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Characteristics and health risk assessment of VOCs from typical hot pot restaurants in Chongqing, China

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As one of the most important cuisines, hotpot has been popular in China for a long time. However, volatile organic compounds (VOCs) from such activities are scarcely researched, and their threat to practitioners remains unknown. In this study, five hotpot restaurants of varying sizes in Chongqing were selected to investigate the emission characteristics of volatile organic compounds (VOCs), assess their ozone generation potential (OFP) and secondary organic aerosol generation potential (SOAp), and evaluate the associated health risks for practitioners. The results showed that the concentration range of TVOCs was 401.7–2199.7 μg m^{-3}. OVOCs were the major components and accounted for about 48.0–96.5%. Ethanol was the largest contributor accounting for 24.7–91.5%. The proportion of alkanes in small and medium scale hotpot restaurants was also high and showed a contribution of 29.1–34.0%. The OFP values fell in the range of 1131.7–3805.3 μg m^{-3}, and ethanol and formaldehyde were the two highest contributors. For the potential of SOA formation, aromatic hydrocarbons yielded the highest contribution and accounted for more than 78%. Meanwhile, the human health risk assessment showed both non carcinogenic and carcinogenic risk for those practitioners, in which the risk value of formaldehyde ranged from 1×10^{-5}–1×10^{-4} and indicated rather high probability of carcinogenic risk.

Environmental significance

Hot pot, a hallmark of Chinese culinary culture, represents a significant yet often overlooked indoor source of volatile organic compounds (VOCs). These emissions contribute to secondary air pollution through ozone and secondary organic aerosol formation and pose both carcinogenic and non-carcinogenic health risks—especially from compounds like formaldehyde and acrolein. This study integrates atmospheric chemistry, exposure science, and health risk assessment to reveal how restaurant size, cooking styles, and ingredient types shape VOC emissions and associated health hazards. The findings identify hot pot restaurants as a critical but underregulated source of indoor air pollution in urban China and highlight the urgent need for targeted emission control strategies in the catering sector to safeguard air quality and human health.

Introduction

Volatile organic compounds (VOCs) play a significant role in atmospheric chemical reactions, acting as precursors for the formation of particulate matter ($PM_{2.5}$) and ozone (O_3).[1–5] Studies have indicated that the rapid development of urbanization and changes in the urban spatial structure have a pronounced impact on the emission, dispersion, and transformation processes of VOCs, thereby indirectly altering the concentration and distribution patterns of $PM_{2.5}$. Controlling the emissions of VOCs is of great importance for improving air quality and reducing $PM_{2.5}$ levels.[6,7] Research by Li *et al.* on urban ozone pollution events has found that controlling VOC emissions is crucial for reducing ozone concentrations, and that reducing emissions of specific categories of VOCs can effectively alleviate ozone pollution.[8] Although China has implemented a series of policies to control VOC emissions and has achieved success in controlling emissions from industrial sources,[9–11] the control of VOC emissions from the catering industry still faces challenges.[12,13]

As a major anthropogenic source of urban VOC emissions, the catering industry had brought increasingly prominent pollution, due to its diverse cooking methods and complex emission components.[14] The World Health Organization (WHO) explicitly identified kitchen fumes as a primary source of air pollution, while the International Agency for Research on Cancer (IARC) further classified benzo(*a*)pyrene and other VOC-

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related substances contained in cooking fumes as confirmed carcinogens.[15]

Chinese cuisine, characterized by high-temperature stir-frying and heavy oil/flavor use, emitted significantly higher levels of VOCs compared to Western cooking styles, in which Sichuan-Hunan cuisine, barbecues, hot pot, and other catering formats exhibit particularly high emission intensities. Existing studies confirmed that VOCs in catering fumes mainly included alkanes, aromatic hydrocarbons, oxygenated VOCs (OVOCs), and other categories.[16,17] Among these, formaldehyde, 1,3-butadiene, and other components were classified as Group 1 carcinogens, while acrolein belonged to Group 2A (probable human) carcinogens.

A comparative study on six catering forms in Shanghai showed that due to the diffusion of most fumes from hot pot restaurants, the mass concentration of VOCs in such establishments reached up to 1900.2 ± 364.8 μg m^{-3}, which was significantly higher than those in Cantonese cuisine, local Shanghai cuisine, and other catering forms. Additionally, the carcinogenic risk values of components such as 1,3-butadiene and acetaldehyde exceeded the threshold standards recommended by the U.S. EPA.[18]

In addition, cooking activities release VOCs such as formaldehyde, benzene, toluene, and chloroform,[19,20] which have been proved to be threats to human health, with long-term exposure to high concentrations of VOCs potentially increasing the risk of respiratory diseases, cardiovascular diseases, and cancer.[6,21] The cooking methods of Chinese cuisine are highly complex, with a multitude of dish types that cannot be categorized for study.[22,23] Research by Chen *et al.* pointed out that the Chinese cooking process released a variety of air pollutants, including fine particulate matter ($PM_{2.5}$), ultrafine particulate matter (UFPs), and volatile organic compounds (VOCs), such as formaldehyde, benzene, and toluene.[24] While some scholars have studied the emissions of volatile organic compounds during stir-frying and barbecue processes,[25] the specific impact of hot pot cooking, one of China's most popular dining methods, on ambient VOC levels remains to be thoroughly investigated.[18,26] In terms of regional characteristic research, the high-resolution emission inventory of catering sources in China, constructed by the research team from Tsinghua University, showed that the per capita emission of organic compounds in areas with concentrated Sichuan-Hunan cuisine reached 1.19–1.35 kg per person, significantly higher than the national average, which confirmed the substantial impact of dietary habits on VOC emissions.[27] Although Song's study revealed that alcohols and alkenes accounted for more than 86% of VOCs in hot pot restaurants, CO and formaldehyde concentrations exceeded the standards during peak hours, and systematic environmental and health risk assessments of VOCs remained relatively scarce.[28]

