glutaric acid)					667	687	4 ± 7	80 ± 28	91 ± 42	56 ± 16
hexanedioic acid (Adipic acid)	1,990		33		429	844	15 ± 17	129 ± 38	109 ± 31	70 ± 13
heptanedioic acid (Pimelic acid0					370	356	84 ± 42	246 ± 65	197 ± 73	154 ± 57
octanedioic acid (Suberic acid)	3,900	58	165	3	1,193	1,326	131 ± 75	413 ± 177	189 ± 72	201 ± 61
nonanedioic acid (Azelaic acid)					3,160	4,934	675 ± 284	1,890 ± 828	1,043 ± 671	975 ± 325
decanedioic acid (Sebacic acid					403	350	97 ± 21	179 ± 62	156 ± 43	107 ± 29
undecanedioic acid							14 ± 18	82 ± 43	62 ± 24	50 ± 21

Table 14. Aldehydes emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	Schauer et al., 1999a	Schauer et al., 2002			Svendsen et al., 2002				He et al., 2004b				Zhao et al., 2007c		Zhao et al., 2007b				Sjaastad and Svendsen, 2008				Sjaastad and Svendsen, 2009
Aldehydes	Hamburger meat charbroiled	stir fry in soybean oil	stir fry in canola oil	deep frying potatoes in hydrogenated oil	Hotel kitchen	Burger chain	Restaurant with grill	Small local restaurants	Hunan cooking	Cantonese cooking	Hunan cooking	Cantonese cooking	Western-style fastfood	Chinese cooking (average)	Cantonese style	Sichuan style	Dongbei style	Hunan style	Margarine	Rapeseed oil	Soybean oil	Olive oil	Norwegian à la carte restaurant
Units	µg/kg of meat cooked	µg/kg of vegetables	µg/kg of vegetables	µg/kg of potatoes	µg/m^3				ng/mg of particles emitted		ng/m^3		ng/mg of POM						µg/m^3				
formaldehyde	1,382,000	20,100	18,600	12,400	11 ± 8	7 ± 0	15 ± 11	14 ± 6															
acetaldehyde	1,092,000	50,100	42,200	20,900	29 ± 30	16 ± 5	34 ± 24	102 ± 33															
propanal	504,000	12,200	17,000	7,000																			
butanal/isobutanal	373,000	19,700	17,400	4,500																			
hexanal	203,000	4,100	6,400	6,700																			
heptanal	125,000	4,300	8,000	5,200																			
octanal	146,000	7,900	9,700	5,700																			
nonanal	148,000	12,400	14,800	13,500					973	827	1,369	555	25,518±7951	2380	1365 ± 393	2281 ± 443	4501 ± 2735	1373 ± 519					
decanal	33,600	5,200	1,090	2,900									651±244	225	49 ± 81	272 ± 80	405 ± 86	174 ± 34					
undecanal	17,200	3,000	200	1,200									430±180	138	33 ± 82	154 ± 92	255 ± 46	109 ± 25					
dodecenal	30,000	1,260	920										352±108	140	8 ± 21	147 ± 100	287 ± 83	120 ± 46					
tridecenal	18,000	550	180										514±127	102	nd	117 ± 72	193 ± 54	99 ± 37					
tetradecenal	18,000	410											536±154	199	62 ± 69	235 ± 59	359 ± 50	141 ± 39					
pentadecenal	14,400	440	411										1172±389	259	62 ± 69	305 ± 123	436 ± 104	232 ± 75					
Acrolein					11 ± 10	14 ± 9	12 ± 11	3 ± 1															
trans,trans-2,4-decadienal																			10.33 (2.52	0.63 (1.32)	0.52 (0.8)	n.d.	9.79 (14.44)
2,4-Decadienal																			25.33 (4.51)	n.d.	n.d.	n.d.	3.12 (4.06)
trans-2-decenal																			25.33 (9.70)	3.60 (6.40)	0.50 (1.20)	0.50 (1.20)	8.23 (9.27)
s-2-decenal		16,100	26,400																n.d.	0.82 (1.08)	2.20 (5.29)	3.67 (2.94)	
2-Undecenal		18,400	29,400																20.67 (7.64)	3.81 (5.21)	2.02 (3.62)	3.33 (2.34)	8.23 (10.07)

