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## Research Article

# Impact of Cooking Methods on Indoor Air Quality: A Comparative Study of Particulate Matter (PM) and Volatile Organic Compound (VOC) Emissions

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Cooking activities are responsible for substantial emissions of both particulate matter (PM) and volatile organic compounds (VOCs), two key indoor air pollutants, which can lead to numerous adverse health effects, including premature mortality. Chicken breast was prepared following tightly constrained cooking procedures with contrasting cooking methods in a well-controlled research kitchen to investigate the PM and VOC emissions by simultaneous measurements with reference instruments (an optical aerosol spectrometer measuring light scattering of single particles for continuous PM monitoring and a proton-transfer-reaction time-of-flight mass spectrometer [PTR-ToF-MS] for VOCs). Peak concentrations of PM<sub>2.5</sub> ranked in the order (median [ $\mu\text{g m}^{-3}$ ]) pan-frying (92.9), stir-frying (26.7), deep-frying (7.7), boiling (0.7), and air-frying (0.6). Peak concentrations of VOCs ranked in the order (median [ppb]) pan-frying (260), deep-frying (230), stir-frying (110), boiling (30), and air-frying (20). Key VOCs from different frying methods were identified in a detailed principal component analysis (PCA), including aldehydes, ketones, furans, aromatic hydrocarbons, alkenes, pyrazines, and alkanes. The cooking temperature was found to be the key factor that positively correlated with both PM and VOC emission strength, while the oil weight was negatively correlated with the PM levels. We also determined PM emission rates (varying over a wide range, e.g., for PM<sub>2.5</sub> from 0.1 to 2931  $\mu\text{g min}^{-1}$ ) and PM exposures (ranging, e.g., for PM<sub>2.5</sub> from approximately 2 to more than 1000  $\mu\text{g m}^{-3}\text{min}$ ). In addition, by using EPR spectroscopy, we measured environmentally persistent free radicals (EPFRs) that formed from heating and cooking processes at levels of approximately  $10^9$  spins  $\mu\text{g}^{-1}$  of PM mass. These EPFR concentrations were shown to be unaffected by ozone exposure.

## 1. Introduction

People spend, on average, more than 80% of their time indoors, with cooking emissions contributing significantly to indoor air pollution, including both particulate and gaseous pollutants [1–3]. Particulate matter (PM) is composed of solid and liquid particles, and its toxic effects on human health depend on the size, surface area, and chemical composition of the particles [4, 5]. Volatile organic compounds (VOCs) include fatty acids, alkanes, alkenes, ketones,

aldehydes, alcohol esters, aromatics, and heterocyclic compounds. They are key indoor pollutants and precursors for the formation of secondary pollutants, including aerosols and ozone (O<sub>3</sub>) [6–10]. Exposure to indoor pollutants may induce various health effects of acute symptoms and chronic diseases, such as heart failure; cardiovascular diseases; cerebrovascular diseases; neurodegenerative diseases; lung diseases including emphysema and bronchitis; irritations in the respiratory system and eyes; respiratory infections and asthma attacks; and increased risks of cancer and mortality,

especially in vulnerable people [5, 11–17]. Furthermore, recent work found that indoor air pollutants emitted from cooking contribute significantly to outdoor pollution [18].

Substantial prior research has gone into understanding cooking emissions under various conditions and has shown cleaner burning fuels reduce emissions, concentrations, and indoor air pollution exposures [19, 20]. Cooking on gas appliances in Europe exposes over 100 million people to indoor air pollution levels surpassing EU outdoor air pollution regulations, emitting NO<sub>2</sub>, carbon monoxide, carbon dioxide, and unburned methane, affecting 35% of the EU population based on the report by CLASP [21]. Various types of oils and ingredients lead to emissions of very different levels of pollutants [3, 22]. Zhang et al. [23] determined that VOC emissions from commonly used oil in Chinese cooking followed the order from high to low: rapeseed oil (81.0 mg m<sup>-3</sup>), soybean oil (75.5 mg m<sup>-3</sup>), peanut oil (70.9 mg m<sup>-3</sup>), corn oil (60.3 mg m<sup>-3</sup>), and lard (20.5 mg m<sup>-3</sup>) due to the higher abundance of unsaturated fatty acids in vegetable oils than in lard. The cooking methods also contribute significantly to emissions of both PM and VOCs: oil-based cooking tends to produce more pollutants than water-based methods [24, 25]. The Maillard reaction is a chemical reaction between amino acids and reducing sugars that gives browned food a distinctive flavour. It occurs when food is heated, producing complex flavours and colours in a variety of cooked foods such as toasted bread, roasted coffee, and grilled meats, and also plays a key role in associated pollutant emissions [26–29]. Although previous studies were conducted in a variety of venues, including domestic and commercial kitchens, canteens, and laboratory chambers [3, 30], there are fewer cooking emission assessments carried out in a well-controlled, but fully equipped research kitchen that can simulate a real-life domestic kitchen with controlled conditions, specifically fixing the ventilation to a relatively low level.

Environmentally persistent free radicals (EPFRs) have been characterised indoors as well as outdoors [31, 32]. They are of key importance because radical species are known to drive multiphase chemistry [33], which can induce oxidative stress in the body and lead to adverse health impacts [34–36]. The fact that EPFRs can last from days to potentially years means it is important to understand their sources and concentrations [37]. We have thus included an analysis of EPFRs in aerosols collected from cooking events described in this study and also tested if and how exposure to ozone affects the EPFR levels detected.

## 2. Materials and Method

**2.1. Sampling Location.** The research kitchen in the School of Sport, Exercise and Rehabilitation Science at the University of Birmingham was chosen for the campaign to conduct cooking activities and pollution detection. The kitchen, with a volume of 82.72 m<sup>3</sup>, is an internally contained unit within the building that lacks external windows or doors, and both the mechanical ventilation and extractor fan were turned off during the cooking process. Consequently, meteorological or outdoor air conditions had very little impact on indoor air

quality through air ventilation and penetration processes (the air exchange rate was determined to be below 0.2 per hour). The induction hob and the heat-compatible cookware were carefully cleaned before each cooking activity.

**2.2. Cooking Activity Recording.** For the cooking activities, we carefully controlled the key factors impacting cooking emissions, specifically the cooking method, amount of oil/water, the initial temperature of oil/water, cookware, and the form of the prepared chicken (see Table 1). The “initial” was defined as the moment when the oil reached the designated temperature before adding chicken breast. The temperatures in the center of the cookware and of the oil at the time when the chicken was added were both measured; additionally, the temperature of the pan was recorded throughout the cooking processes every minute by a handheld infrared thermometer gun (KETOTEK). To be able to focus our study on the impact of the cooking method on emissions and in order to minimise potential influences from differing fat, protein, and sugar proportions in the ingredients, the cooking activities were constrained in the following way: only chicken breast (120 ± 5 g), rapeseed oil (also known as canola oil) or water, and salt were used to simulate basic cooking conditions without additional ingredients or seasoning. Rapeseed oil was chosen due to its high smoke point and widespread use. Additionally, the environmental conditions of the research kitchen, especially the ventilation conditions, as well as the uniformity in cookware (pots and pans with 20 cm diameters) and heating modes, were tightly controlled. The effect of the Maillard reaction on the chicken breast was determined by observing the browning on the chicken; cooking durations were kept similar. Five cooking methods were selected for this study: deep-frying and boiling in the pot by induction, stir-frying and pan-frying in the pan by induction, and air-frying in an air fryer. Each dish, with the same settings for cooking method, oil amount, and initial pan temperature, was replicated two to four times. In total, there were 90 cooking activities: 24 by pan-frying, 20 by stir-frying, 16 by deep-frying, 16 by boiling, and 14 by air-frying. As soon as the cooking process was completed, the pan/pot was covered by a lid immediately and moved away from the hob to avoid emissions by further heating on the hot plate. The experimenter remained in the room throughout the cooking process and until the PM concentrations peaked to ensure that the air exchange rate remained stable. The experimenter then left the room for health and safety reasons, as prolonged exposure to high levels of pollutants could pose risks [38]. The settings of the cooking methods are detailed in Table 1. Detailed recipes can be found in Section S1.

**2.3. Monitoring of PM and VOC.** The concentrations of PM and VOCs from cooking activities in the research kitchen were simultaneously measured by an optical aerosol spectrometer (Fidas 200; Palas GmbH) measuring light scattering of single particles for continuous PM monitoring and a proton-transfer-reaction time-of-flight mass spectrometer (PTR-ToF-MS, Ionicon, Austria) for the VOCs in the period 12–22 February 2023. Both real-time online instruments had

TABLE 1: Conditions chosen for the cooking activities ( $D$ , duration;  $T_{cook}$ , temperatures during cooking processes;  $T_{initial}$ , initial temperature; the different weights in grams of oil or water added at the outset of the cooking activity are listed).

	Pan-frying	Stir-frying	Deep-frying	Boiling	Air-frying
Chicken breast form	Fillet	Slices	Fillet or slices	Fillet or slices	Fillet or slices
$T_{initial\ pan}$ (°C)	220 or 250	270	—	—	—
$T_{initial\ oil}$ (°C)	200 or 215	220 ± 5	160 or 175	25 or 95	160, 175, or 190
Oil/water weight (g)	2, 6, 10, 14, 18, or 26	2, 6, 10, 14, 18, or 26	500 or 800	200, 400, 600, or 800	2
Average $D_{total}$ (min)	9.0 ± 1.1	7.4 ± 0.6	13.8 ± 2.0	14.3 ± 3.9	13.3 ± 1.9
Average $D_{heating\ oil}$ (min)	2.9 ± 0.4	3.4 ± 0.5	9.4 ± 2.6	8.5 ± 3.8	0
Average $D_{food\ cooking}$ (min)	6.0 ± 0.8	4.1 ± 0.5	4.3 ± 1.2	5.8 ± 1.9	13.3 ± 1.9
Average $T_{cook}$ (°C)	207.7 ± 15.7	110.3 ± 11.8	142.5 ± 13.2	89.4 ± 1.9	—
Number of tests	24	20	16	16	14

their inlets placed 1.6 m away from the center of the cooking hob at 1.7 m height, that is, in the adult breathing zone. The distance between the hob and the inlets was chosen to avoid direct fumes from the cookware and immediate emissions of oil drops from entering the instruments, which may have blocked the inlets or caused damage to the instruments. A small fan was placed behind PTR-ToF-MS, facing up with an angle of 45°, to help circulate and mix the air with the emissions before detection. The layout of the kitchen and the settings of the equipment are illustrated in Figure 1.

