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Characteristics of $PM_{2.5}$ emissions from six types of commercial cooking in Chinese cities and their health effects☆

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ABSTRACT

Commercial kitchens may pose significant health risks to workers because they generate large quantities of fine particulate matter ($PM_{2.5}$). In our study, the concentrations and emission rates of $PM_{2.5}$ in cooking environments were measured for six types of commercial kitchens that used electricity and natural gas (including traditional Chinese kitchens, western kitchens, teppanyaki kitchens, fried chicken kitchens, barbecue kitchens, and hotpot cooking area). Furthermore, a preliminary health risk assessment of the chefs was undertaken using the annual $PM_{2.5}$ inhalation and $PM_{2.5}$ deposition rates into the upper airways and tracheobronchial and alveolar regions of the human body. Results showed that cooking in the teppanyaki kitchen generated the highest amount of $PM_{2.5}$, with a mean emission rate of 7.7 mg/min and a mean mass concentration of 850.4 ± 533.4 μg/m^3 in the breathing zone. Therefore, teppanyaki kitchens pose highest $PM_{2.5}$ exposure risks to chefs, with the highest rate of $PM_{2.5}$ deposition in the upper airways (6.38×10^5 μg/year), followed by Chinese kitchens. The $PM_{2.5}$ concentrations and emission rates of each kitchen varied greatly with the dishes cooked. The mean $PM_{2.5}$ concentration was the highest during Chinese stir-frying, with the peak concentration reaching more than 20,000 μg/m^3, followed by pan-frying, deep-frying, stewing, and boiling. A rise in $PM_{2.5}$ concentration was also observed during the start of stir-frying and in the middle to late stages of pan-frying and grilling meat. The results obtained in our study may contribute in understanding the characteristics of $PM_{2.5}$ emissions from various types of commercial kitchens and their health effects.

1. Introduction

$PM_{2.5}$ is particulate matter (PM) with an aerodynamic diameter of less than 2.5 μm (Chow et al., 1994). In urban areas, $PM_{2.5}$ is commonly found in indoor air owing to cigarette combustion (Chen et al., 2018a), aromatherapy combustion (Orecchio, 2011), and high-temperature cooking (Kang et al., 2019; Li et al., 2015). When cooking with electricity and natural gas, significant amounts of $PM_{2.5}$ are generated from high-temperature decomposition of ingredients during cooking and chemical reactions occurring in the air (Chen et al., 2020; Rogge et al., 1991; Wang et al., 2017). Various factors can influence $PM_{2.5}$ emission from cooking, including the cooking style, method, ingredients, and types of cookware (Abdullahi et al., 2013). Cooking of western fast food and Chinese food generated 2.1 and 6.7 times more $PM_{2.5}$, respectively, than that generated when cooking Japanese food (Xu et al., 2020). Different cooking methods for the same cooking style can also significantly impact $PM_{2.5}$ emission, with stewing processes generating 40–50% less $PM_{2.5}$ than that generated during stir- and pan-frying processes when cooking Chinese food (See and Balasubramanian, 2008). In addition, cooking high-fat ingredients such as pork and beef results in fat pyrolysis, which generates $PM_{2.5}$ at higher indoor concentrations than that generated when cooking vegetables (Buonanno et al., 2009). Different types of cooking oils also have different $PM_{2.5}$ emission rates, such as lower emission rates when heating soybean oil compared to those when heating olive oil (Gao et al., 2013; Torkmahalleh et al., 2012).

$PM_{2.5}$ can enter the lungs and circulatory systems of human (Kwon et al., 2020; Liu et al., 2019; Wang et al., 2015a, 2015b). Existing studies

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have demonstrated an association between exposure to $PM_{2.5}$ from the cooking and carcinogenic risk (Zhang et al., 2017). The chemical composition of $PM_{2.5}$ from the cooking process consists mainly of organic carbon, water-soluble ions (Cl^-, SO_4^{2-}, NO^{3-}, K^+, Ca^{2+}, and Mg^{2+}), metals, volatile organic compounds, carbonyls, and polycyclic aromatic hydrocarbons (PAHs) (Abdullahi et al., 2013; Bandowe et al., 2021; Wang et al., 2017). Several studies have demonstrated that PAHs, heavy metals, and aldehydes are the major components that can affect human health (Ho et al., 2006; Karimi et al., 2015; Li et al., 2013). PAHs can cause asthma and other allergies in children and adults and can damage DNA (Jedrychowski et al., 2007; Karimi et al., 2015; Wei et al., 2009). High risk of cancer and damage to lung cells in people exposed to high concentrations of metals (Fang and Zheng, 2014; Zhang et al., 2017). Huang et al. (2011) reported that formaldehyde and acetaldehyde generated from cooking activities also pose a high carcinogenic risk for chefs. Human inhalation of these carcinogens is closely related to the presence of $PM_{2.5}$ in cooking environments.

Commercial cooking when compared to domestic cooking is performed at a larger scale and different ventilation rates. Generally, commercial kitchens are more polluted, have high and more hazardous indoor $PM_{2.5}$ concentrations, and lead to higher $PM_{2.5}$ concentrations in the outdoor environment adjacent to the commercial kitchens (Bandowe et al., 2021; Levy et al., 2002; Sun et al., 2020). More polluted commercial kitchens have higher requirements for designers and engineers to design the interior layouts and select appropriate ventilation equipment (Chen et al., 2018b; Hussein et al., 2006; Wan et al., 2011; Wang et al., 2022).

Most studies on $PM_{2.5}$ emissions from commercial kitchens have focused on western and traditional Chinese kitchens, and most of the experiments have been conducted using the gravimetric method to collect $PM_{2.5}$ samples and analyze their composition (Abdullahi et al., 2018; Bandowe et al., 2021; Liu et al., 2019; Sun et al., 2020; Xu et al., 2020). Few studies have comprehensively explored the emission characteristics of $PM_{2.5}$ from other cooking styles in commercial kitchens using real-time measurements. This makes it difficult to show the variations in indoor $PM_{2.5}$ concentrations during cooking in various types of kitchens and in $PM_{2.5}$ concentrations when cooking different dishes in the same kitchen. In addition, some studies on PM emissions from cooking have been conducted in artificial chambers rather than in actual kitchens (Bandowe et al., 2021; Chen et al., 2017; Wang et al., 2020). However, $PM_{2.5}$ emission characteristics measured in artificially simulated cooking environments may differ from those measured in actual cooking environments (Sun et al., 2020; Wang et al., 2020). Therefore, on-site and laboratory experiments are equally important for such studies (Xu et al., 2021). Overall, it is essential that measurements of real-time $PM_{2.5}$ concentrations and emission rates be conducted in various commercial kitchens. The results obtained in our study may be combined with laboratory experimental results to complement each other and provide a more comprehensive database for future research.