Table 15. Ketones and lactones emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	Schauer et al., 2002						McDonald et al., 2003						Zhao et al., 2007b				Zhao et al., 2007c	
Compound class	stir fry in soybean oil		stir fry in canola oil		deep frying of potatoes in hydrogenated oil		Hamburger Auto-Char	Hamburger Under-Char	Steak Under-Char	Chicken Under-Char	Hamburger Griddle	Chicken Griddle	Cantonese style	Sichuan style	Dongbei style	Hunan style	Western-style fast food	Chinese cooking
Units	μg/kg of vegetables cooked				μg/kg of potatoes		mg/kg						ng/mg of POM				ng/mg of POM	
Compound class	Gas	Particle	Gas	Particle	Gas	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle	Particle
Ketones																		
2-nonanone	3300				78		2.69	11.95	7,50	11.35	0.55	0.59	116±90	326 ±90	504 ± 44	213± 43	240±99	290
2-decanone	2670		3130		590		1.27	5.74	4.06	4.46	0.26	0.58	116±91	361±108	589 ± 45	235 ± 46	203±165	325
2-undecanone	2310				145		1.03	4.25	3.52	2.73	0.28	0.26	58 ±50	259 ± 72	386 ± 39	197± 44	110±135	225
2-Dodecanone													nd	102±42	151±19	69 ± 12	10±24	81
2-tridecanone					84								nd	35 ± 86	64 ± 100	20 ± 49	17±40	30
2-tetradecanone					180								nd	23 ± 56	103± 54	65 ± 95	28±69	48
2-pentadecanone	3900	170	8050	120	1100	30							234 ± 152	592 ± 262	844 ± 181	401± 138	5419±1288	518
2-Hexadecanone													nd	16±26	39 ± 51	8 ± 19	994±177	16
2-heptadecanone	720	60	860	75	300								667 ± 180	1003±489	1383±330	594 ± 134	15,682±2321	912
Furanones (Lactones)																		
5-ethyldihydro-2(3H)-furanone	470		370		41													
5-propyldihydro-2(3H)-furanone	170		170		11								6 ± 16	70 ± 41	86 ± 35	53 ± 17	24±29	54
5-butyldihydro-2(3H)-furanone	430	17	670	30	240	10							21± 45	188± 96	172± 47	177± 67	211±59	140
5-pentyldihydro-2(3H)-furanone	280	30	470	38	75	7	2.69	11.95	7.5	11.35	0.55	0.59	20 ± 42	221± 138	288 ± 135	134± 44	208±76	166
5-hexyldihydro-2(3H)-furanone	74	45	130	40	49	9	1.27	5.74	4.06	4.46	0.26	0.58	8 ± 21	90 ± 44	119±39	56 ± 15	109±45	69
5-heptyldihydro-2(3H)-furanone	33	5		5		3							5 ± 11	65 ± 28	102± 34	39 ± 9	94±18	53
5-octyldihydro-2(3H)-furanone		43		53		1							12± 20	74 ± 37	120± 35	94 ± 33	228±65	75
5-nonyldihydro-2(3H)-furanone		29		33		2							4 ± 9	71± 24	91± 11	37 ± 9	358±69	51
5-decyldihydro-2(3H)-furanone		3		4		1							43 ± 40	117±46	157± 35	58 ± 30	774±604	94
5-undecyldihydro-2(3H)-furanone		41		30		2	1.03	4.25	3.52	2.73	0.28	0.26	50 ± 56	179± 74	147± 42	84 ± 14	1212±337	115
5-dodecyldihydro-2(3H)-furanone		12		10		1							809 ± 125	1401±466	1260± 182	739 ± 135	6646±1235	1052
5-Tridecyldihydro-2(3H)-furanone													19± 23	58 ± 22	7 ± 11	15± 13	885±180	25
5-Tetradecyldihydro-2(3H)-furanone													329 ± 78	311±112	178± 35	184± 37	2573±661	250