In this study, conditions in the research kitchen were at 23 ± 1°C, 38% ± 7% relative humidity (RH), and 1006 ± 9 hPa. For PM measurement, Fidas 200, the fine dust monitor, had a volumetric flow rate of 4.8 L min<sup>-1</sup> and could detect particles ranging from 0.18 to 26 μm in diameter; it can be run with a wide range of time resolutions from 1 s to 24 h. The mass concentrations of PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>4</sub>, PM<sub>10</sub>, and PM<sub>26</sub> and the number concentration of particles (Cn) could be reported (PM<sub>4</sub> was not used in our study). The time resolution of the PM monitor was set to be 1 min. Regarding the VOC monitoring, the PTR-ToF-MS instrument measured the mixing ratios of VOCs in parts per billion by drawing indoor air samples heated at the inlet to 59.9°C with a flow rate of approximately 50 mL/min, maintaining a pressure of 2.5 bar and a voltage of 460 V. The corresponding  $E/N$  value (with  $E$  being the electric field in the drift tube and  $N$  the gas number density) was 120 Td (1 Td corresponds to 10<sup>-17</sup> V cm<sup>2</sup> molecule<sup>-1</sup>). The mixing ratio of H<sub>3</sub>O<sup>+</sup> was maintained at about 4.0 × 10<sup>7</sup> ppb, and the time resolution in this study was set to 1 min to be the same as the simultaneous Fidas 200 measurements. The identification of VOC species relied on interpreting distinct mass-to-charge ( $m/z$ ) ratios of ionised compounds, although isobaric species might complicate precise identification, which was supported by reference libraries and literature on specific emissions. A detailed description of the operating principles and instrument settings for the optical aerosol spectrometer (Fidas 200) and PTR-ToF-MS and the method for identifying VOCs based on PTR-ToF-MS signal output can be found in Section S2.

2.4. PM Emission Rates. Emission rates, which indicated the quantity of pollutants released over a specified duration,

were calculated. This calculation was based on the condition of a stable particle concentration and the assumption that the air in the kitchen was well mixed. Then, the material-balance approach was used to calculate the emission rates of PM during cooking processes in Equation (1):

$$\frac{dC_{in,p}(t)}{dt} = aPC_{out} - \lambda C_{in,p}(t) + \frac{S_p}{V} \quad (1)$$

where  $C_{in,p}(t)$  denoted the real-time indoor concentration (μg m<sup>-3</sup>) of PM at the specific survey time  $t$ ;  $a$  represented the air change rate (min<sup>-1</sup>);  $P$  indicated the penetration factor for outdoor particles entering the indoor environment through the building shell;  $C_{out}$  referred to the outdoor PM concentration (μg m<sup>-3</sup>);  $\lambda$  was the total removal rate within the kitchen, attributed to coagulation, deposition, and air exchange;  $S_p$  signified the emission rate of PM (μg min<sup>-1</sup>); and  $V$  was the kitchen's volume (m<sup>3</sup>) [25, 39]. The air change rate in the research kitchen was determined to be 0.19 h<sup>-1</sup> (0.032 min<sup>-1</sup>) by assessing the decay of the concentrations of CO<sub>2</sub>, the tracer gas [40]. Calculations of air change rate are stated in Section S3.

Given that the indoor particle concentrations were considered to reach a steady state (i.e.,  $C_{in,p}(t_0) = aPC_{out}/\lambda$ ), owing to the absence of any other activities for at least 15 min prior to cooking, we followed the same approach as detailed in our recent study on cooking emissions measured by low-cost sensors [25]. The formula for calculating the PM emission rate has been adapted to

$$S_p = \frac{C_{in,p}(t) - C_{in,p}(t_0)}{1 - e^{-\lambda\Delta t}} \lambda V \quad (2)$$

where  $C_{in,p}(t_0)$  indicated the concentration (μg m<sup>-3</sup>) of particle at the start time  $t_0$ .

Due to the distance between the cookware, which is the emission source, and the inlet of the instrument, the recorded PM concentrations showed a steadily increased trend, representing the accumulation of particles, until they reached the peak and started to decay after cooking. Thus,

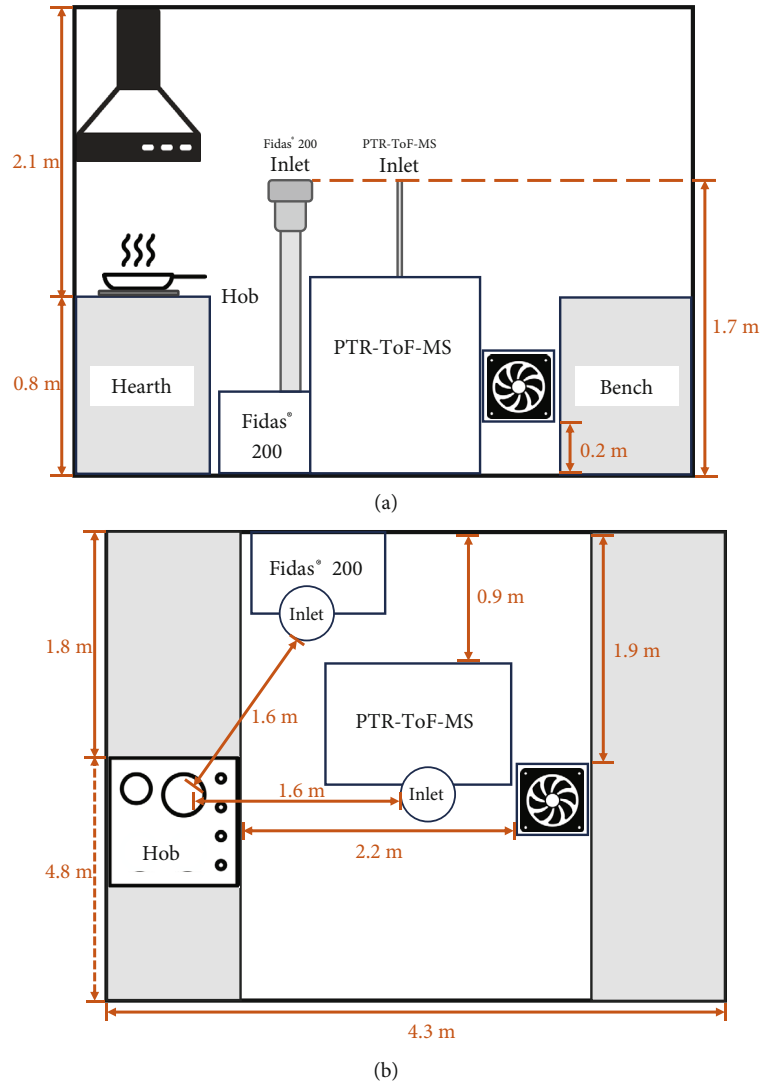


FIGURE 1: (a) Front view and (b) overhead view of the layout of experiment design.

the total removal rate,  $\lambda$ , was determined by the decay of PM concentration after cooking using Equation (3):

$$C_t = C_p e^{-\lambda t} \quad (3)$$

where  $C_t$  was the PM concentration ( $\mu\text{g m}^{-3}$ ) at time  $t$  (minute) after the peak concentrations and  $C_p$  indicated the peak concentration ( $\mu\text{g m}^{-3}$ ) of PM. The emission rate,  $S_p$ , was derived through nonlinear fitting, which was applied to the rising indoor particle concentrations [41]. This fitting process was based on several factors: the real-time concentration  $C_{in,p}(t_0)$ , the air change rate  $a$ , the total removal rate  $\lambda$ , and the volume of the kitchen  $V$  [39].

**2.5. Principal Component Analysis (PCA) of Cooking-Related VOCs.** PCA, a type of multivariate analysis, was conducted using IBM SPSS Statistics Version 29.0 to cluster and identify VOC species associated with cooking activities. This involved assessing the interrelationships among the time series for the concentrations of the 208 species (based on

different  $m/z$  ratios) measured by the PTR-ToF-MS instrument. Varimax rotation was employed to improve the interpretability of the components. The number of principal components (PCs) was determined by employing the Kaiser criterion (eigenvalues greater than 1), evaluating the proportion of variance explained by each component, and using a scree plot for visual assessment [42]. Communalities were examined, and component loadings were set with a threshold of 70% to identify key  $m/z$  species [43, 44]. Due to the very similar changing patterns of VOC concentrations associated with certain activities, VOCs related to certain activities were clustered into one of the PCs. Therefore, one of these PCs was identified as cooking-related based on the VOCs'  $m/z$  ratios and existing literature [29, 43, 45, 46]. Linear regression and the coefficient of determination ( $R^2$ ) were applied to assess the relationship between multiple time series for further evaluation.

**2.6. Collection of Aerosol Samples for Electron Paramagnetic Resonance (EPR) Analysis.** The pan-fried chicken was cooked to the same recipe as described for the exposure

measurements. The same recipe was also followed for minced meat (beef) frying, substituting the chicken breast for minced meat. Ten grams of vegetable oil (rapeseed) was used for each experiment. Oil-only heating experiments were also conducted for comparison. Detailed conditions of sampling are presented in Table S2.

A DC motor pump was used to draw approximately  $2 \text{ L min}^{-1}$  air through a filter holder containing a preweighed 47-mm diameter PTFE filter. This was held 15 cm above the pan during the cooking process. Sampling times were in the range of 4–8 min, depending on when the meat was cooked. The collected filter samples were weighed and stored in a freezer, sealed inside sample tubes, and wrapped in Parafilm. Surface wipes were used to collect material from around the cooker to establish what had splashed out of the pan during frying. EPR measurements were made after transporting the samples out of the freezer between the United Kingdom and Germany for approximately 48 h. In total, the measurements were carried out 4–6 days after the samples were collected.