Our study aimed to measure the real-time indoor $PM_{2.5}$ concentrations and calculate the $PM_{2.5}$ emission rates of six types of commercial kitchens (traditional Chinese commercial kitchen, western kitchen, fried chicken kitchen, teppanyaki kitchen, barbecue kitchen, and hotpot cooking area). The indoor $PM_{2.5}$ concentrations and emission rates in these six commercial kitchens during cooking were compared. Health risk assessments of the chefs in the kitchens were conducted using the annual $PM_{2.5}$ inhalation and $PM_{2.5}$ deposition rates in the upper airways, tracheobronchial, and alveolar regions.

2. Experiment method

2.1. Instruments and measurements

Six small- and medium-sized commercial kitchens with different cooking styles (traditional Chinese kitchen, western kitchen, fried chicken kitchen, teppanyaki kitchen, barbecue kitchen, and hotpot cooking area) in Shanghai were selected for on-site measurements in November 2021. Measurements were taken once in each kitchen, and the durations are listed in Supplementary Table S1. As the restaurants selected in this study primarily catered to students and teachers, these restaurants had a steady flow of customers (FC) during meal hours every day (10 people min^{-1}> FC > 7 people min^{-1}). Measurements were taken for each kitchen during the lunch or dinner hours. Hotpot cooking area is a special type of cooking area where the cooking and dining areas are integrated; thus, measurements of $PM_{2.5}$ concentrations were taken in the dining area. During the measurements, four kitchens used exhaust hoods, except for the western kitchen, which used exhaust fans, and the hotpot cooking area, which did not use any exhaust equipment. The air conditioning was turned off in all the tested kitchens. The tested kitchens did not use wood, coal, or other solid fuels that can produce significant amounts of $PM_{2.5}$ when burned. Electricity was used for cooking in the hotpot cooking area and the western and teppanyaki kitchens, while natural gas was used in the remaining kitchens. The Supplementary Table S2 summarizes the characteristics of the various kitchens.

The measuring points were arranged in accordance with the requirements of the National Standard of the People's Republic of China "Indoor Air Quality Standard GB18883-2002," which states that 1–3 measuring points are required for an indoor area of less than 50 m^2. As all the tested kitchens were less than 50 m^2 in area, two measuring points were used. The locations of the measuring points were determined based on previous studies (Wan et al., 2011; Zhao et al., 2019; Zhao and Zhao, 2020), which also used two measuring points per kitchen. Measuring point 1 was located in the breathing zone of the cook (0.3 m from the edge of the pot, 1.5 m (standing)/1.2 m (sitting) from the floor). Measuring point 2 was located as far as possible in the middle of the kitchen at a height of 1.2 m above the ground. Supplementary Fig. S1 shows the layout of the six kitchens. Two SidePak personal aerosol monitors (AM520; TSI Inc., Shoreview, MN, USA) equipped with 2.5 μm particle cutter heads were used to measure $PM_{2.5}$ concentrations at the measuring points on a real-time basis. The SidePak Model AM520 monitors were calibrated prior to the experiments, and the details of the zero calibration, inter-instrument calibration, and concentration calibration factors are shown in Supplementary Fig. S2. The data loggers (TR-76Ui; T&D Corporation, Matsumoto, Japan) equipped with a temperature sensor (range: 0–45 °C, accuracy: ±0.5 °C), relative humidity sensor (range: 10–95%, accuracy: ±5%), and CO_2 concentration sensor (range: 0–9999 ppm, accuracy: ±50 ppm + 5%) were located at the measuring points (Cao et al., 2022). A thermal anemometer (Testo-425; Testo SE&Co. KGaA, Lenzkirch, Germany) was used to determine the exhaust air velocity of the smoke extraction equipment.

The measurements were taken in commercial kitchens, wherein dishes were prepared by professional chefs, except in the case of hotpot cooking area. The number of chefs was not limited and was consistent with what was required each day. Notably, four chefs in the Chinese kitchen cooked the same meal simultaneously, whereas only one chef cooked at a time in the other kitchens. There were three measurement periods: 1) before cooking: the windows and doors were opened, and the exhaust hood was turned on for at least 8 min to reduce the concentration of pollutants in the room until it stabilized; 2) during cooking: the windows and doors were closed and only the exhaust hood was turned on; and 3) after cooking: the windows and doors remained closed and the exhaust hood was turned off for at least 15 min. The AM520 personal aerosol monitors and data loggers were turned on during the measurements, and the data-recording interval was set to 1 s. All the equipment remained stationary throughout the measurement. A thermal anemometer was used to measure exhaust air velocity at multiple points before cooking. In addition, the chefs prepared the ingredients before cooking, so they could simply wash the pans and begin cooking the next dish after completing each dish. Therefore, the time spent preparing the ingredients and cleaning the cookers was not considered in the measurement period of the experiment. A summary of the dishes cooked in each kitchen is provided in Supplementary Table S1.

2.2. Data analysis

2.2.1. Determination of the decay rate constant

The mass balance equation for indoor particles is expressed as follows (Chen et al., 2017):

$$\frac{dC_{in}(t)}{dt}=\left(a+\frac{Q_{ex}}{V}\right)\times P\times C_{out}-\left(a+\frac{Q_{ex}}{V}+k\right)\times C_{in}(t)+\frac{S}{60\times V} \tag{1}$$

where $C_{in}(t)$ and $C_{out}(t)$ are the indoor and outdoor particle concentrations (mg/m^3), respectively; a is the infiltration rate of the indoor environment (h^{-1}); k is the indoor ultrafine particle deposition rate (h^{-1}); Q_{ex} is the exhaust air rate (m^3/h); V is the kitchen volume (m^3); P is the fraction of particles entering the indoor environment through the building envelope (−); and S is the emission rate (mg/min).

The indoor $PM_{2.5}$ concentration at the steady state before the start of cooking is expressed as follows:

$$C_{balance}=\frac{\left(a+\frac{Q_{ex}}{V}\right)\times P\times C_{out}}{a+\frac{Q_{ex}}{V}+k} \tag{2}$$

The real-time indoor particle concentration with the hood turned on is expressed as follows (assuming time t = t_1 to start cooking and t = t_2 to end cooking):

$$C_{in}(t)=\left(C_{in}(t_1)-C_{balance}-\frac{S}{\left(a+\frac{Q_{ex}}{V}+k\right)\times V}\right)\times e^{-\left(a+\frac{Q_{ex}}{V}+k\right)\times t}+C_{balance}+\frac{S}{\left(a+\frac{Q_{ex}}{V}+k\right)\times V} \tag{3}$$

The real-time indoor particle concentration after cooking with the hood turned off is expressed as follows:

$$C_{in}(t)=\left(C_{in}(t_2)-\frac{a}{(a+k)}\times\frac{a+\frac{Q_{ex}}{V}+k}{\left(a+\frac{Q_{ex}}{V}\right)}\times C_{balance}\right)\times e^{-\left(a+\frac{Q_{ex}}{V}+k\right)\times t}+\frac{a}{(a+k)}\times\frac{a+\frac{Q_{ex}}{V}+k}{\left(a+\frac{Q_{ex}}{V}\right)}\times C_{balance} \tag{4}$$

For the cooking environment $C_{out} \ll C_{in}$, Eq. (4) can be converted into the following:

$$C_{in}(t)=C_{in}(t_2)\times e^{-(a+k)\times(t-t_2)} \tag{5}$$

By combining $a+k$ in Eq. (5) as the decay rate K of $PM_{2.5}$, Eq. (5) can be converted to the following:

$$C_{in}(t)=C_{in}(t_2)\times e^{-K\times(t-t_2)} \tag{6}$$

A non-linear fit of the real-time indoor $PM_{2.5}$ concentration after cooking gives the K value.