As the hotpot capital of China, Chongqing has an unparalleled number and scale of hotpot restaurants. However, VOCs from such activities and their impact on environment and human health still remain unknown. In this paper, five different scale typical hot pot restaurants in Chongqing were investigated, and VOCs were sampled and analyzed, and assessment of environmental and human health impacts was also carried out. The purpose of this research was to provide the public with basic information on VOC emission characteristics and impacts on environmental and human health from such activities.

Materials and methods

Sample collection

Chongqing has numerous hot pot restaurants, with the majority being small and medium-sized ones. To ensure that the research results are representative, the size of the business area, business capacity, the typical table occupancy rate and so on were considered, and five selected restaurants ranging from super large to small in scale were selected, which were named restaurant 1 (large scale), restaurant 2 (small and medium scale), restaurant 3 (small and medium scale), restaurant 4 (small and medium scale), and restaurant 5 (extra large scale), respectively. A detailed overview of the selected restaurants is presented in Table 1.

As for the VOC sampling, passive sampling was performed by using a negative pressure Summa canister, which featured polished inner walls and had undergone silanized treatment to prevent sample contamination. Similar VOC sampling could be seen elsewhere.[13,29,30] The sampling period of this study spanned the entire month of August 2024, during which the weather featured high temperatures (28–38 °C) and low wind speeds (<1 m s^{-1}). The specific sampling times were precisely set from 17 : 30 to 20 : 30, a period considered the peak hours for hotpot restaurants. For each restaurant, the VOC sampling points were located in the central area, 1.5 meters high above the ground. Each sampling was carefully conducted for 20 minutes under controlled flow valve conditions to maintain a consistent sampling rate, ensuring the collection of representative samples. Approximately two samples were collected per restaurant, one among 17 : 30–19 : 00 and the other among 19 : 00–20 : 30. In total, about 10 samples were collected. Furthermore, to investigate the volatile organic compounds released during boiling, ten fresh base ingredient samples (50 grams each) were collected from the five hotpot restaurants during the sampling period.

Analysis methods

Analysis of VOC samples. The Summa canister VOC samples were analyzed for composition in accordance with the TO-14 and TO-15 methods recommended by the USEPA. The qualitative and quantitative analysis of VOCs was conducted using a two-dimensional GC-MS/FID system that was equipped with a three-stage cold trap pre-concentration device. Initially, the Summa canister samples were introduced into the automatic pre-concentration instrument (Entech 7100) for pre-treatment. After the removal of water and CO_2, the VOCs were trapped in the third stage cold trap, which was then rapidly heated to vaporize the enriched VOC components and introduce them into the GC-MS/FID system (Agilent 7890A/5975C) for further separation and quantification.

Table 1 Restaurant information

Restaurant	Business area	Business capability	Number of dining tables occupied	Cooking characteristics
Restaurant 1	800 m^2	30–35 tables	10 tables	Open boiling with natural gas; main ingredients: vegetables and beef and mutton; added oil: beef tallow
Restaurant 2	60 m^2	7–10 tables	3 tables	Open boiling with natural gas; main ingredients: vegetables and beef and mutton; added oil: beef tallow
Restaurant 3	120 m^2	10–15 tables	2 tables	Open boiling with natural gas; main ingredients: vegetables and beef and mutton; added oil: beef tallow
Restaurant 4	80 m^2	12–15 tables	3 tables	Open boiling with natural gas; main ingredients: vegetables and beef and mutton; added oil: beef tallow
Restaurant 5	2666.7 m^2	80 tables	22 tables	Open boiling with natural gas; main ingredients: vegetables and beef and mutton; added oil: beef tallow

High-purity helium, with a purity of greater than 99.999%, was utilized as the carrier gas. The standard gases include TO-15 mixed custom standard gases containing 63 compounds (Scott Gases, USA), a PAMS standard gas mixture containing 56 ozone precursors (PAMS, USA), and internal standard gases containing four compounds: bromochloromethane, 1,4-difluorobenzene, D5-chlorobenzene, and 1-bromo-4-fluorobenzene (Spectra gases, USA).More information about the analysis could be seen elsewhere.[31]

Analysis of chafing dish materials. Hotpot base materials were analyzed by utilizing headspace gas chromatography mass spectrometry (HS-GCMS),which was reported by Yang.[32] The heating box was maintained at 80 °C, while the transmission line was set at 160 °C. The sample bottle was allowed to equilibrate for 10 minutes, followed by a 0.2 minutes pressure equilibration period. The injection time, and the blowback time, were both set at 0.2 minutes.

The injection port was heated to 250 °C, with samples injected using a split ratio of 50 : 1. The chromatographic column used was a DB^{-1}, with a length of 60.0 m, an inner diameter of 0.32 mm, and a coating thickness of 2.0 μm. The heating method involved programmed heating, starting at 35 °C for 10 minutes, followed by a heating rate of 20 °C min^{-1} up to 280 °C for an additional 10 minutes. The chromatographic column flow rate was 2.0 ml min^{-1}, with high-purity helium used as the carrier gas. The ion source was an electron bombardment (EI) source operating at an energy of 70 eV. The ion source temperature was 200 °C, and the fourth level pole temperature was 150 °C. The scanning mode was set for the full scan. Each component was semi-quantitatively analyzed using ethanol, with relative content determined by the peak area normalization method.