**2.7. EPR Spectroscopy.** Radicals were detected using a continuous-wave electron paramagnetic resonance (CW-EPR) X-band spectrometer (EMXplus; Bruker). Following the methodology from previous studies [31, 32], a filter containing the sample was folded and inserted into a 4-mm inner diameter quartz tube, which was placed directly into the resonator. The following operating parameters were used: a modulation frequency of 100 kHz, a microwave frequency of 9.84 GHz, a microwave power of 20 db, a modulation amplitude of 3.0 G, a sweep width of 80.0 G, a sweep time of 20.63 s, a receiver gain of 30 db, and a scan number of 50. Quantification of radicals was performed using the spin-counting method installed in the Bruker software, Xenon. Concentrations of radicals are reported in spins  $\mu\text{g}^{-1}$ .

### 3. Results and Discussion

**3.1. PM Concentrations and Emission Rates.** In Figure 2, the averaged real-time concentrations of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , and  $\text{PM}_{26}$  emitted from five distinct cooking methods are depicted, capturing the dynamic progression of PM levels over a period of approximately 20 min, depending on the cooking duration. The measurement was continuous and started at the initiation of each cooking activity, marked by the time when the hob was turned on. PM concentrations began to rise approximately 4 min after the heating started, with a delay attributable to the time required for emissions to mix with the air and reach from the hob to the instrument inlet. Each measurement was stopped when PM concentrations peaked, which took  $14.4 \pm 3.6$  min from the end of the cooking process. The observed trends and peak concentrations demonstrated clear differences in the cooking methods with respect to PM emissions, ranking from the highest to the lowest emissions in the order of pan-frying, stir-frying, deep-frying, boiling, and air-frying. This was similar to the findings presented by Tang and Pfrang [25] and See and Balasubramanian [24], as the oil-based cooking processes emitted substantially higher PM levels than water-based ones. The standard deviation represented by the

shaded areas in the graph indicates the spread of the data, underscoring the considerable variability within these cooking methods, particularly in pan-frying and stir-frying, which was due to factors such as cooking temperature and the amount of oil used.

Figure 3 illustrates the dynamics of PM emissions from pan-frying with different weights of oil, which resulted in the large standard deviations in Figure 2, and Figure 3(b) illustrates the PM concentrations from pre-cooking condition to post-cooking decay of a typical pan-frying sample. Values of the averaged peak PM concentrations of each cooking method are stated in Table 2. No statistically significant differences were found between the peak PM concentrations of boiling and air-frying, and their PM levels were only slightly higher than the background levels of 0.3, 0.5, 1.3, and  $2.5 \mu\text{g m}^{-3}$  for  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , and  $\text{PM}_{26}$ , respectively. The maximum peak PM concentrations among all samples were found in one of the pan-frying processes, with the  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , and  $\text{PM}_{26}$  at 250.11, 447.91, 906.66, and  $1123.13 \mu\text{g m}^{-3}$ , respectively, while the lowest peak PM concentrations were found in both boiling and air-frying, which were close to the background level. Previous studies demonstrated that cooking high-fat foods produced more PM compared to low-fat foods, with oil-based techniques including frying and grilling more highly emitting than water-based methods like boiling and steaming [38, 47]. It is important to note that Figure 3(b) represents the real-life PM concentration decay after cooking, during which external factors such as the experimenter opening the door to leave the kitchen for health and safety reasons, contributed to a sharper initial decline, followed by a more gradual decay phase.

The emissions rates of PM and the cumulative exposure of PM stated in PM exposure, assessed by calculating the area under the curve (AUC), are illustrated in Figures 4(a) and 4(b), respectively. The ranking for both ER and PM exposure is consistent with that for PM peak concentrations. The cumulative exposure contains a total measure of PM concentrations that accumulated over the entire cooking duration, which provides a comprehensive view of the potential risk of exposure [48]. Liu et al. [49] assessed the integrated  $\text{PM}_{2.5}$  concentration from pan-frying bacon by calculating AUC as well, and their results indicated a range at the same order of magnitude, with the median at approximately  $60,000 \mu\text{g m}^{-3} \text{ min}$ . Emission rates illustrated the time evolution of the cooking emissions. Both followed the same order of the averaged peak PM concentrations of the cooking method.

In Table 3, we compare the dishes and PM emission rates from cooking in previous work with the results presented here. Our study found lower values of PM emissions compared to earlier studies [39, 50, 51]. This could potentially be influenced by the smaller amount of ingredients used and larger volume of the research kitchen ( $82.72 \text{ m}^3$ ) than their study sites ( $10\text{--}26 \text{ m}^3$ ), which may lead to a more diluted environment. Our conditions are more representative of student studios, flats, or houses with open-plan kitchens. The heating source in the study by Zhao et al. [50] was a gas stove, which was shown to emit many more particles than electric hobs [53]. This is also consistent with

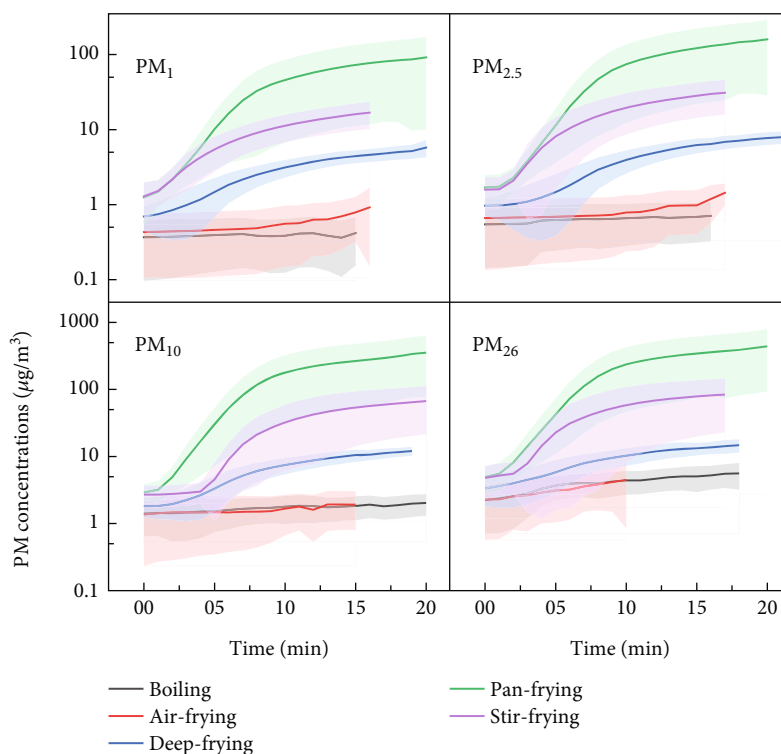


FIGURE 2: Time series of averaged real-time PM concentrations ( $\mu\text{g m}^{-3}$ ) with standard deviations.

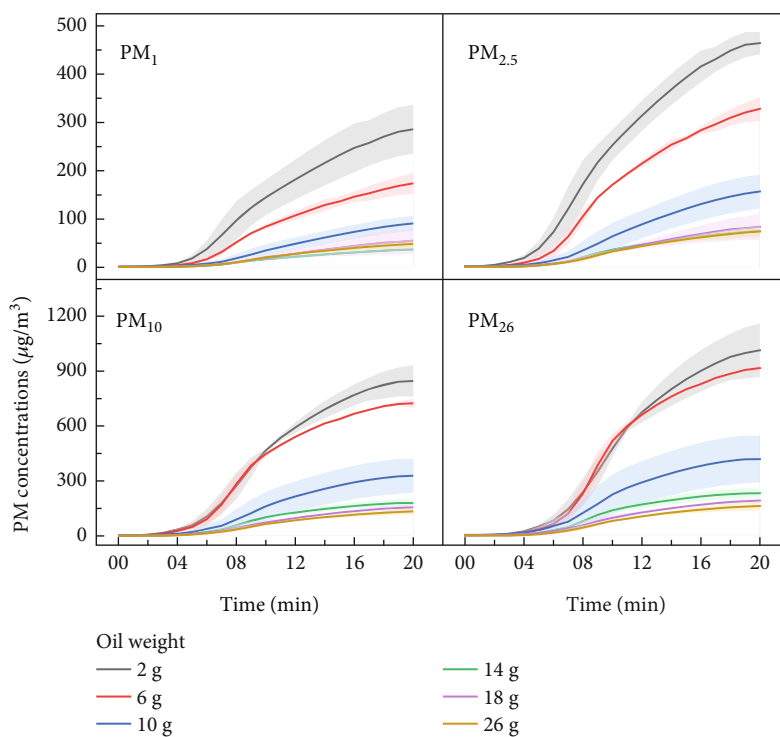
the recent CLASP report by Blair et al. [21], reporting lower  $\text{PM}_{2.5}$  levels in domestic kitchens using electric hobs in comparison to those from gas stoves of households in Italy, France, and Spain. Even though no significant differences between averaged  $\text{PM}_{2.5}$  concentrations from both cooking appliances were discovered in surveyed households of other European countries, they indicated that gas stoves produced much higher gaseous pollutants and provided longer exposure times [21].

In terms of the impact of cooking oil type and temperature, a study by Gao et al. [54] assessed the  $\text{PM}_{0.1-10}$  emissions from six typical vegetable oils and concluded that the type of vegetable oil affected emissions only insignificantly. However, the temperature of the oil could potentially play a more critical role due to the differing smoke points of the different oils together with the possibility of further reactions with food and seasonings in high-temperature conditions.