The $PM_{2.5}$ concentration at measuring point 1 represents the $PM_{2.5}$ concentration in the chef's breathing zone, which is denoted as $C_1(t)$. The $PM_{2.5}$ concentration data at measuring point 2 was considered as the mean indoor concentration, which is denoted as $C_2(t)$.

2.2.2. Determination of emission rate

For cooking environments with the hood turned on ($C_{out} \ll C_{in}$), Eq. (3) can be converted into the following:

$$C_{in}(t)=\left(C_{in}(t_1)-\frac{S}{\left(\frac{Q_{ex}}{V}+K\right)\times V}\right)\times e^{-\left(\frac{Q_{ex}}{V}+K\right)\times t}+\frac{S}{\left(\frac{Q_{ex}}{V}+K\right)\times V} \tag{7}$$

After calculating the K value in each kitchen, the K value and actual indoor $PM_{2.5}$ concentration during cooking were added to Eq. (7), and the $PM_{2.5}$ emission rates during cooking were determined.

2.2.3. $PM_{2.5}$ concentration normalization

In an on-site experiment, it is difficult to control the amount of cooking in the kitchens. In a study by Zhu and Wang (2003), the amount of PAHs generated during each cooking process was determined by averaging the total concentrations of PAHs of individual samples. Our study referred to their method and normalized the $PM_{2.5}$ concentrations in the breathing zones of the chefs during cooking, which is expressed as follows:

$$\mathrm{C_{ave}}=\frac{\int_{t1}^{t2}\mathrm{C_1(t)Dt}}{\mathrm{t2-t1}} \tag{8}$$

$$C_{\mathrm{nomal}}=C_{\mathrm{ave}}\times\frac{\mathrm{n}}{\sum_1^{\mathrm{n}}\mathrm{M_i}} \tag{9}$$

where, for each kitchen measured, C_{ave} is the mean concentration in the breathing zone during cooking (μg/m^3); C_{nomal} is the normalized mean $PM_{2.5}$ concentration in the breathing zone during cooking (μg/m^3 kg^{-1}); M_i is the amount of ingredients (kg) used to cook each dish; and n is the number of dishes.

2.2.4. $PM_{2.5}$ exposure and health risk assessment

The annual inhalation rate of $PM_{2.5}$, which was used as an exposure indicator to assess the risk of PM exposure (Jo et al., 2017), was calculated as follows:

$$D_{pot}=\left(\int_{T0}^{T1}C_1(t)\,Dt+\int_{T1}^{T2}C_1(t)\,Dt+\int_{T2}^{T3}C_1(t)\,Dt\right)\times IR\times EF \tag{10}$$

where D_{pot} is the annual $PM_{2.5}$ inhalation dose (μg/year); T_0 to T_1 is the time the chef spends in the kitchen before cooking during the day (h); T_1 to T_2 is the cooking time during the day (h); T_2 to T_3 is the time the chef spends in the kitchen after cooking during the day (h); IR is the human inhalation rate, which is 0.66 m^3/h for males and 0.59 m^3/h for females (Lu et al., 2019); and EF is the exposure frequency (day/year). The EF of the kitchen staff was determined by the labor standards of the People's Republic of China and the U.S. Fair Labor Standards Act (both of which state that workers may not work more than 40 h a week). As each staff member should work no more than 8 h a day, it was determined that the EF should be set to 250, which excluded national and double holidays when they did not work. Field questionnaire research was conducted to determine the $PM_{2.5}$ exposure time for kitchen workers; the details are summarized in the Supplementary Table S3.

In addition, it is necessary to assess the health risks associated with chefs in commercial kitchens. The respiratory deposition model proposed by the International Commission on Radiation Protection (ICRP) was used to calculate $PM_{2.5}$ deposition rate in the upper airways, tracheobronchial region, and alveolar region (Bair, 1995), using the following equation:

$$RD = D_{pot} \times DF \tag{11}$$

Where RD refers to the annual $PM_{2.5}$ deposition rate in parts of the body (μg/year), and DF is the deposition fraction in the upper airways (DF_{UA}), tracheobronchial region (DF_{TB}), and alveolar region (DF_{AL}). Supplementary Fig. S3 shows that for the deposition of $PM_{2.5}$, the deposition was approximately maximum when all the particle sizes were 2.5 μm. Our study assumed that all particle sizes were 2.5 μm, and the values of DF_{UA}, DF_{TB}, and DF_{AL} were 0.66, 0.006, and 0.108, respectively (Bair, 1995).

2.3. Statistical analysis

A one-way repeated measures analysis of variance was used to analyze the differences between $PM_{2.5}$ emission rates within the same kitchen when cooking different dishes. The least significant difference post hoc test was used when equal variance existed, and Tamhane's T2 post hoc test was applied when the variances were unequal. Correlation analyses of the data were performed using Spearman's correlation analysis. The Spearman coefficient between the two variables were strongly correlated at greater than 0.6, moderately correlated at 0.4–0.6, and weakly correlated at 0.2–0.4. The nonparametric Wilcoxon rank sum test was used to assess the statistical differences between the $PM_{2.5}$ concentrations in the breathing zone and the mean indoor $PM_{2.5}$ concentration recorded by the 2 AM520 monitors in the tested kitchen. Two-tailed statistical significance tests were performed, and $p < 0.05$ was considered to indicate a statistically significant difference. All data were statistically analyzed using SPSS software (version 26.0; SPSS, Inc., Chicago, IL, USA).

Table 1
Spearman's correlation coefficients between $PM_{2.5}$ concentrations at measuring points 1 and 2.

	Spearman's correlation coefficients
Barbecue kitchen	0.820[a]
Hotpot cooking area	0.991[a]
Teppanyaki kitchen	0.867[a]
Western kitchen	0.731[a]
Chinese kitchen	0.466[a]
Fried chicken kitchen	0.922[a]

[a] $p < 0.01$.