Assessment of secondary pollution generation potential. The secondary pollution generation potential of volatile organic compounds (VOCs) emitted from hot pot restaurants was discussed, which mainly focused on their impact on atmospheric chemical reactivity-ozone formation potential (OFP) and the formation of ozone and secondary organic aerosols (SOAs). The OFP[33,34] of VOCs was quantified using the Maximum Incremental Reactivity (MIR) approach, which reflected the propensity of ingredients of VOCs to engage in atmospheric chemical reactions. The formula was as follows:

$$\mathrm{OFP}_i = \mathrm{MIR}_i \times \mathrm{VOC}_i \quad (1)$$

Here, OFP_i represented the ozone generation potential of species i in μg m^{-3}, $\mathrm{MIR}_i$was the ozone generation coefficient for species i derived from Carter's study,[35] measured in g g^{-1}, and $\mathrm{VOC_i}$ was the emission concentration of species i observed under actual conditions, also in μg m^{-3}.

In terms of SOA generation, the aerosol generation coefficient method (FAC method)[35,36] was employed to estimate the potential for secondary organic aerosol formation from VOC emissions. The formula for this estimation was:

$$\mathrm{SOA_p} = (\mathrm{VOC_i} \times \mathrm{FAC})/(1 - \mathrm{FVOC_r}) \quad (2)$$

where $\mathrm{SOA_p}$was the potential for SOA generation from VOC compounds in μg m^{-3}, FAC was the SOA generation coefficient as a percentage, and $FVOC_r$ was the fraction of VOC compounds involved in the reaction, also in percentage. The values for FAC and $FVOC_r$ were obtained from relevant literature.[35,36]

Health risk assessment. The potential health hazards posed by volatile organic compounds (VOCs) in the environment of hot pot restaurants using existing research data were assessed. The assessment employed the United States Environmental Protection Agency's (USEPA) method,[37] to estimate the Hazard Index (HI) and Lifetime Cancer Risk (LCR). These metrics were pivotal for assessing the non-carcinogenic and carcinogenic risks associated with respiratory inhalation of VOCs among the hotpot practitioners. The calculation formulae were listed as follows:

$$\mathrm{HI} = \frac{(\mathrm{VOC}_i \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED})}{365 \times \mathrm{AT}_{\mathrm{nca}} \times 24} \times 90\% \times \frac{1}{\mathrm{Rfc}} \tag{3}$$

$$\mathrm{LCR} = \frac{(\mathrm{VOC}_i \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED})}{365 \times \mathrm{AT}_{\mathrm{ca}} \times 24} \times \mathrm{IUR} \tag{4}$$

The formula took into account exposure time (ET, measured in hours per day, h d^{-1}, with a value of 8,[38] exposure frequency (EF, in days per year, $d \cdot a^{-1}$, set at 250), and exposure duration (ED, in years, a, with a value of 20). Additionally, it also included the averaging times for non-carcinogenic (AT_{nca}) and carcinogenic effects (AT_{ca}), both in years, with values of 25 and 70, respectively. Based on the general assumptions for environmental health risk assessments, a default human absorption efficiency of 90% was adapted, aligning with the conservative parameters recommended by EPA IRIS and Du.[39] The assessment also utilized the reference concentration (Rfcis, in micrograms per cubic meter, $\mu g\ m^{-3}$) and the inhalation unit risk (IUR, in cubic meters per microgram, $m^3\ \mu g^{-1}$), both of which were sourced from the comprehensive information system of the United States Environmental Protection Agency (US EPA), ensuring a scientifically robust evaluation framework.[40,41] This methodical approach allowed for a precise estimation of both the hazard index (HI) for non-carcinogenic risks and the lifetime cancer risk (LCR) for carcinogenic risks, providing a thorough understanding of the health implications associated with VOC exposure in hot pot restaurants.

According to US EPA standards, an HI greater than 1 indicated the presence of non-carcinogenic health risks, with higher values signifying greater risk. Conversely, an HI less than 1 is considered to be no risk.[37] Studies suggested that species with HI values exceeding 10^{-1} may warrant attention for potential non-carcinogenic risks.[42,43] This study meticulously evaluated 41 non-carcinogenic volatile organic compounds (VOCs) for their hazard index (HI) potential in the context of hot pot restaurants.

Results and discussion

Compositions of hotpot base ingredients

The composition characteristics of the base ingredients from five hot pot restaurants are illustrated in Fig. 1. The analysis showed minimal differences in the classification of the hot pot base ingredients among the restaurants, in which 12 to 14 components were detected. In Restaurant 1, ethanol and acetonitrile were predominant, constituting 39.4% and 38.1%, followed by D-terpene and (S)-(+)-1-cyclohexylethylamine. Restaurant 2 exhibited main components of acetonitrile (32.5%), ethanol (12.9%), (S)-(+)-1-cyclohexanethylamine (10.6%), terpene (10.3%), and erythritol (9.5%). Restaurant 3 main components were acetonitrile (50.7%), terpene (10.9%), and linalool (10.3%), while Restaurant 4 yielded acetonitrile (42.2%), ethanol (35.2%), linalool (5.8%), and terpene (4.6%). Restaurant 5 primarily yielded ethanol (33.0%), acetonitrile (26.8%), linalool (14.3%), and β-pinene (7.2%), among others. Overall, the characteristic components of hot pot restaurants were identified as ethanol, acetonitrile, and D-terpene, which were different from components reported in other studies. For instance, a study by Yan *et al.*[44] showed that the key volatile compounds in butter hot pot bases include cyperene, γ-terpinene, terpenoid oleene, linalool, *etc.* Li *et al.* [32] suggested that olefins and alcohol compounds are abundant in hot pot seasoning. Liu *et al.*[45] proposed that alcohols (30.1%) and hydrocarbons (22.7%) are significantly present in hot pot bases, in which ethanol and ethyl maltol were particularly high. These differences may have been related to the raw materials and quantities used in hot pot base ingredients, as well as cooking and frying durations.