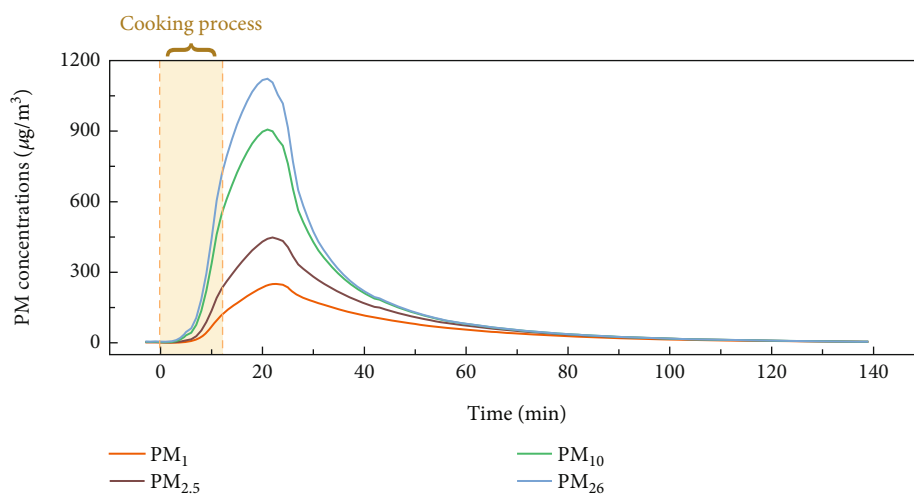
Elevated particle emissions in oil-based cooking were attributed to the pyrolysis of oil and food at higher temperatures following the Maillard reaction; this was particularly apparent in pan-frying, stir-frying, and deep-frying and clearly distinct from the lower emissions associated with boiling and steaming [3]. However, with increased oil use in the three frying methods, the PM emissions were found to decrease, in contrast to previous work suggesting that increased oil use resulted in higher PM emissions, especially for particles with larger diameters ( $>\text{PM}_{10}$ ) [3, 52]. We found statistically significant negative correlations between the peak PM concentrations and oil amounts used in frying methods (see Figure 5; also compare the downward trends for pan-frying and stir-frying in Figure 6). Higher cooking

temperatures were consistently associated with increased PM emissions, showing strong positive correlations.

These contrasting trends implied a complex interplay between oil amount and temperature during cooking, where temperature played a dominant role in PM production, while the impact of oil was less straightforward, potentially influenced by the cooking method and other factors. One possible explanation could be that additional oil leads to a more equal heat distribution in the cookware, and a protective barrier may be formed by additional oil preventing food from overheating or burning and thus reducing the emissions. The larger volume of oil might potentially reduce the peak temperatures and also reduce the direct contact between the food and the pan, thereby diminishing the pyrolysis of food particles (pictures of coverage of chicken and different amounts of oil are presented in Figures S2 and S3, respectively). According to Torkmahalleh et al. [52], the smoke temperature of rapeseed oil, which was used in our study, was  $210 \pm 11^\circ\text{C}$ . The mean temperature and average maximum temperature during pan-frying were found at  $208.6 \pm 15.2^\circ\text{C}$  and  $225.0 \pm 16.6^\circ\text{C}$ , respectively, with the highest temperature recorded at  $255^\circ\text{C}$  in our study, which was above the smoke point of rapeseed oil. In stir-frying, the mean temperature and average maximum temperature during cooking were only  $101.3 \pm 9.2^\circ\text{C}$  and  $120.0 \pm 11.5^\circ\text{C}$ , respectively, which indicated that the smoke from oil did not play a significant role in the PM emissions since the temperatures were lower than the smoke points; Gao et al. [55] also pointed out that PM emissions rose with increasing temperatures. The temperatures of the pan and oil were set to  $270 \pm 5^\circ\text{C}$  and  $210 \pm 5^\circ\text{C}$  to meet the



(a)



(b)

FIGURE 3: (a) Time series of averaged PM concentrations of pan-frying with different amounts of oil until emission peak is reached. (b) PM concentrations for a typical sample of pan-frying over the entire measurement period.

TABLE 2: Maximum concentrations (Peak C in  $\mu\text{g m}^{-3}$ ) of PM of four size categories from each cooking method (range [median]).

Cooking method	Peak $C_{\text{PM}_1}$	Peak $C_{\text{PM}_{2.5}}$	Peak $C_{\text{PM}_{10}}$	Peak $C_{\text{PM}_{26}}$
Pan-frying	22.36–321.92 (55.96)	39.11–480.32 (92.90)	76.41–906.66 (193.94)	98.77–1123.13 (244.74)
Stir-frying	9.34–32.50 (14.57)	16.43–76.07 (26.68)	27.00–209.42 (53.13)	30.57–289.91 (66.41)
Deep-frying	3.87–8.15 (5.01)	5.48–11.71 (7.67)	7.81–16.27 (12.08)	9.56–19.78 (14.33)
Boiling	0.15–0.82 (0.39)	0.33–1.27 (0.65)	0.94–3.41 (2.42)	3.10–9.42 (5.70)
Air-frying	0.23–0.83 (0.53)	0.28–0.99 (0.59)	0.36–3.38 (1.67)	1.46–9.19 (3.37)

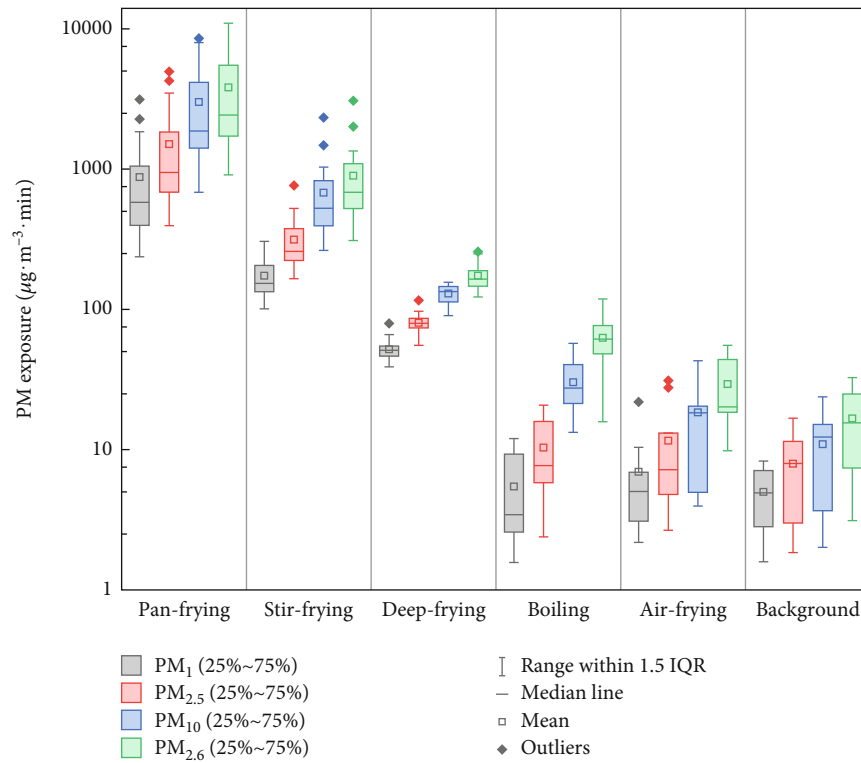
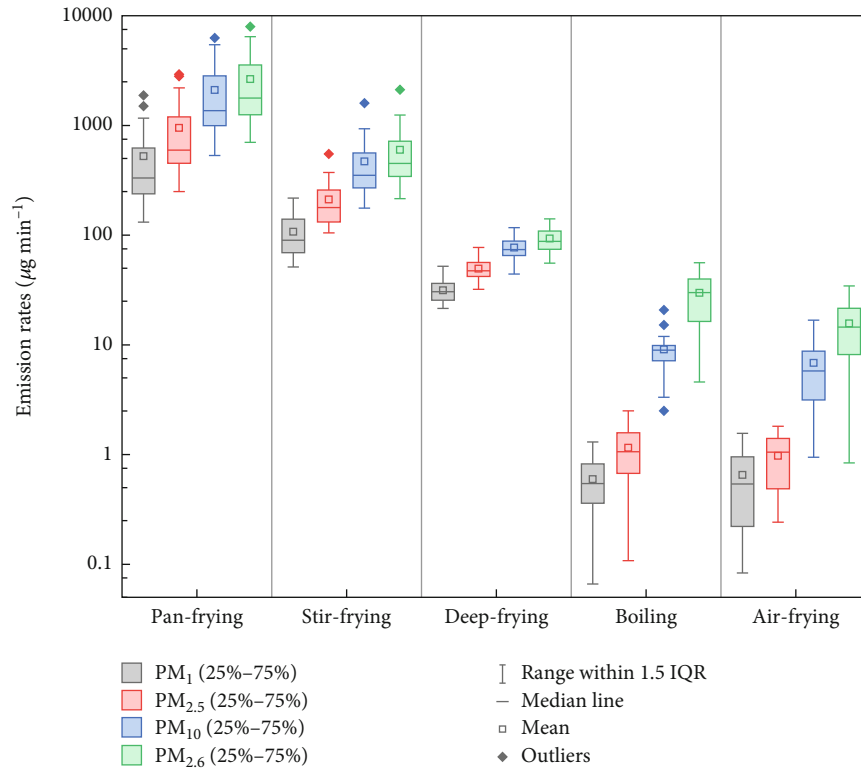


FIGURE 4: (a) Emission rate (ER,  $\mu\text{g min}^{-1}$ ) of PM from each cooking method. (b) PM exposure ( $\mu\text{g m}^{-3} \text{min}$ ) by calculating the area under the curve (AUC) in each cooking method. IQR, interquartile range which described the spread of the middle 50% of a dataset. Outliers were identified by those 1.5 IQR higher than the upper quartile (75%) or 1.5 IQR lower than the lower quartile (25%).

TABLE 3: Comparison of emission rates (*mean ± standard deviation or min–max [median],  $\mu\text{g min}^{-1}$* ).