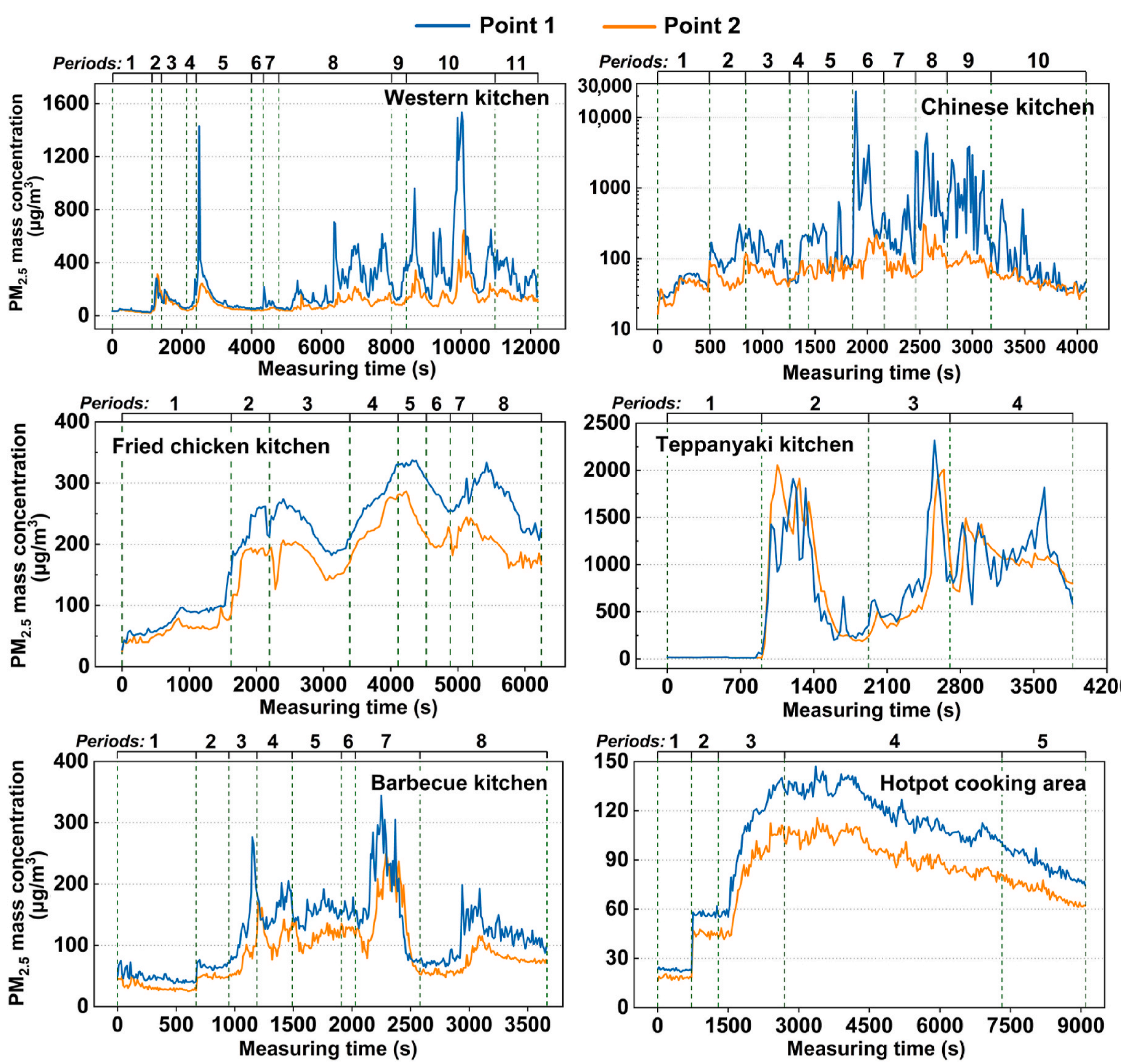

Fig. 1. Real-time $PM_{2.5}$ concentrations at measuring points 1 and 2 during measurement in six types of kitchens.

3. Results

3.1. $PM_{2.5}$ concentrations

In our study, $C_1(t)$ and $C_2(t)$ were the real-time $PM_{2.5}$ concentrations in the breathing zones of the chefs and the mean indoor $PM_{2.5}$ concentration, respectively. Fig. 1 shows the $C_1(t)$ and $C_2(t)$ values during the experiments. The results of Spearman's correlation analysis are shown in Table 1. The $C_1(t)$ and $C_2(t)$ values in the kitchen showed a strong correlation, except for the Chinese kitchen, which showed moderate correlations.

The $PM_{2.5}$ concentration characteristics in the breathing zone during the cooking process for each dish are listed in Supplementary Table S4. The teppanyaki kitchen had the highest mean C_1 value during cooking (850.4 ± 533.4 μg/m^3), followed by that of the Chinese kitchen (679.1 ± 1922.5 μg/m^3), western kitchen (272.2 ± 250.1 μg/m^3), fried chicken kitchen (257.2 ± 44.5 μg/m^3), barbecue kitchen (146.6 ± 59.8 μg/m^3), and hotpot cooking area (110.8 ± 59.8 μg/m^3). The barbecue kitchen contained the highest normalized $PM_{2.5}$ concentrations for the breathing zone (1085.9 ± 442.9 μg/m^3 kg^{-1}), followed by that of the western kitchen (561.2 ± 502.7 μg/m^3 kg^{-1}), Chinese kitchen (452.7 ± 1182.4 μg/m^3 kg^{-1}), teppanyaki kitchen (1085.9 ± 442.9 μg/m^3 kg^{-1}), fried chicken kitchen (274.3 ± 51.3 μg/m^3 kg^{-1}), and hotpot cooking area (56.7 ± 13.4 μg/m^3 kg^{-1}).

There was a significant difference between the values of $C_I(t)$ and $C_2(t)$ in the breathing zones of western kitchens during the middle and late stages of cooking (t > 4500 s; p < 0.001), with a maximum difference of more than 1400 μg/m^3. In addition, there were differences in the indoor $PM_{2.5}$ concentrations when cooking different dishes. Compared to other dishes, indoor $PM_{2.5}$ concentrations were the highest when pan-frying steak (Fig. 1a, periods 8 and 10). The mean C_1 values were 240.1 ± 160.7 and 564.6 ± 324.4 μg/m^3 for periods 8 and 10, respectively.

The mean C_1 values were relatively low during cooking periods 2, 3, and 4 of the stewing process in the Chinese kitchen (Fig. 1b), with values of 129.9 ± 62.3, 140.1 ± 58.2, and 126.1 ± 76.7 μg/m^3, respectively. The corresponding mean C_2 values were 59.0 ± 21.9, 62.3 ± 16.4, and 65.3 ± 17.8 μg/m^3, respectively. In addition, the C_I value was higher during the stir-frying process than during cooking other dishes. It increased abruptly within a short timeframe at the beginning of the stir-frying process. The peak of C_1 was observed in period 6 at 23,043.1 μg/m^3, far exceeding the maximum C_1 value during stewing (118.6 μg/m^3).