Concentration and components of VOCs

The compositions of VOCs from hot pot restaurants are shown in Fig. 2. OVOCs constituted the largest proportion of VOC emissions among the five restaurants ranging from 48.0% to 96.5%. Notably, both large and extra-large restaurants accounted for over 85.0%. For restaurant 2 and restaurant 3, the emission compositions were identical; OVOCs were the largest contributors, followed by alkanes. In Restaurant 2, the proportion of OVOCs and alkanes were 48.0% and 34.0%, respectively. The proportion of alkanes in restaurant 3 was close to that of restaurant 2, which yielded 29.1% contribution. The proportions of alkynes across the three small and medium scale restaurants were relatively close and ranged from 7.3% to 8.1%.

There were some differences between this study and other studies. Zeng *et al.*[46] believed that alcohols are important volatile compounds in hotpot seasoning. Hu *et al.*[47] found that alkanes (45.0%) and OVOCs (40.0%) were the main components in the composition of VOCs in hotpot, which was similar to this study's results as far as small and medium-scale hot pot restaurants were concerned. However, there were significant differences among results from large and extra-large hot pot restaurants. Song *et al.*[48] believed that the air VOCs emitted from hot pot restaurants were mainly composed of olefins and alcohols, with the main components being (+)-limonene and β-pinene, which accounted for 60.26% to 80.92% of TVOCs. These compositions were significantly different from the results of this study. The primary reason for these differences was the difference in sampling and analysis methods. In contrast, both VOCs and hotpot bases were collected in the present study.

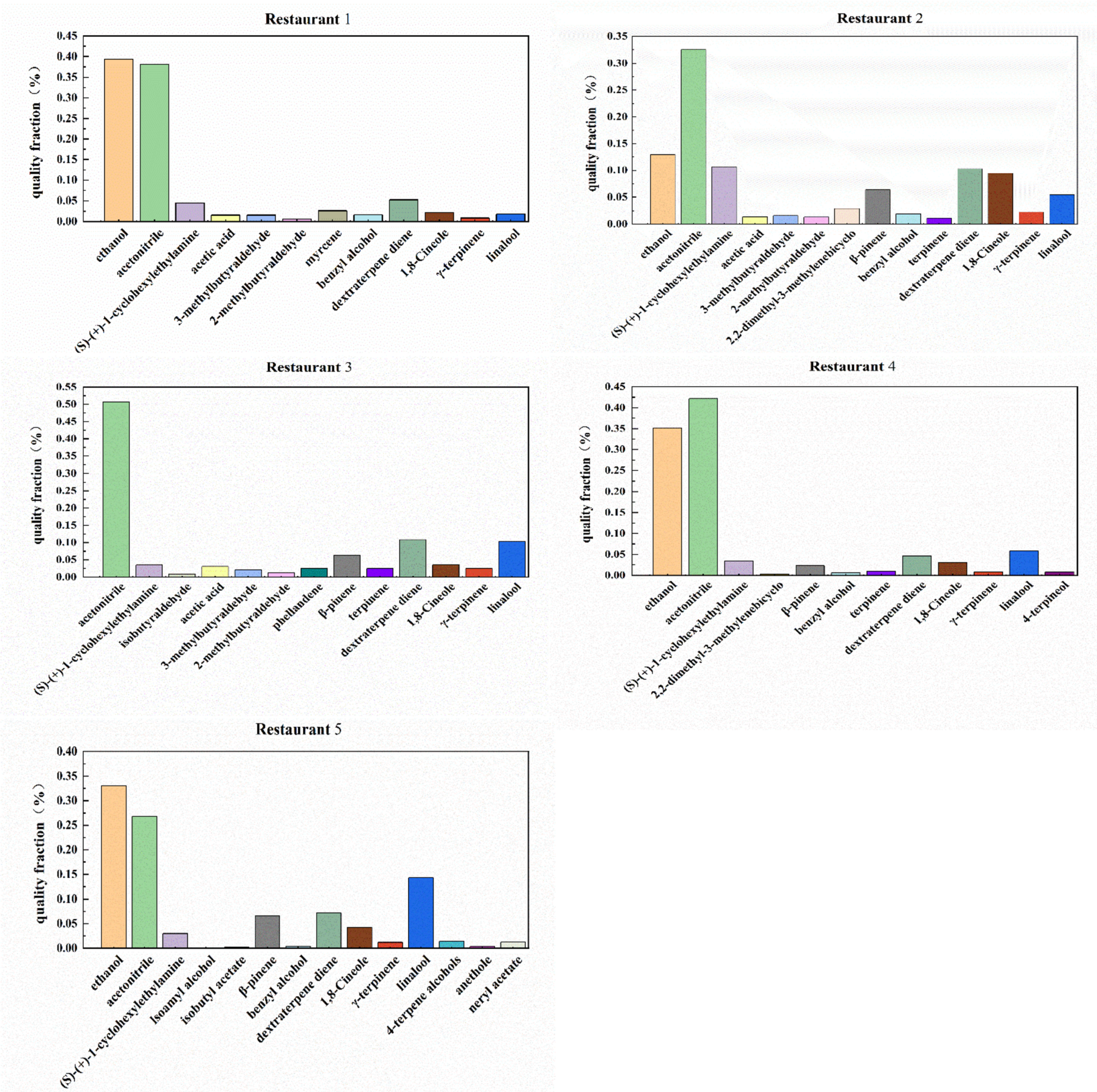

Fig. 1 Composition characteristics of hot pot base ingredients from five restaurants.