Study	Volume of room/ chamber ( $\text{m}^3$ )	Heating source	Cooking method	Ingredients		Oil		Average emission rates				
				Type	Weight (g)	Type	Weight (g)	$\text{PM}_{2.5}$	$\text{PM}_{10}$	$\text{PM}_{2.5}$	$\text{PM}_{10}$	$\text{PM}_{2.5}$
Chen, C. Zhao, and Y. Zhao [50]	10.88	Gas stove	Stir-frying	Fish with vegetable	240	Peanut oil	20	9915 ± 1500				
			Stir-frying	Chicken	480	Sunflower oil	20	2416 ± 254				
			Pan-frying	Chicken with vegetable	150	Canola oil	15	10,018 ± 466				
			Pan-frying	Fish	360	Blend oil	25	5416 ± 2861				
			Deep-frying	Beef with vegetable	210	Blend oil	300	1030 ± 442				
			Deep-frying	Mutton	240	Peanut oil	300	771 ± 102				
Chen et al. [39]	12.42	Electric stove	Stir-frying	Pork with pepper	400	Corn oil	40	1420 ± 310	2940 ± 1070			
			Pan-frying	Tofu	450	Corn oil	40	1210 ± 240	2200 ± 820			
			Pan-frying	Fish with pepper	450	Corn oil	40	5620 ± 1150	11,220 ± 4240			
			Deep-frying	Potato	500	Corn oil	800	1540 ± 410	2840 ± 1030			
			Deep-frying	Chicken	500	Corn oil	800	850 ± 250	1490 ± 640			
						Chicken and vegetable				620 ± 41		
O'Leary et al. [51]	26.02	Gas stove	Mix	Chicken and vegetable		Olive oil						
			Mix	Chicken and vegetable		Olive oil						
			Mix	Pasta with beef and vegetable		Olive oil						
Torkmahalleh et al. [52]	0.81	Hot plate	Stir-frying	Noodles with chicken and vegetable		Olive oil						
			Heating oil			Rapeseed oil						
This study	82.72	Induction hob	Pan-frying	Chicken	120	Rapeseed oil	2–26	132–1883 (332)	250–2931 (596)	533–6282 (1367)	702–7959 (1777)	
			Stir-frying	Chicken	120	Rapeseed oil	2–26	51–218 (90)	105–550 (178)	176–1599 (351)	216–2116 (450)	
			Deep-frying	Chicken	120	Rapeseed oil	500 or 800	21–52 (31)	32–77 (47)	44–117 (74)	56–141 (88)	
			Boiling	Chicken	120	Water	200–800	0.1–1.3 (0.5)	0.1–2.5 (1.1)	2.5–20.8 (9.0)	4.6–56.0 (30.0)	
			Air-frying	Chicken	120	Rapeseed oil	2	0.1–1.6 (0.5)	0.2–1.8 (1.1)	0.9–16.8 (5.8)	0.9–34.5 (14.5)	

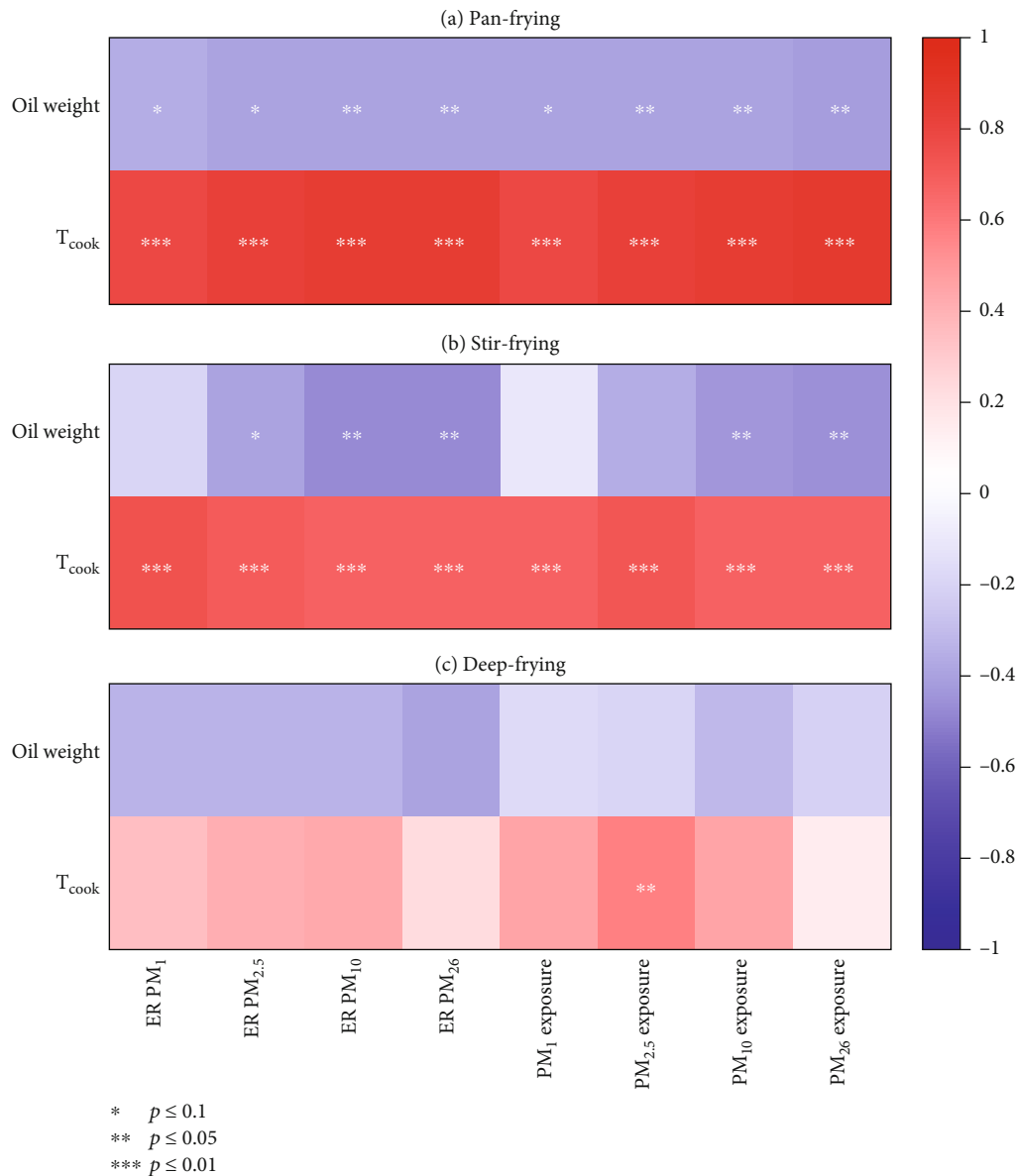


FIGURE 5: Correlation coefficients ( $r$ ) with significances ( $p$ ) of emission rate (ER) and PM exposure with the mean temperatures during cooking processes ( $T_{cook}$ ) and oil weight used in pan-frying and stir-frying.

real-life stir-frying cooking conditions. Thus, the initial high temperatures at the start of the cooking activity contributed significantly to the PM emissions. An inverse relationship was also found between the oil amounts and PM emissions from stir-frying, except for an anomaly observed for stir-frying with 2 g of oil. This anomaly may possibly be due to the much larger surface area of chicken in stir-frying compared to pan-frying (slices vs. whole fillet), so that 2 g of oil may be too little to play a role for the stir-frying process with the liquid seeping out of the chicken lowering the temperature and thus leading to lower emissions in this specific stir-frying condition. Chiavaro et al. [56] compared RHs in the oven while cooking raw pork with temperatures at 100°C, 110°C, 120°C, and 140°C and summed up with a negative correlation between temperatures and RH. This also indicated a drier condition of cookware during cooking plays

a role in maintaining a higher temperature. This indicates that, during frying on induction hobs, less oil in the pan leads to higher temperatures, which likely avoids meat juices seeping out but generates more PM emissions.

**3.2. VOC Emissions.** Table 4 presents the ranges of peak levels of total volatile organic compounds (TVOCs, i.e., the sum of all VOC levels detected by PTR-ToF-MS), including primary and secondary VOCs and/or by-products, and the sum of VOCs in cooking-related PCs with higher than 70% PC loadings (CVOCs), along with their increased peak levels, from the five studied cooking methods. The increased peak levels were calculated by subtracting the background levels from the peak levels of the specific VOC. The absolute TVOC peak levels for different cooking methods varied from their increased TVOC peak levels due to different background

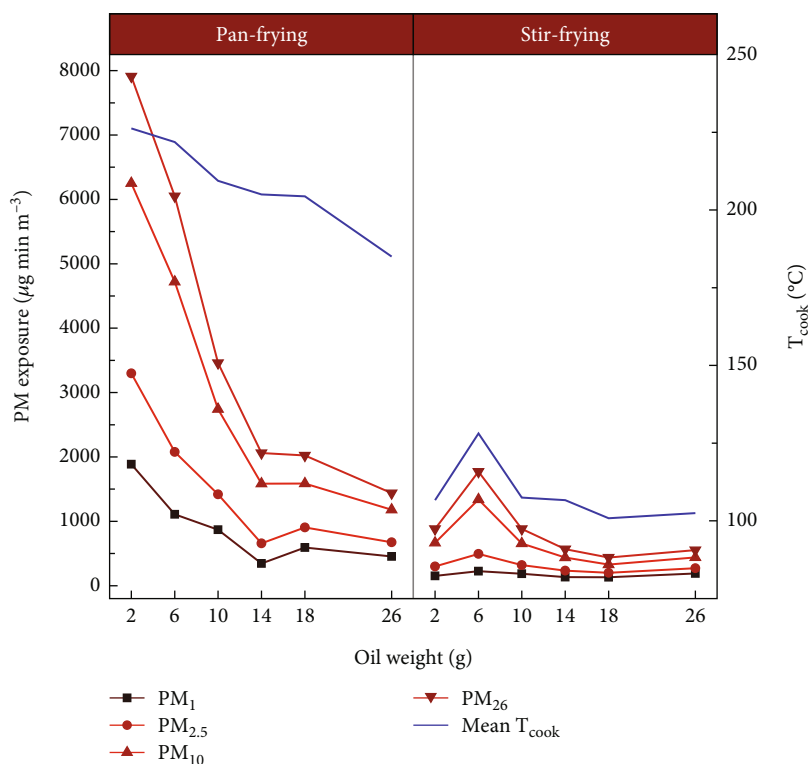


FIGURE 6: Mean PM exposures and mean temperatures during cooking processes ( $T_{cook}$ ) of pan-frying and stir-frying.

levels for each cooking activity. PCA was unable to cluster and extract specific VOCs emitted from boiling and air-frying. This was because the emissions were not as substantial as those from traditional frying methods, and the research kitchen's relatively large volume played a critical role in diluting them. The inlet of the instrument was positioned at a distance from the cooking hob or the air fryer to detect pollutant levels within the room; hence, changes caused by minor emissions tended to be insignificant, resulting in very small increases in the levels of TVOCs. Therefore, the assessment of TVOCs was conducted first because it encompassed not only CVOCs but also other VOC species in cooking-related PCs. However, it excluded VOCs, which are not directly emitted from cooking processes but potentially produced as by-products and thus clustered into other PCs due to being below the 70% threshold for the PC loadings.