During the periods 4 to 7 in the fried chicken kitchen, the highest mean C_1 value was found when deep-frying chicken drumsticks (325.1 μg/m^3), followed by the mean C_1 values when deep-frying chicken fillets (275.3 μg/m^3), spicy chicken breasts (282.8 μg/m^3), and non-spicy chicken breasts (271.3 μg/m^3) (Fig. 1c). Fig. 1d shows that during teppanyaki cooking, the C_2 value was higher than that in other kitchens, up to 848.9 ± 602.9 μg/m^3. The $C_2(t)$ value in the teppanyaki kitchen was sometimes even higher than the $C_1(t)$ value; similar characteristics were not observed in other kitchens. In the barbecue kitchen, C_1 and C_2 values were relatively low, at less than 100 μg/m^3 during cabbage grilling (Fig. 1e, period 2). In periods 5–6, the $PM_{2.5}$ concentrations did not vary greatly. The C_1 value increased greatly when grilling meat, with a peak concentration of 306.5 μg/m^3, and the peak concentration of C_2 was 250.4 μg/m^3. In the hotpot cooking area, neither the $PM_{2.5}$ concentration in the breathing zone nor the mean indoor $PM_{2.5}$ concentration were greater than 150 μg/m^3 during cooking.

Real-time measurements of indoor CO_2 concentration, temperature, and relative humidity (RH) for the six kitchens are shown in Supplementary Fig. S4. The RH of the barbecue kitchen was the lowest among the tested kitchens at a value less than 30%. In the hotpot cooking area, the RH was maintained at a value of 85% or more, and the CO_2 concentration increased above 2000 ppm. Supplementary Table S5 provides a summary of the correlation analysis results of CO_2 concentration, RH, and temperature with $PM_{2.5}$ concentration at each measurement point.

Table 2
Comparison of non-linear fitting results of $PM_{2.5}$ decay rates at measuring points 1 and 2.

	Point 1		Point 2	
	K	R^2	K	R^2
Barbecue kitchen	4.78	0.3[a]	4.62	0.56[b]
Hotpot cooking area	0.55	0.77[b]	0.57	0.76[b]
Teppanyaki kitchen	0.88	0.11[a]	2.13	0.62[b]
Western kitchen	2.24	0.45[b]	2.21	0.8[b]
Chinese kitchen	2.77	0.13[a]	2.75	0.71[b]
Fried chicken kitchen	1.25	0.77[b]	1.52	0.7[b]

K is decay rate constant.
R^2 is coefficient of determination.
[a] $p < 0.05$.
[b] $p < 0.01$.

A positive correlation was observed between CO_2 and $PM_{2.5}$ concentration at each measurement point in the barbecue and teppanyaki kitchens (p < 0.05). In the hotpot cooking area, the $PM_{2.5}$ concentration showed a positive correlation with RH, whereas the $PM_{2.5}$ concentration in the fried chicken kitchen showed a negative correlation with RH (p < 0.05).

3.2. $PM_{2.5}$ emission rates

Table 2 shows the $PM_{2.5}$ decay rate at measurement points 1 and 2. The results show that the difference between the two K values calculated for all kitchens was small, except for that of teppanyaki kitchen. Because point 2 had a better non-linear fitting of the K value (R^2 was larger), the K values in the six kitchens were determined using $C_2(t)$ values, as shown in Fig. 2.

Fig. 3 shows the mean $PM_{2.5}$ emission rate during cooking in each kitchen, calculated according to Eq. (6). As four chefs simultaneously prepared the same dish in the Chinese kitchen during the experiment, the total emission rate was divided by four to determine the $PM_{2.5}$ emission rate from one cooking source. The differences in the emission rates of $PM_{2.5}$ during cooking in different kitchens are shown in Supplementary Table S6. The mean $PM_{2.5}$ emission rates during cooking in the Chinese, teppanyaki, and barbecue kitchens were not significantly different (p > 0.05). The highest mean $PM_{2.5}$ emission rate was 9.98 ± 5.31 mg/min for the Chinese kitchen, whereas the lowest was 0.13 ± 0.03 mg/min for the hotpot cooking area.

Fig. 4 illustrates the $PM_{2.5}$ emission rates for different dishes cooked in each kitchen. $PM_{2.5}$ emission rates were higher in the Chinese kitchen when stir-frying than when stewing, with stir-frying cabbage being the greatest source of $PM_{2.5}$ emission (mean value of 9.98 mg/min), followed by stir-fried tofu. There was no significant difference in the emission rates of $PM_{2.5}$ when stewing beef, chicken, and fish, with an mean emission rate of 5.1 mg/min (p > 0.05). The $PM_{2.5}$ emission rate for pan-frying meat was relatively high and fluctuated considerably in the western kitchen. In addition, deep-frying both fries and beef increased the emission rate by 0.8 mg/min compared to that when deep-frying only fries of approximately the same total weight. Generally, the $PM_{2.5}$ emission rate during western cooking was lower than that during Chinese cooking.

$PM_{2.5}$ emission rates fluctuated greatly when meat was pan-fried in the teppanyaki kitchen and when steaks were pan-fried in the western kitchen. In the fried chicken kitchen, when deep-frying chicken drumsticks with high fat content, the emission rate reached a peak of 8.6 ± 0.8 mg/min. When deep-frying chicken breasts with a lower fat content, the emission rate decreased. In addition, if the surface of the chicken breast was coated with spices and then deep-fried, the $PM_{2.5}$ emission rate was higher. In the hotpot cooking area, the $PM_{2.5}$ emission rate was generally low, and the emission rate when boiling meat was approximately double to that when boiling vegetables and soybean products. The $PM_{2.5}$ emission rate was three times higher when grilling meat in the

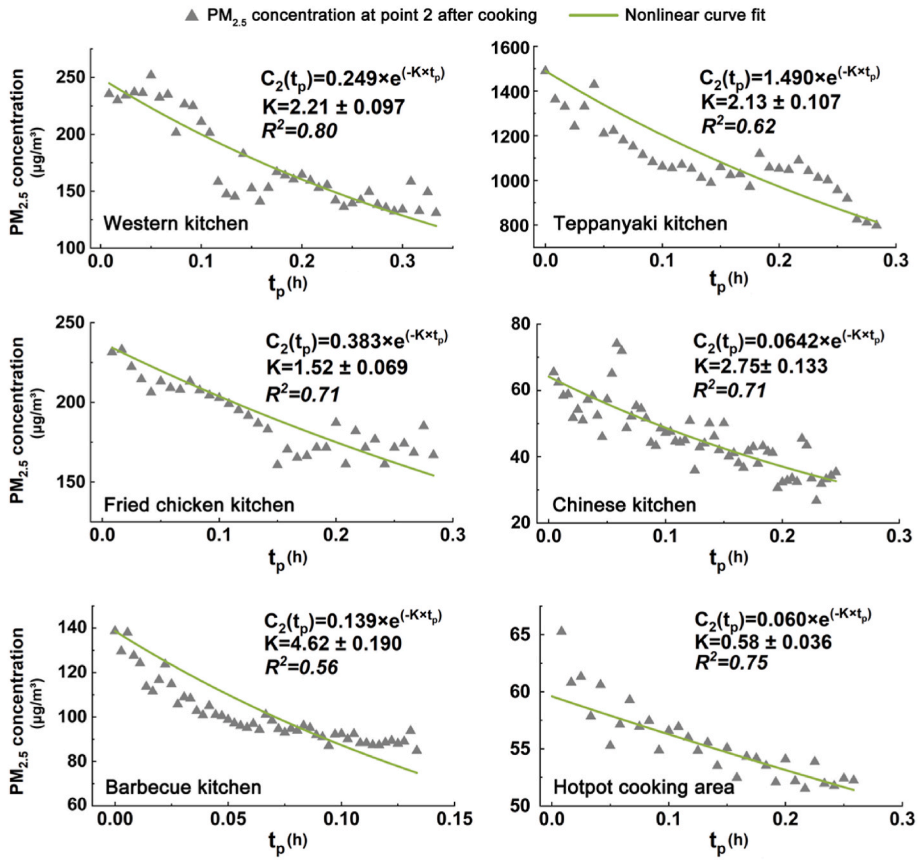

Fig. 2. Non-linear fit of $PM_{2.5}$ decay rates after cooking in six types of kitchens. t_p is the time after stopping cooking. C_2 (t_p) is $PM_{2.5}$ concentration at point 2 at t_p (grey triangle). The green curve is the nonlinear curve obtained by fitting Eq. (6) for the calculation of K. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