The distinctive taste of Chongqing hot pot is derived from its diverse hot pot seasonings and a rich selection of ingredients. The variations in the formulations of hot pot bases, cooking methods, types of ingredients, as well as the scale and ventilation conditions of different hot pot restaurants, lead to differences in the levels of volatile organic compounds (VOCs) observed in the sampling. These variations are summarized in Fig. 2. The primary VOCs emitted by the five hot pot restaurants were all ethanol, which accounted for 24.7% to 91.5% of the total emissions, followed by formaldehyde. Ethanol was one of the primary pollutants in hot pot restaurants, which might originate from with two main sources: on the one hand, the inherent ethanol could be released from the hot pot base material during the boiling process (which volatilized continuously in the former stages and significantly decreased in the later stages); on the other hand, ethanol could also be yielded from the continuous volatilization during beer and liquor consumption. The contents of formaldehyde and acetaldehyde in large and extra-large hot pot restaurants were lower than those in small and medium-sized ones. Restaurant 2 had the highest content of formaldehyde at 12.8%, while those of the other four restaurants remained at levels below 10.0%. The contents of acetaldehyde in all five restaurants were less than 5.0%. The proportions of alkanes in small and medium-sized hot pot restaurants were relatively high, which was 7.0%, and the reason behind this still needs further study.

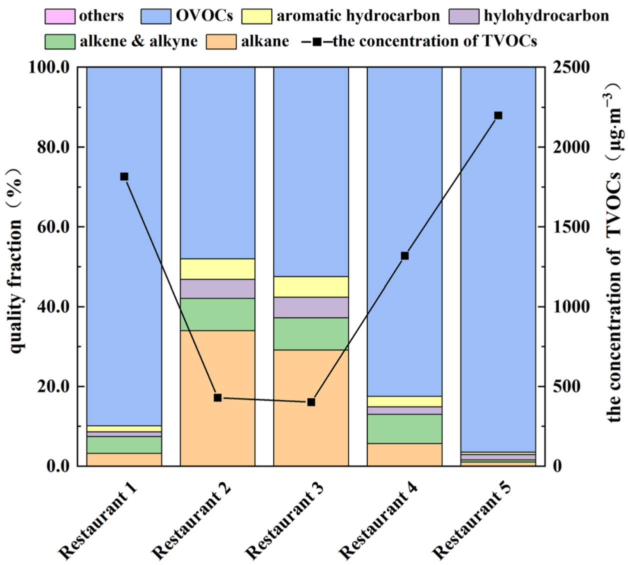

Fig. 2 VOC emissions from five hot pot restaurants.

Identification of VOC sources

By integrating the base sauce characteristics of five hotpot restaurants, VOC concentration data, and component contribution rates, we further explored the potential emission sources of key pollutants.

Ethanol was the predominant VOC component across all hotpot restaurants, accounting for 24.7% to 91.5% of total TVOCs (SI). Restaurant 5 (extra-large) exhibited the highest ethanol proportion at 91.5%, followed by Restaurant 1 (large) at 80.6%. The VOC emission profiles of restaurants 2, 3, and 4 were generally similar, but differences also existed in terms of specific components and concentrations. Overall, ethanol was predominant, but the proportions varied significantly: 24.7%, 34.1% and 69.1% for Restaurants 2, 3 and 4, respectively. Additionally, alkanes constituted a higher proportion of the emissions in restaurants 2 and 3, which might originate from the thermal decomposition of fats in the ingredients. Meanwhile, the high ethanol proportion in restaurant 4 might influence the relative contribution of alkanes to a certain extent, resulting in a similar VOC composition profile to restaurant 1. These differences might be attributed to the volatility of the hotpot base ingredients (which contain different ethanol levels, as shown in Fig. 1), restaurant size, cooking duration, patrons' alcohol consumption intensity, the types of dishes served and so on. Extra-large and large restaurants typically featured larger operating areas and higher occupancy rates (restaurant 1 occupied 10 tables and restaurant 5 occupied 22 tables, as shown in Table 1), leading to more patrons consuming beer and liquor. The evaporation of alcohol from beverages directly caused a significant increase in ethanol concentrations. In contrast, medium-to-small restaurants showed lower ethanol proportions in VOCs due to fewer diners and less alcohol consumption. Furthermore, analysis of the hotpot base sauces (Fig. 1) revealed that ethanol was a characteristic component of the bases (accounting for 39.4% in restaurant 1's base and 35.2% in restaurant 4's base), but its contribution to ethanol levels was much lower than that of alcohol evaporation. The reason is that the boiling temperature of the hotpot base (approximately 100 °C) could affect the volatilization of ethanol from the base, while the wide consumption of beer and liquor might lead to more direct and extensive volatilization, resulting in high ambient VOC concentration in restaurants.