The increased levels of TVOCs from each cooking method were averaged and are presented in Figure 7(a); the time series of TVOC and CVOC levels from pan-frying were averaged and are displayed in Figure 7(b). The mean peaks of TVOC increased levels ranked pan-frying, stir-frying, deep-frying, boiling, and air-frying, mostly following the same order as PM emissions, except for stir-frying and deep-frying. Their large standard deviations, particularly for pan-frying, were attributed to the varying settings (i.e., oil amounts) that had been applied, which led to similar circumstances as was the case for the PM results.

The linear regressions between both increased and absolute levels of TVOCs and CVOCs from pan-frying are shown in Figures 7(c) and 7(d) together with the coefficients

of determination ( $R^2$ ). The very high values of  $R^2$  demonstrate that cooking was the dominant source of emission in the experiments, and the subsequent analysis of correlations between CVOCs and various factors would be representative. Due to the threshold of PC loadings set at 70%, a gap between TVOC and CVOC levels was inevitable as VOCs with lower scores than 70% were extracted. However, the CVOCs represented the VOC species that contributed most to indoor emissions. On average, the increased levels of CVOCs represented 60%, 56%, and 73% of increased levels of TVOCs from pan-frying, stir-frying, and deep-frying, respectively. Additionally, TVOCs generally reached their peaks delayed by  $4.6 \pm 1.7$  min after cooking finished, while PM peaks took a longer time to be reached, averaging  $14.4 \pm 3.6$  min. This could be explained by their physical properties, as VOCs are in the gas phase at room temperature and gases disperse more quickly than particles [57].

A sample of pan-frying was selected to represent the time series of VOC emissions from the cooking processes and is illustrated in Figure 8. The background conditions were stable, and VOC levels started to rise 3 min after cooking had started and reached the peak 3–5 min after cooking had finished, then started to decay. The durations for the VOCs to increase after cooking had started as well as the time it takes for VOCs to reach their peak after the cooking activity are very similar; this duration is indicative of the time it takes for the gases to disperse and be transported to the instrument's inlet. The TVOC peak showed a two-minute delay compared to the CVOC peak, likely influenced by the differing dispersion speeds and emission

TABLE 4: Peak levels of VOCs from five cooking methods (min–max, [median], in parts per billion).

	Pan-frying	Stir-frying	Deep-frying	Boiling	Air-frying
TVOCs	4320–5290 (4690)	3910–4660 (4240)	4250–5240 (5050)	4060–4280 (4120)	4520–4720 (4580)
Increased TVOCs	100–560 (260)	70–270 (110)	110–340 (230)	20–60 (30)	10–50 (20)
CVOCs	145–528 (256)	41–155 (72)	143–381 (266)	—	—
Increased CVOCs	59–376 (127)	21–128 (47)	42–273 (152)	—	—

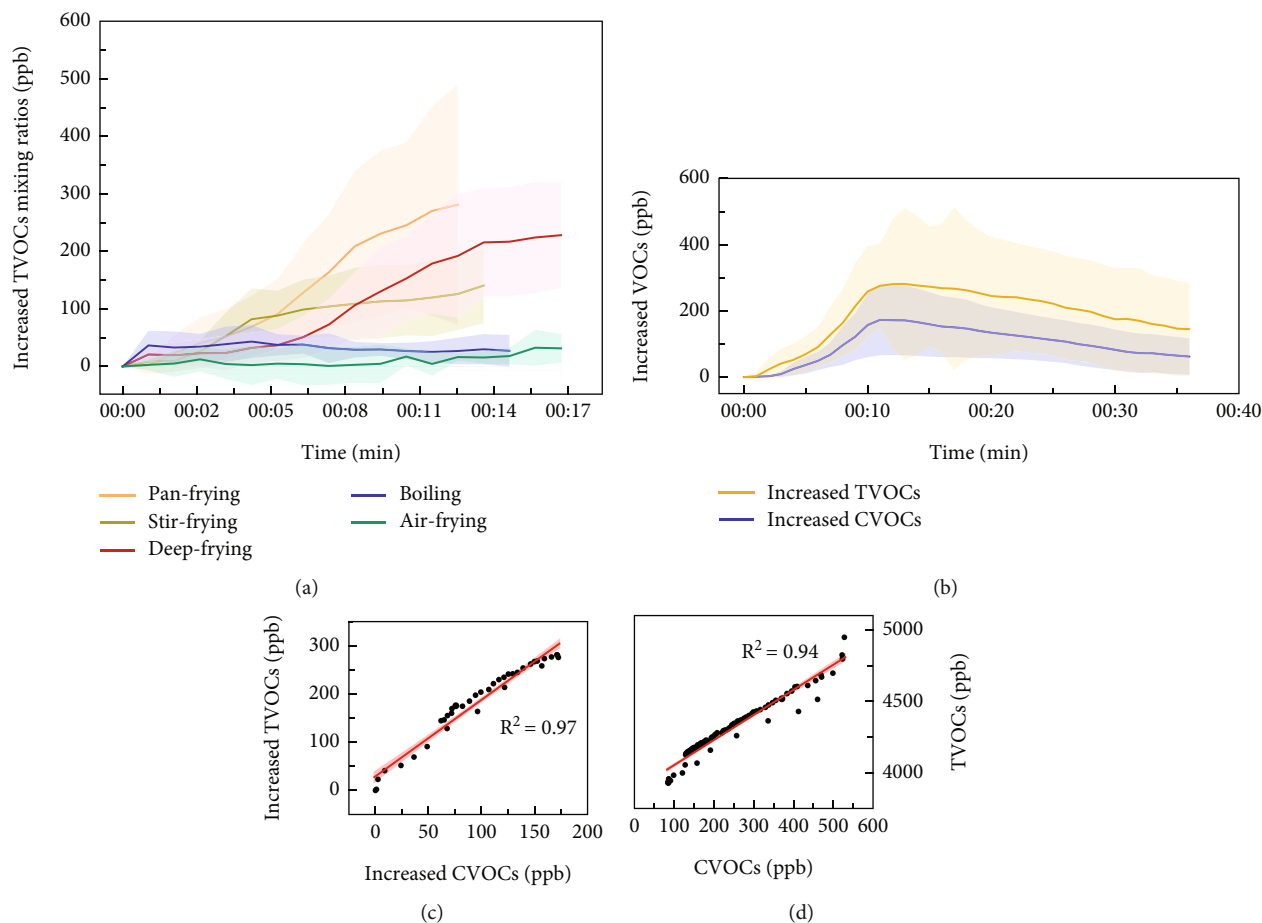


FIGURE 7: (a) Time series of averaged increased levels of mixing ratios (parts per billion) of TVOCs from each cooking method; (b) time series of averaged increased levels of TVOCs and CVOCs from pan-frying; (c) linear regression between increased levels of TVOCs and CVOCs from pan-frying; (d) linear regression between levels of TVOCs and CVOCs from pan-frying.

characteristics of various VOC species [57, 58]. Figure 8(c) shows the CVOC species with the highest abundance in a sample, which are also among the top TVOCs. Compounds like acetaldehyde, 1,3-butadiene, and butene/isobutene are likely VVOCs and disperse quickly. The presence of VOCs or SVOCs that transport more slowly in TVOCs potentially contributes to the observed delay.

Table 5 presents the most contributing VOC species in the emissions from pan-frying, stir-frying, and deep-frying, ranked by their mean levels. In general, these VOCs could be classified into several categories: aldehydes, ketones, furans, aromatic hydrocarbons, alkenes, pyrazines, and alkanes, which were identified in past studies as well [45, 46, 59]. Aldehydes were typically formed through the oxidation of fats and oils and the Maillard reaction, including the

oxidative degradation of unsaturated fatty acids, due to the high temperature of oils [46, 60]. Ketones resulted from the oxidation of fatty acids, the Maillard reaction, and the degradation of amino acids [61, 62]. Furans were generated from carbohydrate degradation, including enolization and dehydration, and the Maillard reaction [63]. Aromatic hydrocarbons could be products of the pyrolysis of proteins or the decomposition of certain amino acids, associated with high direct heat [64, 65]. Pyrazines were associated with the Maillard reaction and the development of flavour and aroma during cooking [29].