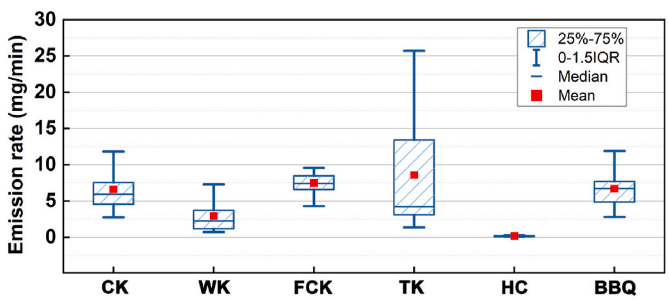

Fig. 3. $PM_{2.5}$ emission rates in six types of kitchens. (BBQ: barbecue kitchen; HC: hotpot cooking area; TK: teppanyaki kitchen; WK: western kitchen; CK: Chinese kitchen; and FCK: fried chicken kitchen).

barbecue kitchen than that when grilling cabbage.

3.3. *Exposure and health risk assessment*

Table 3 depicts the results of the $PM_{2.5}$ exposure and health risk assessments for the chefs in each kitchen. The annual $PM_{2.5}$ inhalation rates of males were slightly higher than those of females because of the higher inhalation base rate of males. The highest annual $PM_{2.5}$ inhalation rates were found in the teppanyaki kitchen (967.2 mg for men and 864.3 mg for women), followed by Chinese (798.2 mg per capita), western (293.7 mg per capita), fried chicken (277.5 mg per capita), barbecue (183.5 mg per capita), and hotpot cooking area (116.5 mg per capita). In addition, as $PM_{2.5}$ inhalation rate increased, the internal $PM_{2.5}$ deposition rate also increased. The highest $PM_{2.5}$ concentration in the cooking area of the teppanyaki kitchen resulted in its highest deposition in kitchen chefs, with the highest annual $PM_{2.5}$ deposition rate in the upper airways (604 mg per capita), followed by the alveolar (98.5 mg per capita) and tracheobronchial regions (11.1 mg per capita).

4. Discussion

The teppanyaki kitchen had the highest mean $PM_{2.5}$ concentrations in the breathing zone during cooking and the greatest variability in emission rates (Fig. 1 d). This might be because the teppanyaki chefs used a large hot teppan for cooking, and the ingredients had a larger contact area with the hot surface. In addition, oil and ingredients were more fully pyrolyzed. This increased the $PM_{2.5}$ emission rates. In addition, the mean indoor $PM_{2.5}$ concentration in the teppanyaki kitchen was sometimes higher than that in the breathing zone. It is possible that the exhaust hood installed at the edge of the teppan resulted in the easy removal of the $PM_{2.5}$ generated near the vent, whereas that generated away from the vent was more difficult to capture in a timely manner. With the airflow disturbance generated by the chef's swinging arm, these unexhausted particles quickly spread to other areas in the kitchen, causing the $PM_{2.5}$ concentration in other areas to increase significantly.

The $PM_{2.5}$ concentration in the Chinese kitchen was the second highest, followed by that in the teppanyaki kitchen, and the normalized $PM_{2.5}$ concentration was also high. Four chefs in the Chinese kitchen cooked the same dishes simultaneously. Measuring point 1 was located in the breathing zone of one of the chefs. Although point 1 was relatively far away from the other chefs, the $PM_{2.5}$ generated by the cooking of other chefs may still cause an increase in $PM_{2.5}$ concentration at point 1. However, the $PM_{2.5}$ concentrations in the breathing zone measured in our study for Chinese kitchens were in good agreement with those of the

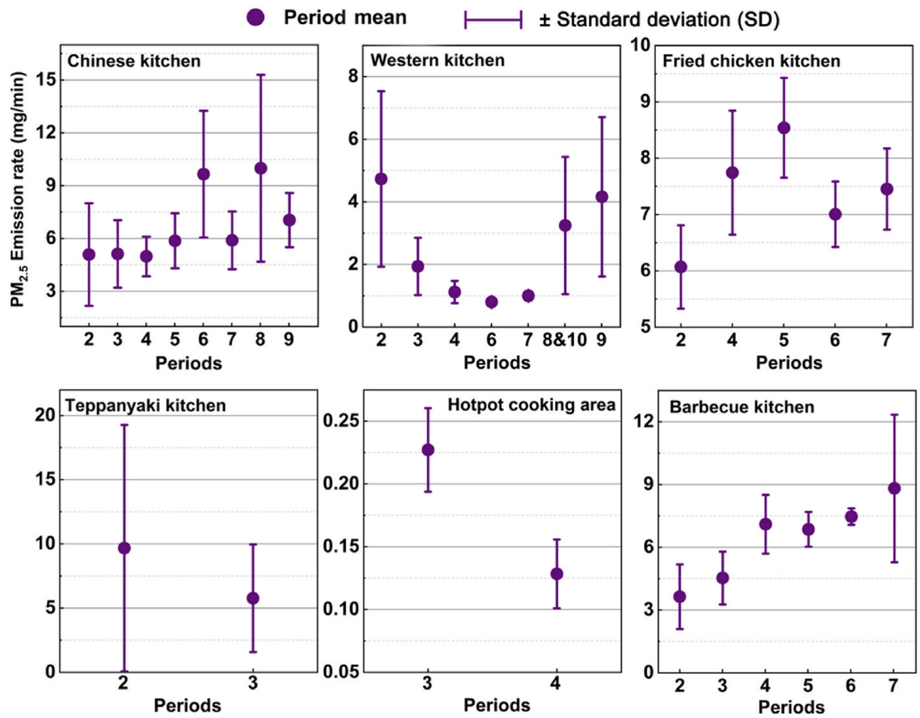

Fig. 4. $PM_{2.5}$ emission rates for different dishes cooked in six types of kitchens.

Table 3
Annual $PM_{2.5}$ inhalation and $PM_{2.5}$ deposition rates in different parts of the human body.