Formaldehyde and acetaldehyde were the second most significant OVOCs among VOCs, accounting for 1.9% to 12.8% of TVOCs, with acetaldehyde contributing less than 5.0% (SI). Analysis of hotpot base sauces revealed no detectable formaldehyde or acetaldehyde in samples from all five restaurants, indicating that these aldehydes did not originate from the sauces. Considering the cooking characteristics of hotpot, the primary sources of these aldehydes were the thermal decomposition and oxidation of organic matter in ingredients during boiling. Specifically, meat components (*e.g.*, beef, lamb, and pork) contained significant amounts of fats and proteins. When heated at high temperatures (100–105 °C, the boiling point of hotpot broth), fats underwent oxidative decomposition to produce acetaldehyde, while proteins underwent thermal degradation through hydrolysis to generate formaldehyde.[49,50] Additionally, vegetable components (*e.g.*, Chinese cabbage, mushrooms, and potatoes), which were abundant in carbohydrates and cellulose, underwent partial thermal decomposition of carbohydrates during prolonged boiling, generating small-molecule aldehydes like formaldehyde.[51,52] The observed VOC results showed higher formaldehyde levels in small-to-medium-sized restaurants (*e.g.*, 12.8% in restaurant 2 and 7.1% in restaurant 4), further proving that VOCs could accumulate at worse ventilation, which made it difficult for aldehydes generated by the thermal decomposition of ingredients to disperse, resulting in higher accumulated concentrations compared to larger and extra-large restaurants (restaurant 1 : 2.9%; Restaurant 5 : 1.9%). Alkanes constituted the second-largest component in small and medium-sized restaurants, accounting for 29.1% to 34.0%, while in large and extra-large restaurants, alkanes accounted for less than 5% (Fig. 2). This difference could be attributed to mixed sources, particularly food volatilization. Certain fat components (*e.g.*, processed meat products like luncheon meat and vegetable oils used for marinating ingredients) contained small-molecule alkanes (*e.g.*, butane, propane, and isobutane), which could be released into the air during the boiling process of hotpot cooking.[53–55]

Aromatic hydrocarbons (such as toluene and *m*-xylene) were key precursors to secondary organic aerosols (SOAs), contributing more than 78% to SOA generation (Fig. 4). According to the SOA formation formula, the contribution value was related to the concentration and correlation coefficient of VOCs. Based on the detection results, the concentration of aromatic hydrocarbons was lower than those of ethanol and alkanes, suggesting that their higher SOA contribution value might have been attributed to their higher FAC generation coefficients, which played an important role in the SOA contribution rate.

Based on the VOC observation data at the Jinyun Mountain background site (with no significant anthropogenic pollution sources) and urban sites (mainly residential and commercial areas) in Chongqing,[56] the following results were obtained: the TVOC concentrations in hotpot restaurants (401.7–2199.7 μg m^{-3}) were 8.6 to 46.9 times higher than those at the Jinyun Mountain. Ethanol (accounting for 24.7–91.5% in restaurants, not in the top ten species at the background site), acetonitrile, and other characteristic species were not detected at the background site, confirming that hotpot activities were strong emission sources of ethanol, acetonitrile and so on. In contrast, the concentrations of formaldehyde (1.9–12.8%) and ethylene (1.2–3.1%) in the restaurants were higher than those at the background site and the urban site. Furthermore, the proportion of alkanes in small-to-medium-sized restaurants (29.1–34.0%) was significantly higher than in large restaurants (<5%), and the alkane composition (mainly butane and propane) differed from that of the urban site.

Assessment of secondary pollution generation

The OFP values for different scales of hot pot restaurants are presented in Fig. 3, showing a close range with the large restaurants yielding the highest OFP value of 3805.3 μg m^{-3}. Notably, oxygenated VOCs (OVOCs) contributed the most to O_3 generation, with contribution exceeding 60.0% and the maximum of 96.1% was found in a super large restaurant. Ethanol, formaldehyde, acetaldehyde, and ethylene were the components with the most significant contribution to O_3 generation.

Fig. 4 displays the SOA generation potential for the five hot pot restaurants, with values ranging from 0.9 to 2.1 μg m^{-3}. Aromatic hydrocarbons were identified as the components with the highest contribution rate to SOA generation, with rates varying from 78.6% to 87.2%. For SOA generation control, the primary compounds to target were aromatic hydrocarbons, particularly toluene and *m*-xylene, which had higher contribution rates among those different scale restaurants.

Health risk assessment

Acrolein was identified as a significant non-carcinogenic risk in hotpot restaurant environments, with Hazard Index (HI) values

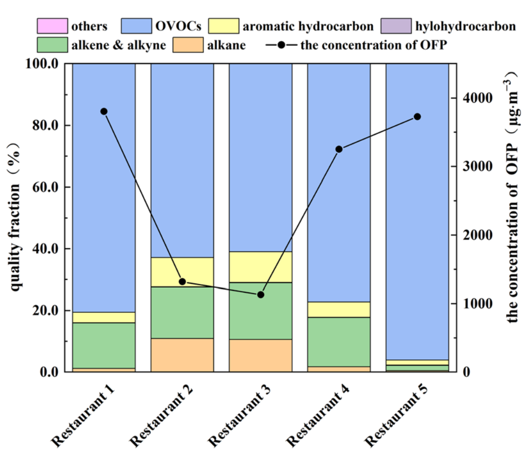

Fig. 3 Ozone generation potential of VOCs in five hot pot restaurants.