A correlation matrix was created based on the ranking of key VOC species (Figure 9). This matrix allowed us to assess the correlation coefficients between the dominant VOCs and factors, including oil weight and temperatures at different

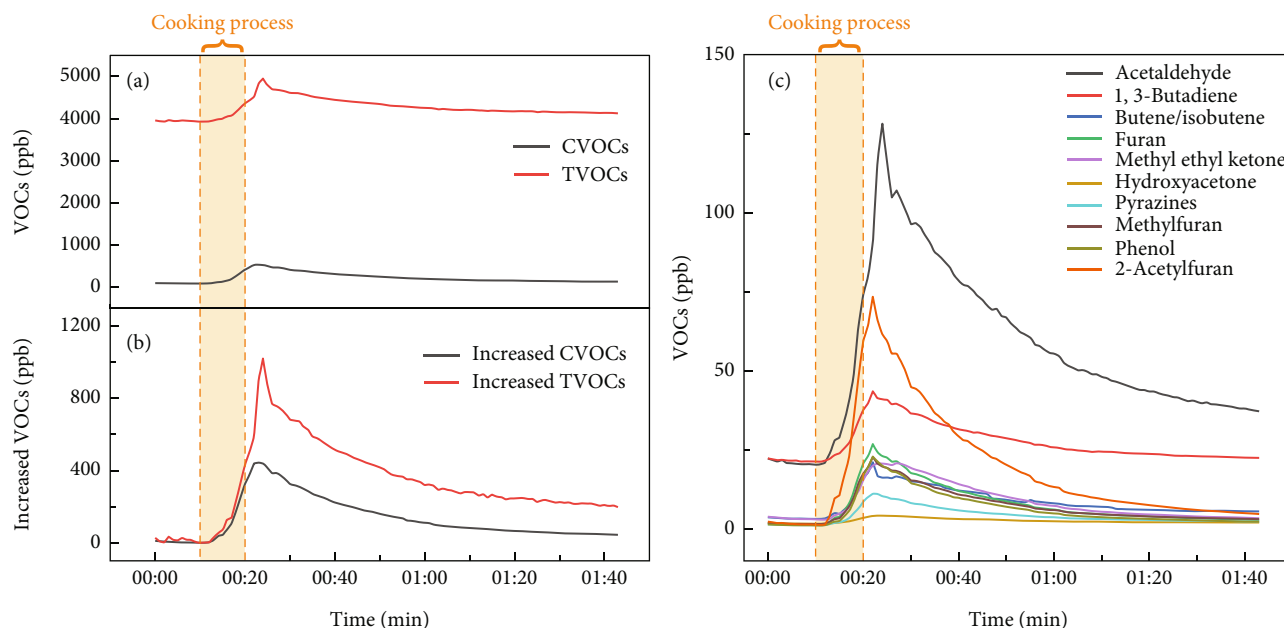


FIGURE 8: (a) Levels (mixing ratio, parts per billion) of TVOCs and CVOCs during a representative example of pan-frying; (b) increased levels of TVOCs and CVOCs during the sampling time; (c) VOCs with the Top 10 highest levels for this sample.

stages and durations, alongside the PM emission correlations. Beginning with CVOCs from the three frying methods, pan-frying exhibited strong positive correlations with cooking durations, especially for the period when chicken was added, and with both the mean and highest temperatures during cooking. Stir-frying displayed a strong positive correlation with the oil weight, and key VOCs also showed strong positive correlations with the temperatures at the time of chicken addition. Deep-frying revealed strong positive correlations with oil weight and both mean and minimum cooking temperatures, alongside a marked negative correlation with the chicken cooking duration.

The sources of the various key VOCs can be identified from Table 5, and the correlation coefficients ( $r$ ) between the factors stated in Table 1 are presented in Figure 9. For pan-frying, which entailed higher temperatures and direct heat, intense Maillard reactions were induced, potentially leading to the formation of higher levels of aldehydes and furans. Due to consistently high temperatures and the use of whole chicken fillets, the cooking process required more time, resulting in prolonged heat exposure and increased lipid oxidation in the oil, yielding more aldehydes and ketones. Furthermore, the direct contact between the chicken and the pan surface could enhance the formation of aromatic hydrocarbons and pyrazines, associated with browning and flavour development in the chicken. As for stir-frying, a rapid process involving the continuous movement of chicken slices and a pan fully covered by food and oil ensured more even heat distribution and reduced the exposure time of the food to high heat. Although the initial temperature was high, the average temperature during cooking was significantly lower than that of pan-frying and deep-frying, potentially leading to lower levels of heat-induced VOCs such as furans, aldehydes, and aromatic

hydrocarbons, which were typically produced by the Maillard reaction.

For deep-frying, which involved submerging the food in hot oil, there was a lower initial oil temperature, but durations were longer for heating the oil and the total cooking process. This led to extensive lipid oxidation, likely resulting in elevated ketone emissions. The cooking temperature, which was higher than that for stir-frying, contributed to the formation of alkenes, furans, and aromatic hydrocarbons due to prolonged heating. Notably, despite the weak or moderately positive correlations between VOC peak levels and the durations of the total cooking process and oil heating, strong negative correlations were observed between the VOCs and the duration of food cooking. This was ascribed to the intensity of the cooking process, as the correlation coefficients ( $r$ ) between the oil weight and the duration of oil heating and food cooking were 0.58 and  $-0.81$ , respectively, while the correlation coefficient ( $r$ ) between the mean temperature and the cooking duration was  $-0.61$ . This indicated that a higher volume of oil for deep-frying could maintain the temperature of the oil at a relatively high level after food at room temperature was added, and longer cooking times were a result of lower cooking temperatures. Higher temperatures could enhance the intensity of the cooking process, and vice versa. Thus, the negative correlations between cooking durations and VOC emissions were due to the lower temperatures in deep-frying with less oil used.

Moreover, 1,3-butadiene was notably present in both pan-frying (33.5 ppb [median]) and deep-frying (35.9 ppb [median]) yet absent from the stir-frying VOC list as per PCA selection. The peak levels of stir-frying ranged from 21.3 to 42.3 ppb, averaging 29.1 ppb and with a median of 27.5 ppb. Nevertheless, 1,3-butadiene, a significant emission from rapeseed oil, exhibited very weak correlations with oil

TABLE 5: VOC species with the highest peaks ( $C_{peak}$ ) (min–max, [median], in parts per billion) from pan-frying, stir-frying, and deep-frying, ranked by means.

Pan-frying		Stir-frying		Deep-frying	
VOCs	$C_{peak}$	VOCs	$C_{peak}$	VOCs	$C_{peak}$
Acetaldehyde	43.4–132.0 (69.2)	2-Acetylfuran	3.6–46.5 (15.5)	Acetaldehyde	44.1–95.9 (72.9)
1,3-Butadiene	28.6–47.7 (33.5)	Butene/isobutene	5.0–13.3 (7.2)	1,3-Butadiene	30.9–41.9 (35.9)
2-Acetylfuran	4.0–73.5 (24.7)	Methyl ethyl ketone	3.3–15.3 (5.9)	2-Acetylfuran	7.2–64.8 (34.3)
Furan	4.6–28.1 (14.3)	Furan	3.0–11.8 (6.6)	Methyl ethyl ketone	8.4–26.0 (13.4)
Methylfuran	3.8–22.9 (10.6)	Methylfuran	2.9–10.3 (5.9)	Furan	5.2–23.1 (14.4)
Methyl ethyl ketone	4.1–20.9 (10.0)	Phenol	2.1–11.0 (4.3)	Methylfuran	4.3–19.9 (11.5)
Butene/isobutene	4.6–21.1 (9.5)	Pyrazines	2.2–6.4 (4.1)	Butene/isobutene	6.3–13.4 (9.7)
Phenol	2.0–22.9 (7.4)	Acenaphthylene	0.9–10.5 (3.6)	Hexene	2.5–11.7 (6.8)
Acenaphthylene	0.8–17.7 (5.4)	Toluene	2.1–6.2 (2.8)	Phenol	3.2–9.9 (6.4)
Pyrazines	2.1–12.5 (5.1)	2-Pentanone	2.3–3.7 (2.9)	Pyrazines	2.9–7.2 (5.1)
Hexene	1.5–11.4 (5.4)	Hexene	1.4–5.1 (2.6)	Octene	1.7–8.2 (4.8)
Octene	1.2–12.3 (4.6)	Octene	1.0–6.0 (2.4)	2-Pentanone	3.1–6.6 (4.6)
2-Pentanone	2.9–6.3 (4.5)	Decane	0.8–3.4 (2.1)	Hydroxyacetone	3.8–5.4 (4.5)
Hydroxyacetone	3.1–5.4 (4.0)	Furfural	1.0–3.4 (1.9)	Toluene	2.4–6.5 (4.2)
Toluene	1.7–8.5 (3.3)	Pentene	1.4–3.0 (1.9)	Acenaphthylene	0.4–10.0 (3.0)

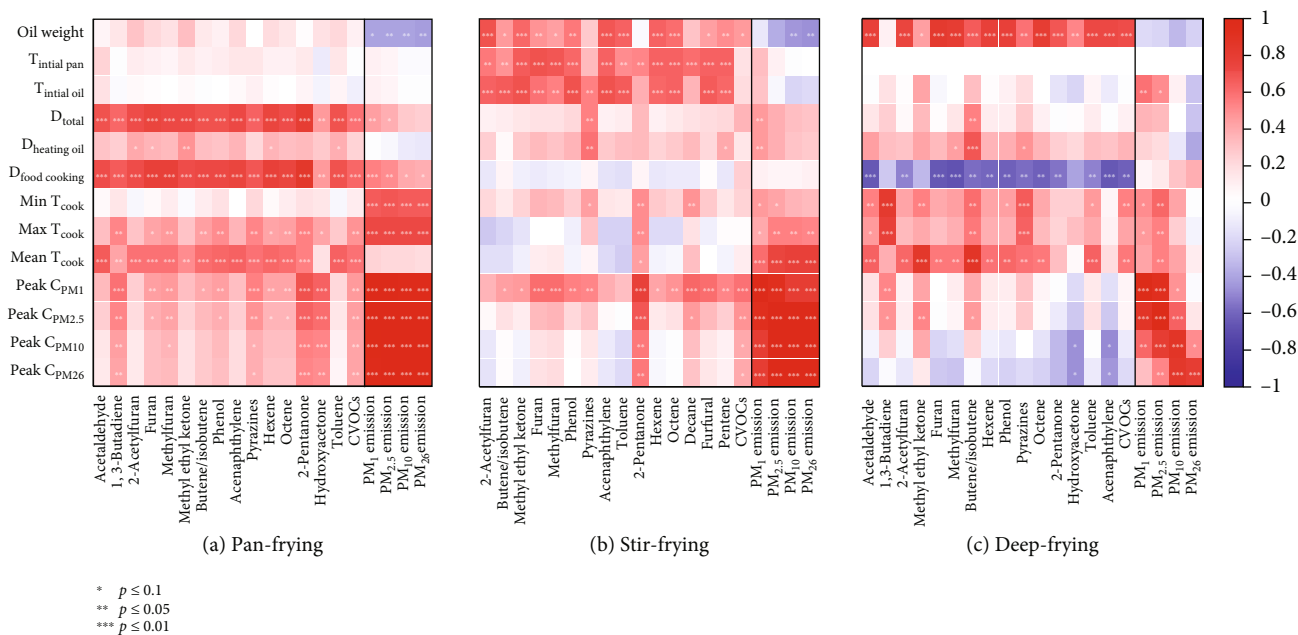


FIGURE 9: Correlations coefficients ( $r$ ) with significances ( $p$ ) between factors and emissions of VOCs and PM ( $T$ , temperature;  $T_{cook}$ , temperatures during the cooking process;  $D$ , duration;  $C$ , concentrations).

weight in both pan-frying ( $r = 0.142$ ,  $p > 0.1$ ) and deep-frying ( $r = 0.098$ ,  $p > 0.1$ ), suggesting consistent emission levels from the heated oil [66, 67]. Its omission from the stir-frying VOC list was due to its distinct concentration curve, which did not correlate with other key VOCs, thereby failing to cluster into the same PC. In stir-frying, the peak occurred immediately after the food was added, followed by a plateau, a pattern distinct from other cooking-related VOCs that typically peaked postcooking. This was attributed

to the high initial temperature, which then dropped during the cooking process, leading to a swift initial emission that quickly tapered off.