Table 16. Concentrations of organic ions emitted from cooking food

Reference	See and Balasubramanian, 2008				
Pollutant	Steaming	Boiling	Stir-frying	Pan-frying	Deep-frying
Units	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3
Organic Ions					
Acetate	0.09 ± 0.02	0.19 ± 0.02	0.67 ± 0.05	0.77 ± 0.07	1.0 ± 0.1
Formate	0.07 ± 0.01	0.14 ± 0.02	0.32 ± 0.03	0.33 ± 0.04	0.39 ± 0.05
Methanesulfonate	BDL	BDL	BDL	BDL	BDL
Pyruvate	BDL	BDL	BDL	BDL	BDL
Succinate	2.2 ± 0.4	3.3 ± 0.6	5.0 ± 0.8	7.8 ± 0.9	14.3 ± 1.6
Glutarate	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	0.02 ± 0.01	0.04 ± 0.01
Malonate	BDL	BDL	BDL	BDL	BDL
Oxalate	0.39 ± 0.05	0.47 ± 0.06	0.78 ± 0.12	0.79 ± 0.15	0.93 ± 0.18

Table 17. Molecular markers, amides and other organic compounds emitted from cooking food - indoor concentrations and emission factors (see columns for units)

Reference	He et al., 2004b		Zhao et al., 2007b				Zhao et al., 2007c		McDonald et al., 2003					
Compound class	Hunan cooking	Cantonese cooking	Cantonese style	Sichuan style	Dongbei style	Hunan style	Western-style fast food cooking	Chinese cooking	Hamburger Auto-Char	Hamburger Under-Char	Steak Under-Char	Chicken Under-Char	Hamburger Griddle	Chicken Griddle
Units	ng/mg of particles emitted		ng/mg of POM				ng/mg of POM		mg/kg					
Sterols														
Cholesterol	525	369	261 ± 61	353 ± 125	114 ± 19	315 ± 84			1.35	7.44	1.41	7.87	0.004	0.29
Stigmasterol	336.9	145.2	619 ± 104	621 ± 245	84 ± 17	516 ± 133								
β-sitosterol	1352	2604	1168 ± 181	1313 ± 527	293 ± 31	1080 ± 286								
Monosaccharide Anhydrides														
Galactosan	2.2	6.1	nd	20 ± 7	30 ± 11	4 ± 4								
Mannosan	2.8	7.4	nd	7 ± 3	14 ± 9	3 ± 2								
Levoglucosan	50.5	196.8	282 ± 147	218 ± 56	554 ± 296	124 ± 33								
Other compounds														
2-Pentylfuran	49.1	52.6	237 ± 127	237 ± 119	170 ± 228	82 ± 40								
Benzoic acid	ND	10	39 ± 11	30 ± 6	20 ± 6	17 ± 4								
Amides														
Tetradecanamide			nd	3 ± 8	3 ± 6	nd	841±173	1						
Hexadecanamide			376 ± 99	249 ± 57	494 ± 137	172 ± 47	2797±676	323						
9-Octadecenamide			185 ± 73	112 ± 23	165 ± 54	92 ± 23	344±231	139						
Octadecanamide			129 ± 33	48 ± 25	53 ± 28	43 ± 13	710±186	68						

Table 18. EC/OC, metals and inorganic ions emitted from cooking food -indoor concentrations and emission factors (see columns for units)