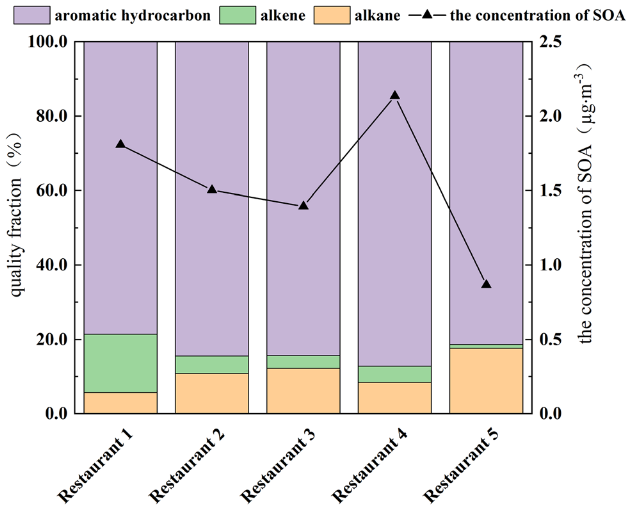

Fig. 4 SOA generation potential of five hot pot restaurants.

reaching 3.2 in both large and small establishments. This represents a substantial 55.9% to 61.9% of the total risk, emphasizing acrolein's substantial impact on respiratory issues such as irritation and potential lung damage. The HI values for acrolein are significantly above the acceptable threshold of 1.0, suggesting a considerable health risk. Additionally, formaldehyde, known for causing discomfort to the eyes, nose, and throat, was recognized with HI values of 1.0 and 1.7 in medium scale restaurants. These levels are close to or exceed the acceptable threshold, indicating a notable potential for non-carcinogenic health risks, including allergic reactions and skin irritation.

A detailed overview of the pollutants with high HI values, including acrolein and formaldehyde, is presented in Table 2, providing a comprehensive assessment of the non-carcinogenic risks associated with VOC exposure in hot pot restaurants.

The total HI range across the five hot pot restaurants was 1.9 to 5.7, indicating the highest non-carcinogenic health risks in small and medium scale restaurants. Some pollutants exhibit HI values greater than 10^{-1}, suggesting potential non-carcinogenic health risks that merited attention. Comparative studies from Shanghai[18] and Beijing[26] revealed varying HI values, with Shanghai's hot pot restaurants showing significantly higher values, particularly for acrolein, while all had HI values less than 1 in Beijing.

Relation of VOC pollution and health risk effects

The variations in the composition and concentration of volatile organic compounds (VOCs) in hotpot restaurants of different scales in Chongqing were primarily influenced by factors such as operational scale and dining behaviors. These factors collectively impacted the health risk levels for staff by altering both VOC exposure concentrations and the types of pollutants to which they were exposed. Regarding operational scale, large and extra-large restaurants (*e.g.*, restaurant 1 with an operating area of 800 m^2 and restaurant 5 with 2666.7 m^2) featured a higher number of dining tables (30–35 tables in restaurant 1

Table 2 Hazard index (HI) of human inhalation of VOCs in five hot pot restaurants

Pollutant	Large	Small and medium-sized1	Small and medium-sized2	Small and medium-sized3	Extra large
1,3-butadiene	0.2	$<10^{-1}$	$<10^{-1}$	0.1	$<10^{-1}$
Formaldehyde	0.9	1.0	0.6	1.7	0.8
Acetaldehyde	0.7	0.2	0.3	0.5	0.5
Acrolein	3.2	0.7	0.8	3.2	0.5
Total HI of other components	0.2	0.2	0.2	0.3	0.2
Total hazard index	5.1	2.1	1.9	5.7	2.0

and 80 tables in restaurant 5) and greater table occupancy rates (10 occupied tables in restaurant 1 and 22 occupied tables in restaurant 5). This increase in table occupancy not only led to greater ethanol emissions due to elevated alcohol consumption (ethanol accounting for 80.6% of emissions in restaurant 1 and 91.5% in restaurant 5), but also indirectly heightened inhalation exposure to other hazardous pollutants. Additionally, the increased consumption of food ingredients in these larger establishments elevated the emissions of aldehydes (*e.g.*, formaldehyde and acetaldehyde) and alkanes (*e.g.*, butane and propane), which were generated during the thermal decomposition of ingredients. As a result, the total VOC concentrations in large and extra-large restaurants (*e.g.*, Restaurant 1 : 1816.1 μg m^{-3}; Restaurant 5 : 2199.7 μg m^{-3}) were significantly higher than those observed in small and medium-sized establishments (ranging from 401.7 to 1318.3 μg m^{-3}). Notably, in restaurants where occupancy rates ranged from 20% to 43%, TVOC concentrations did not exhibit a strict linear relationship with occupancy rates. Instead, they were influenced by the "per-table pollution intensity," which included factors such as per-table alcohol consumption and ingredient types. For instance, restaurant 2 (TVOCs: 429.9 μg m^{-3}), with a 30–43% occupancy rate, exhibited a smaller concentration variation compared to Restaurant 3 (TVOCs: 401.7 μg m^{-3}) with a 13–20% occupancy rate. However, Restaurant 4, with a 20–25% occupancy rate, had significantly higher TVOCs (1318.3 μg m^{-3}) due to its high per-table alcohol consumption, where ethanol made up 69.1% of total emissions. These observations suggested that the number of occupied tables determined the "lower bound" of total VOC emissions, while the per-table pollution intensity defined the "upper bound" of health risks. Even when occupancy rates were similar, higher per-table emissions of hazardous pollutants could significantly increase the exposure risks for staff.