3.3. Comparison of the Factors Influencing PM and VOC Emissions. Figure 9 clearly illustrates the differing impacts of oil weight on PM and VOC emissions. PM emissions consistently showed negative correlations with oil weight, whereas VOCs generally displayed positive correlations.

Given that each chicken sample achieved a very similar level of browning (based on visual observation), the Maillard reaction is very unlikely to account for the variance in VOC emissions. Rather, the increased volume of oil likely experienced greater thermal degradation due to more reactive material being present, leading to a higher VOC output despite a similar culinary endpoint [45, 59].

The oil amount was inversely related to average cooking temperatures, suggesting the oil's thermal mass mitigated overheating, which could otherwise result in PM formation, especially finer particles from pyrolysis at elevated temperatures [3, 50]. With consistent browning across the samples, the additional oil served as a thermal buffer, preventing the extreme temperature hotspots typically associated with high PM production. This increased oil volume also meant particulates were more likely to be entrapped within the oil, thus reducing airborne PM concentrations.

In addition, the VOCs from pan-frying and stir-frying were found to positively correlate with  $PM_{10}$  peak concentrations, while they were insignificant in the deep-frying samples. The strong correlation observed between VOCs and  $PM_{10}$  in the study suggested that they might have been generated simultaneously through similar high-temperature processes, such as the thermal decomposition of oils and the Maillard reaction due to less oil used in pan-frying and stir-frying compared to deep-frying. Given that VOCs are gaseous emissions that can condense into particulates under certain conditions, the presence of VOCs could have directly influenced the formation of  $PM_{10}$ . During cooking, particularly when involving oils and proteins, a variety of organic compounds were released that may have vaporised and subsequently condensed into the PM with smaller diameters. In contrast,  $PM_{2.5}$  and  $PM_{10}$ , which represent larger particles, were typically produced through different mechanisms. These included mechanical actions like the splattering of oil or food particles. The fact that these larger particles showed a weaker correlation with the VOCs suggests that while they might have had some common sources with  $PM_{10}$  and VOCs, they also resulted from additional, non-VOC-producing processes. Larger particles were likely formed by the agglomeration of smaller particles or were directly emitted from the food, such as from bits of batter or charred substances, which were not directly related to the high-temperature reactions responsible for VOC generation [3, 9, 68–70].

**3.4. EPFRs.** Figure 10 shows the spin concentration of the various cooking samples, measured using EPR spectroscopy. We find that surface wipes collected from around the cooker after cooking showed the lowest number of spins per mass. The meat cooking samples showed significant spin concentrations in the range of  $0.1$ – $1 \times 10^9$  spins  $\mu\text{g}^{-1}$ . We observed a particularly high number of spins ( $\sim 3 \times 10^9$  spins  $\mu\text{g}^{-1}$ ) for one of the oil heating experiments—possibly because some smoking may have occurred during this specific experiment (although this was not visually observed at the time), which may have increased the concentration of EPFRs collected on the filter. This suggests that the heating and cooking process may produce EPFR.

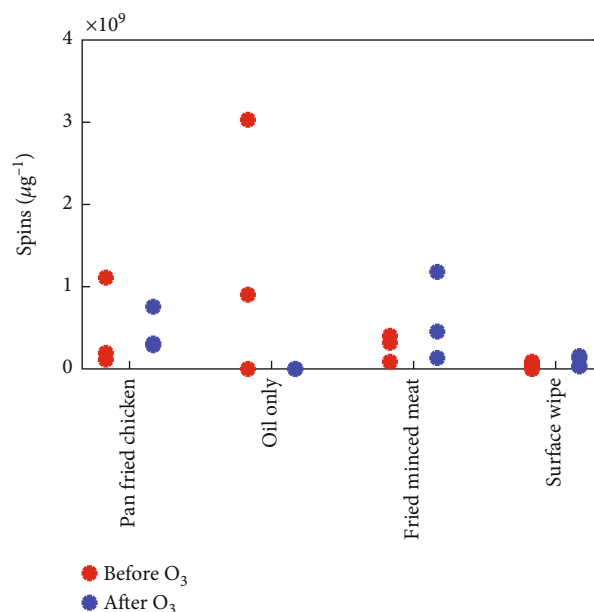


FIGURE 10: Number of spins per microgram for different cooking methods before and after ozone exposure.

Exposure to ozone did not consistently affect the number of spins in the collected filter samples. This suggests that the formation and destruction of EPFR may have either been balanced or that ozone exposure did not destroy or produce further EPFR species.

Our measured values from cooking events are generally lower by about 1–2 orders of magnitude compared to those measured in an indoor environment by Filippi et al. [32] ( $\sim 2 \times 10^{10}$ – $2 \times 10^{11}$  spins  $\mu\text{g}^{-1}$ ). This is likely due to other processes contributing to EPFR concentration, such as entrainment of outdoor particles or other household activities that lead to particle emissions in the longer-term measurements under less controlled conditions in Filippi et al. Two key differences between this study and samples including cooking events by Filippi et al. [32] are as follows: (i) we sampled at  $\sim 2 \text{ L min}^{-1}$  for  $\sim 4$ – $8$  min, while Filippi et al. [32] sampled at much higher flows of  $16 \text{ L min}^{-1}$  for 1–7 days; (ii) we focussed on sampling directly from the cooking event (i.e., approximately 15 cm from the pan), while Filippi et al. [32] placed their sampler in the kitchen of an inhabited apartment (although they did not specify where exactly).

#### 4. Limitations

This study provides valuable insights into real-world PM and VOC emissions, but several limitations should be noted. First, the assumption of well-mixed air introduces some uncertainty. Although a fan was used to promote air circulation, the kitchen's dimensions and airflow patterns may have caused localised variations in particle concentrations. External factors, such as the experimenter leaving the kitchen as the PM started to decay for health and safety reasons, contributed to a sharper decay rate.

The material–balance approach employed in this study does not account for the deposition and adsorption of PM and VOCs on surfaces, potentially biasing concentration measurements. While our study aimed to replicate real-world kitchen conditions, a more controlled environment, such as the chamber setup used in a kitchen laboratory by Huang et al. [71], would provide more precise measurements by eliminating external variables. Finally, some spatial variability in pollutant concentrations may have occurred despite efforts to place instruments in representative locations. Many of these limitations are unavoidable when moving from tightly controlled laboratory conditions towards a more realistic representation of real-world cooking experiences, with our research kitchen approach providing particularly valuable insights for this crucial step to understand people's actual exposures.

## 5. Conclusions

Our study identified the key factors that impact the levels of indoor PM and VOCs from cooking emissions, specifically the cooking method, oil amount, and initial temperature, while factors including the weight of ingredients and the air exchange rate were tightly controlled, allowing us to collect and analyse a unique set of data. As expected, oil-based cooking methods produced much more PM and VOCs in the indoor environment than water-based methods owing to the Maillard reaction. The air fryer generated the least PM emissions. While higher temperatures lead to higher concentrations of both pollutants in most cases, larger amounts of oil result in lower PM concentrations but higher VOC mixing ratios. Key VOC species emitted from the three frying methods were identified and could be categorised into aldehydes, ketones, furans, aromatic hydrocarbons, alkenes, pyrazines, and alkanes. We also determined PM emission rates and PM exposures, which allowed us to contrast the potential health impacts of the different cooking methods. EPFR concentrations were assessed by collecting the emissions during cooking, and it was found that EPFR concentrations are related to heating and cooking activities. EPFR levels were in the order of  $10^9$  spins  $\mu\text{g}^{-1}$  PM mass and were unaffected by ozone exposure.

## Data Availability Statement

The data supporting the conclusions of the study will be made available by the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

Conceptualisation was performed jointly by C.P. and R.T. for the cooking experiments and jointly by A. Milsom, A. Mishra, T.B., and C.P. for the EPFR work; funding acquisition, supervision, and project administration were carried out by C.P.; investigation, visualisation, data curation, for-

mal analysis, validation, and writing the original draft were carried out by R.T. for the entire manuscript, except for the EPFR work, and by A. Milsom and A. Mishra for the EPFR work; cooking experiments were carried out by R.T. with support from R.S. and Y.S.; EPFR work was carried out by A. Milsom and A. Mishra and supervised by T.B.; reviewing and editing of the manuscript was performed jointly by C.P., R.T., A. Mishra, T.B., A. Milsom, and Y.S.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*) The supporting information is presented in five sections: (i) Section S1 provides an overview of the cooking procedures in Table S1, including recipes and settings for the cooking of chicken breast for the five different cooking methods; (ii) Section S2 detailedly describes the operating principles, instrument settings for the optical aerosol spectrometer (S2.1) and PTR-ToF-MS, and the method for identifying VOCs based on PTR-ToF-MS signal output (S2.2); (iii) Section S3 outlines the air change rate assessment used in the manuscript with Figure S1 illustrating the measured decay curve and associated fitting for CO<sub>2</sub> levels in the research kitchen; (iv) Section S4 lists the conditions of cooking in sample collections for EPR analysis in Table S2, including ingredient types and weights, temperature of pan, sampling time, mass, spins, and numbers; and (v) Section S5 provides images of each of the cooking methods (Figures S2(a), S2(b), S2(c), S2(d), and S2(e)) and illustrates the different amounts of oil used in the pan (see Figure S3).

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