Reference	McDonald et al., 2003						See and Balasubramanian, 2008					See and Balasubramanian, 2006	He et al., 2004b	
Pollutant	Hamburger Auto-char	Hamburger Under-Char	Steak Under-Char	Chicken Under-Char	Hamburger Griddle	Chicken Griddle	Steaming	Boiling	Stir-frying	Pan-frying	Deep-frying	Chinese cooking in Commercial food stall	Hunan cooking	Cantonese cooking
Units	mg/Kg						$\mu g/m^3$					$\mu g/m^3$	wt%	
EC/OC														
EC	119	343.55	201.9	19.14	n.d	n.d.	6.16 ± 0.71	8.11 ± 1.08	14.5 ± 1.4	14.7 ± 2.0	15.8 ± 2.2		1	1.6
OC	4464.21	15541.42	7061.25	6881.12	n.d	n.d	29.3 ± 3.6	36.1 ± 4.0	62.6 ± 5.6	71.6 ± 7.0	121.5 ± 16.3		81.6	52.6
Metals														
Al	0.95	4.88	0	0	n.d	n.d.	61.7 ± 8.7	64.5 ± 9.4	72.3 ± 8.5	83.1 ± 8.1	137.3 ± 12.6	523.6±78.0		
As							10.5 ± 1.7	11.9 ± 1.9	17.9 ± 2.0	21.6 ± 2.6	28.9 ± 3.2	17.1±2.4		
Cd							2.17 ± 0.23	3.16 ± 0.52	6.67 ± 0.86	6.58 ± 0.68	13.1 ± 1.2	4.2±0.5		
Co							0.56 ± 0.07	0.70 ± 0.06	1.07 ± 0.11	1.61 ± 0.11	1.63 ± 0.24	9.7±1.0		
Cr							29.7 ± 2.9	30.4 ± 2.7	57.0 ± 4.0	68.4 ± 5.3	95.2 ± 9.2	137.1±14.6		
Cu	0.13	0	0	0	n.d	n.d.	367.2 ± 20.9	416.5 ± 41.7	670.1 ± 54.9	1093 ± 126	1107 ± 119	3534.5±426.2		
Fe	1.76	6.06	0	0	n.d	n.d.	441.5 ± 59.5	527.4 ± 68.0	1693 ± 196	3157 ± 335	4527 ± 463	4754.8±480.9		
Mn							12.5 ± 1.3	19.5 ± 1.9	28.9 ± 3.0	54.5 ± 4.6	62.8 ± 8.5	128.6±14.9		
Ni							20.9 ± 2.1	24.0 ± 4.2	30.7 ± 3.1	45.2 ± 3.2	71.2 ± 10.2	119.8±14.1		
Pb							10.6 ± 1.4	12.2 ± 1.3	52.5 ± 4.6	55.7 ± 6.2	109.6 ± 12.5	480.0±50.8		
V							16.7 ± 2.3	20.5 ± 2.3	22.9 ± 2.4	30.8 ± 2.9	74.1 ± 8.6	272.2±29.0		
Ti							69.0 ± 8.6	102.5 ± 14.4	190.0 ± 27.1	223.9 ± 22.4	368.8 ± 51.6			
Zn	4.15	0	0	0	n.d	n.d.	529.9 ± 48.8	558.0 ± 38.9	796.0 ± 53.8	815.0 ± 73.8	937.4 ± 110.6	5486.9±755.7		
Sb												163.0±16.6		
Inorganic Ions														
Li^+							BDL	BDL	BDL	BDL	BDL			
Na^+							0.48 ± 0.08	0.54 ± 0.09	0.44 ± 0.05	0.45 ± 0.08	0.56 ± 0.11		0.29	0.15
NH_4^+	0.52	2.53	0	0	n.d	n.d.	1.0 ± 0.1	1.2 ± 0.1	1.1 ± 0.1	1.3 ± 0.1	1.3 ± 0.3		0.13	0.34
K^+	12.81	60.14	4.86	0	n.d	n.d.	1.2 ± 0.1	1.3 ± 0.2	0.87 ± 0.11	1.0 ± 0.2	1.1 ± 0.3		0.06	0.05
Mg^{2+}							BDL	BDL	BDL	BDL	BDL		0.02	0.02
Ca^{2+}							0.63 ± 0.08	0.73 ± 0.10	0.59 ± 0.08	0.95 ± 0.09	0.99 ± 0.10		0.1	0.1
F^-							1.9 ± 0.4	3.2 ± 0.5	0.52 ± 0.07	0.55 ± 0.08	1.1 ± 0.2			
Cl^-	3.25	14.23	0	0	n.d	n.d.	1.3 ± 0.2	2.6 ± 0.3	0.39 ± 0.04	0.56 ± 0.08	0.98 ± 0.11		0.3	0.24
NO_2^-							BDL	BDL	BDL	BDL	BDL			
NO_3^-	0.54	7.15	0	0	n.d	n.d.	5.1 ± 0.6	6.0 ± 0.6	4.4 ± 0.4	4.5 ± 0.4	5.0 ± 0.4		0.32	0.34
SO_4^{2-}	4.68	17.01	0	0	n.d	n.d.	3.9 ± 0.5	4.1 ± 0.7	3.1 ± 0.3	3.3 ± 0.4	3.4 ± 0.5		0.23	0.77
PO_4^{3-}							BDL	BDL	BDL	BDL	BDL			