Kitchen Types [a]	D_{pot} (μg/year)		RD_{UA} [b] (μg/year)		RD_{TB} [c] (μg/year)		RD_{AL} [d] (μg/year)	
	Male	Female	Male	Female	Male	Female	Male	Female
CK	8.43×10^5	7.53×10^5	5.56×10^5	4.97×10^3	5.13×10^3	4.58×10^3	9.08×10^4	8.11×10^4
WK	3.09×10^5	2.76×10^5	2.04×10^5	1.81×10^5	1.88×10^3	1.68×10^3	3.32×10^4	2.97×10^4
FCK	2.93×10^5	2.62×10^5	1.93×10^5	1.72×10^5	1.78×10^3	1.59×10^3	3.16×10^4	2.82×10^4
TK	9.67×10^5	8.64×10^5	6.38×10^5	5.70×10^5	5.80×10^3	5.26×10^3	1.04×10^5	9.30×10^4
HC	1.23×10^5	1.10×10^5	8.12×10^4	7.27×10^4	7.49×10^2	6.69×10^2	1.33×10^4	1.19×10^4
BBQ	1.94×10^5	1.73×10^5	1.28×10^5	1.14×10^5	1.17×10^3	1.05×10^3	2.08×10^4	1.86×10^4

[a] BBQ: barbecue kitchen; HC: hotpot cooking area; TK: teppanyaki kitchen; WK: western kitchen; CK: Chinese kitchen; and FCK: fried chicken kitchen.
[b] RD_{UA}——deposition rate in upper airways.
[c] RD_{TB}——deposition rate in tracheobronchial region.
[d] RD_{AL}——deposition rate in alveolar region.

previous studies (Fig. 5) (He et al., 2004a, 2004b; Liu et al., 2019; Pei et al., 2016; See and Balasubramanian, 2006a; Xu et al., 2020). Some of the dishes in the Chinese kitchen were pre-prepared using semi-finished products that only required reheating during cooking, such as for stew beef with potatoes, stew fish, and stew chicken with potatoes. These reheating processes were similar to water-based cooking that has low $PM_{2.5}$ emissions (See and Balasubramanian, 2006b; Xiang et al., 2017; Zhao and Zhao, 2018). Some ingredients (e.g., tofu and cabbage) must be soaked in water before stir-frying because of their susceptibility to oxidation. Water carried by the surface entered the wok when the ingredients were stir-fried. Water droplets vaporized in the oil rather than on the surface of the oil, causing many oil droplets to splash out of the wok. This results in a sudden increase in $PM_{2.5}$ concentration in the breathing zone during the first few minutes of the Chinese cooking periods 6, 8, and 9. Previous studies have reported that water vapor affects AM520 readings (Wang et al., 2015a, 2015b). However, the Spearman correlation analyses showed no statistically positive correlation between the RH and $PM_{2.5}$ concentration in the chef's breathing zone in the Chinese kitchen during stir-frying. The water vapor generated during frying in the Chinese kitchen might have a small effect on instrument readings.

High-temperature oxidation of fats and oils produces CO_2. Several researchers have indicated that deep frying allows better contact between high-temperature oil and ingredients, leading to adequate pyrolysis of the organic matter (See and Balasubramanian, 2008; See and Balasubramanian, 2006b; To and Yeung, 2011). Therefore, $PM_{2.5}$ concentration in fried chicken kitchens showed a significant correlation with CO_2 concentration during cooking. $PM_{2.5}$ was released in greater amounts when cooking high-fat ingredients (McDonald et al., 2003). Because chicken drumsticks contain approximately twice as much fat as chicken breasts (Pikul et al., 1984), the $PM_{2.5}$ emission rate may be higher when deep-frying chicken drumsticks compared to that when deep-frying chicken breasts. Furthermore, deep-frying different types of chicken breast resulted in variability in $PM_{2.5}$ emission rates, possibly because spiced chicken breasts were more likely to scorch during cooking, resulting in a higher $PM_{2.5}$ emission rate.

The $PM_{2.5}$ concentration was lower in the western kitchen than in the Chinese kitchen, which was consistent with previous research (He et al., 2004a, 2004b). The $PM_{2.5}$ concentration in the breathing zone of the western kitchen in our study was in good agreement with that of

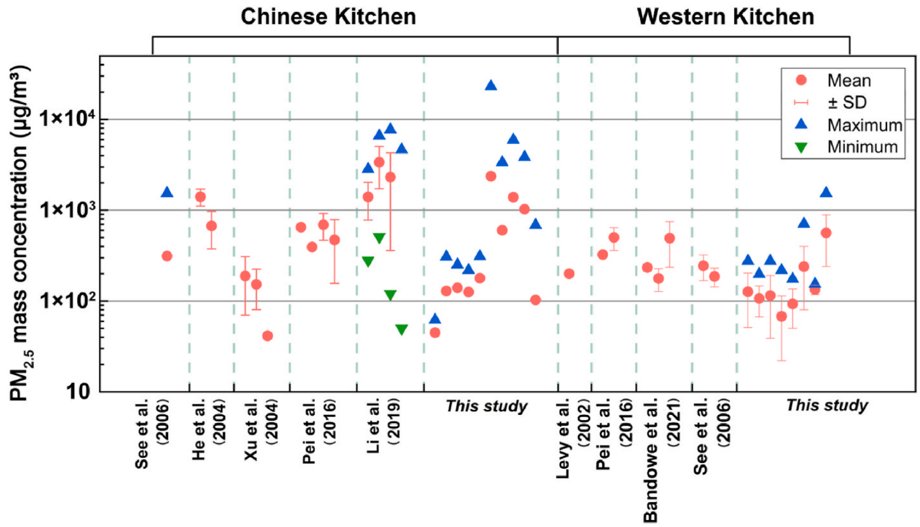

Fig. 5. Comparison of the results of our study with those of existing studies.

previous studies (Fig. 5) (Bandowe et al., 2021; Levy et al., 2002; Pei et al., 2016; See et al., 2006). There were significant fluctuations in the $PM_{2.5}$ emission rates when pan-frying steaks in the western kitchen, which were similar to the results obtained in the teppanyaki kitchen. The $PM_{2.5}$ emission rates were unstable when cooking meat with relatively high fat content. Moreover, the elevated $PM_{2.5}$ concentrations observed in the cooking period 10 might be related to the charring of the steak surface in the late cooking stage (Fortmann et al., 2001).

Compared to other kitchens, $PM_{2.5}$ concentration in the breathing zone of the barbecue kitchen was relatively lower. However, Sun et al. (2020) found that the mean $PM_{2.5}$ concentration in the chef's breathing zone in a barbecue kitchen could reach 3400 ± 978 μg/m^3, which exceeded that of a Sichuan cuisine kitchen. Notably, the type of oven used for the barbecue kitchen had a significant impact, as some barbecue kitchens used open flames and solid fuels such as wood or coal. However, solid fuel combustion products contain large amounts of $PM_{2.5}$. All these factors led to an increase in the $PM_{2.5}$ concentrations. In contrast, the barbecue kitchen tested in our study used a cleaner heating tube grill that was not operated over an open fire. This may have led to a lower concentration of $PM_{2.5}$. Furthermore, the normalized $PM_{2.5}$ concentration in the barbecue kitchen was the highest among all the kitchens, reaching 1085.9 ± 442.9 μg/m^3 kg^{-1}. This indicated that barbecue cooking had a high risk of pollution, which might increase further with the amount of cooking.