Table 19. Comparison of diagnostic ratios of PAHs

REFERENCES	SOURCE OF PM	Pollutant	Phe/ (Phe+Ant)	Flu/ (Flu+Pyr)	BaA/ (BaA+Chry)	Ind/ (Ind+Bpe)	BeP/ (BaP+BeP)	Ant/ (Ant+Phe)	IcP/ (IcP+BgP)
COOKING STYLES									
See et al., 2006	CHINESE	$PM_{2.5}$	0.21	0.32	0.4	0.43			
	MALAY	$PM_{2.5}$	0.28	0.38	0.32	0.38			
	INDIAN	$PM_{2.5}$	0.21	0.43	0.5	0.39			
Li et al., 2003	CHINESE	TSP and gas	0.86	0.5	0.62	0.63			
	WESTERN	TSP and gas	0.86	0.46	0.38	0.63			
	FAST FOOD	TSP and gas	0.96	0.6	0.32	0.53			
	JAPANESE	TSP and gas	0.97	0.66	0.13	0.83			
He et al., 2004	CHINESE, HUNAN	$PM_{2.5}$	0.96	0.44	0.51	–			
	CHINESE, CANTONESE	$PM_{2.5}$	1	0.36	0.47	0.19			
Zhu and Wang, 2003	CHINESE	TSP and gas	0.51	0.18	0.74	–			
	CHINESE	TSP and gas	0.41	0.19	0.18	–			
	CHINESE	TSP and gas	0.37	0.23	0.22	–			
	CHINESE	TSP and gas	0.51	0.23	0.38	–			
COOKING METHODS									
See and Balasubramanian, 2008	STEAMING	$PM_{2.5}$	0.96	0.51	0.31	0.54			
	BOILING	$PM_{2.5}$	0.96	0.52	0.34	0.52			
	STIR-FRYING	$PM_{2.5}$	0.94	0.56	0.28	0.45			
	PAN-FRYING	$PM_{2.5}$	0.94	0.55	0.29	0.46			
	DEEP-FRYING	$PM_{2.5}$	0.95	0.53	0.28	0.44			
OTHER SOURCES									
CITY OF SHANGAI Gu et al., 2010	TRAFFIC			0.52	0.27		0.63	0.13	0.45
Miguel and Pereira, 1989	TRAFFIC			0.4-.5					
	PETROLEUM			<0.2					
	GRASS			>0.5					

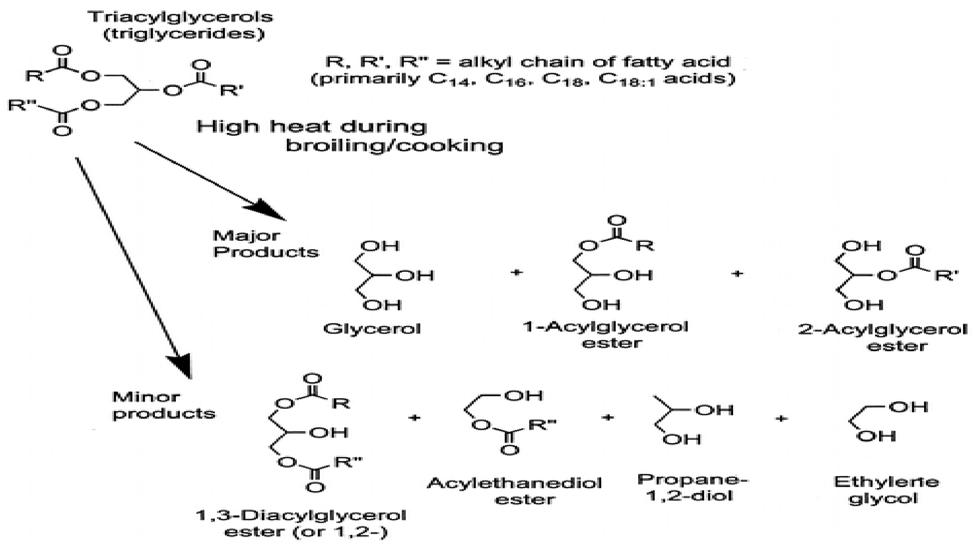

Figure 1: Break down products of triglycerides (Nolte et al., 1999)

Figure 2: Marker to OC ratio for meat cooking profiles (Robinson et al., 2006)