As the hotpot cooking area was mainly based on water boiling and the temperature of the soup prepared during cooking was lower than that of oil-based cooking, the ingredients were not generally subjected to pyrolysis. Consequently, the $PM_{2.5}$ emission rates and concentrations in hotpot cooking area were lower than those of the other five commercial kitchens. Notably, the highest RH was observed in the hotpot cooking area. A high RH environment may affect the SidePak performance, leading to less accurate readings (Wang et al., 2015a, 2015b).

The higher the $PM_{2.5}$ concentration in the breathing zone of a kitchen, the greater the health risk to the chef. Particles larger than 1 μm in diameter are deposited mainly in the throat and upper respiratory tract by inertial mechanisms, with a portion deposited in the bronchi by gravity and in the alveoli by Brownian motion (Cheng et al., 1999). Particles deposited in the tracheobronchial region are rapidly cleared by mucociliary transport and ingested into the gastrointestinal tract; however, alveolar-deposited particles are cleared more slowly. Therefore, the amount of PM deposited in the alveoli was higher than that deposited in the bronchi. Ji et al. (2014) studied indoor $PM_{2.5}$ exposure in the daily life of the general population and showed that the annual $PM_{2.5}$ inhalation exposure for adults was 1.75×10^5 μg/year. Using the Chinese kitchen as an example, the annual $PM_{2.5}$ inhalation exposure for men and women during cooking in this commercial kitchen was 8.46×10^5 and 7.57×10^5 μg/year, respectively. This was 4.83 and 4.33 times higher than the daily exposure for men and women, respectively. It should be noted that our study used the deposition model proposed by ICRP and assumed a particle size of 2.5 μm. This resulted in differences between the actual $PM_{2.5}$ deposition rate and the data presented in the manuscript. Because one of the focuses of the paper was to compare the $PM_{2.5}$ exposure risks of chefs in different commercial kitchens rather than focusing on the exact $PM_{2.5}$ deposition rate in chefs, the conclusions obtained in our study were informative.

Indoor $PM_{2.5}$ concentrations in western and Chinese kitchens were not constantly high during cooking but were high at specific times. Taking the stir-frying stages in a Chinese kitchen as an example, the $PM_{2.5}$ concentration increased rapidly over a short time when the ingredients entered the wok, but this period did not last for too long. Therefore, if extra precautions are taken (such as increasing the exhaust volume or providing air curtains) during times of high $PM_{2.5}$ concentration in cooking process and a low exhaust volume is maintained during times of low concentration, the energy consumption by exhaust equipment and health risk of kitchen workers may be reduced. Furthermore, the results in Table 3 indicate that the total $PM_{2.5}$ inhalation rate was higher in men exposed to cooking environments, but this did not mean that women faced fewer health risks. According to previous studies, cooking pollutants are a major cause of cancer in women worldwide, and pregnant women exposed to high $PM_{2.5}$ concentrations experience more significant health impacts (Lu et al., 2019). According to the latest global air quality guidelines (AQG 2021) issued by the World Health Organization (WHO), the mean annual indoor $PM_{2.5}$ concentration should not exceed 5 μg/m^3 (World Health Organization, 2021). However, the measured $PM_{2.5}$ concentrations in the tested kitchens far exceeded this standard, posing a greater health risk for chefs working in commercial kitchens.

5. Limitations

Our study had three major limitations that should be addressed in future research. First, the calibration factor (CF) value for SidePak instruments was not calibrated for each kitchen during different cooking types. Owing to the variety of cooking types in each commercial kitchen, it was difficult to determine the CF value on a case-by-case basis. Our study referred to some previous studies and used CF values obtained in similar studies (Torkmahalleh et al., 2018; Dacunto et al., 2013; Zhao and Zhao, 2020). Hence, the data in our study might not accurately reflect the real $PM_{2.5}$ concentration in each kitchen. In the future, CF values of main dishes cooked in different kitchens can be tested and summarized, which will be beneficial for the real-time measurements of $PM_{2.5}$ concentrations in kitchens. Second, we did not perform repeated measurements in our study. As the measurements in our study were real-time field measurements, chefs in commercial kitchens cannot cook the same kind of dishes in the same quantity for consecutive days. In addition, measuring instruments located in the breathing area interfered with the work of the chefs. Therefore, our study did not conduct continuous measurements for a long time. In the future, the $PM_{2.5}$ emission characteristics of various commercial kitchens should be measured over a longer period by optimizing the experimental design and instrument layout, which may make the health risk assessment of chefs more robust. Third, our study used the $PM_{2.5}$ deposition model proposed by ICRP and assumed a particle size of 2.5 μm. To use this model more accurately to assess the human $PM_{2.5}$ deposition risk, the particle size characteristics of $PM_{2.5}$ emissions from cooking can be further investigated in the future.

6. Conclusion

Indoor $PM_{2.5}$ concentrations and emission rates in six commercial kitchens during cooking were investigated using real-time field measurements. The $PM_{2.5}$ concentration in the breathing zones of commercial cooking environments decreased as follows: teppanyaki kitchen (850.4 ± 533.4 μg/m^3) > Chinese kitchen (679.1 ± 1922.5 μg/m^3) > western kitchen (272.2 ± 250.1 μg/m^3) > fried chicken kitchen (257.2 ± 44.5 μg/m^3) > barbecue kitchen (146.6 ± 59.8 μg/m^3) > hotpot cooking area (110.8 ± 24.9 μg/m^3). $PM_{2.5}$ concentrations in all the tested kitchens far exceeded the recommended values provided by the WHO. The high concentration of $PM_{2.5}$ in the commercial kitchens puts chefs at higher health risks, especially in the teppanyaki and Chinese kitchens. The real-time $PM_{2.5}$ data show that $PM_{2.5}$ concentrations and emission rates in each kitchen varied greatly when cooking different dishes. The mean $PM_{2.5}$ concentration during Chinese stir-frying was the highest, and the peak concentration reached more than 20,000 μg/m^3, followed by the mean $PM_{2.5}$ concentration during pan-frying, deep-frying, stewing, and boiling. In addition, $PM_{2.5}$ concentrations increased greatly in the preliminary stages of stir-frying and in the middle to late stages of pan-frying and grilling meats.

Author contribution statement

Junmeng Lyu: Experiment, Data analysis, Writing - original draft, Visualization. **Yongxiang Shi:** Experiment, Methodology. **Cong Chen:** Investigation, Data curation. **Xinqiao Zhang:** Investigation, Data curation. **Wei Chu:** Investigation, Data curation. **Zhiwei Lian:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.120180.

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