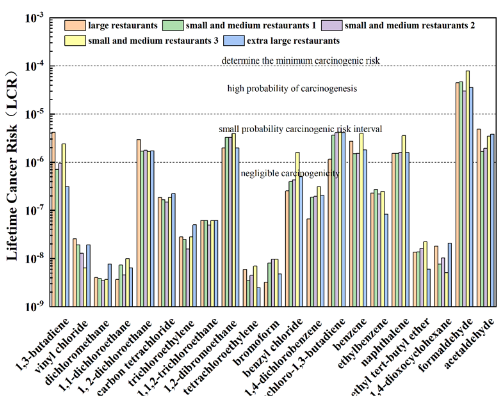

Fig. 5 Lifetime cancer risk assessment (LCR) of five hot pot restaurants.

Dining behaviors, particularly alcohol consumption patterns, could also contribute to the variation in VOC composition, thereby affecting health risks. Large and extra-large restaurants, which predominantly catered to family gatherings and business banquets, were characterized by high drinking frequencies and large single-serving quantities. This resulted in ethanol accounting for over 80% of TVOCs in these establishments (*e.g.*, restaurant 1: 80.6%; restaurant 5: 91.5%). Under such conditions, VOCs were primarily dominated by low-toxicity ethanol, and the health risks were largely related to respiratory irritation due to high concentrations of organic vapors, rather than significant carcinogenic threats. In contrast, small and medium-sized restaurants, which catered mainly to individual customers or small groups, exhibited lower or no alcohol consumption. As a result, ethanol's proportion in VOCs decreased to 24.7–34.1% (restaurant 2: 24.7%; restaurant 3: 34.1%), while alkanes (29.1–34.0%) and aldehydes (formaldehyde 6.6–12.8%) became the predominant components. Formaldehyde, a potent carcinogen (LCR values ranging from 3.0×10^{-5} to 8.0×10^{-6}, which far exceeded the 1×10^{-6} safety threshold), accounted for 12.8% in Restaurant 2, thereby significantly increasing the carcinogenic risk for staff. Although alkane pollutants did not exhibit significant carcinogenicity, prolonged inhalation could increase respiratory burdens and amplify non-carcinogenic risks (*e.g.*, restaurant 2 total HI value: 2.1; restaurant 3 total HI value: 1.9). The distinction between the "ethanol-dominated low risk" and "aldehyde-alkane-dominated high risk" highlighted dining behavior as a crucial factor influencing the health.

In terms of carcinogenic risk, the study categorized risk levels[57] and evaluated the LCR of 21 VOC components (Fig. 5). All evaluated hot pot restaurants' LCR values surpass the maximum acceptable carcinogenic risk level (1×10^{-6}), indicating a potential carcinogenic risk. Notably, formaldehyde presented the highest cancer risk with an LCR ranging from 3.0 $\times 10^{-5}$ to 8.0×10^{-5}, suggesting a substantial probability of cancer risk for hotpot practitioners. Other species such as 1,3-butadiene, 1,2-dichloroethane, and benzene were also identified as low-probability carcinogenic risks.

The findings from this study aligned with other research indicating that aldehydes and benzene had significant potential carcinogenic risk. Notably, formaldehyde presented the highest cancer risk with an LCR ranging from 3.0×10^{-5} to 8.0×10^{-5}, suggesting a substantial probability of cancer risk for hotpot practitioners. Other species such as 1,3-butadiene, 1,2-

dichloroethane, and benzene were also identified as low-probability carcinogenic risks.

The findings from this study aligned with other research indicating that aldehydes and benzene were significant carcinogens.[23] Given the substantial contribution of formaldehyde to cancer risk,[18] it was imperative for Chongqing to prioritize the control of formaldehyde emissions to mitigate potential health threat. It should be noted that this study did not include customer exposure, as it was characterized by short-term, random exposure, which differed significantly from the long-term, occupational exposure patterns observed among staff.

Conclusions

(1) VOCs from hot pot bases and ambient air in five restaurants were sampled and analyzed. VOC levels varied widely (401.7 to 2199.7 μg m^{-3}), suggesting a link between restaurant size and VOC emissions. Oxygenated VOCs made up 48.0% to 96.5% of emissions, with medium-sized restaurants showing a higher alkane presence at 29.1% and 34.0%. Ethanol was the dominant pollutant, contributing up to 91.5%, followed by formaldehyde.

(2) The ozone formation potential (OFP) in hot pot restaurants ranged from 1131.7 to 3805.3 μg m^{-3}. Oxygenated VOCs (OVOCs) were the largest contributors to OFP, accounting for 61.0% to 96.1%. Alkynes were the second largest contributors to OFP (14.8% to 18.3%), in which ethanol and formaldehyde were the major contributors. As far as SOA was concerned, toluene and meta-xylene were the key factors with 78.0% contribution.

(3) As for non-carcinogenic risk assessment, acrolein had the highest HI values (3.21), significantly exceeded the EPA's safe threshold of 1.0. Besides, formaldehyde's HI was 1.7, which also indicated the possible non-carcinogenic risk. As for carcinogenic risk, the calculated LCR values exceeded the acceptable level of 1×10^{-6} and yielded potential carcinogenic risks, in which formaldehyde showed the highest LCR, ranging from 3.0×10^{-5} to 8.0×10^{-5}. As a result, staff from small and medium-sized restaurants could be more easily affected by both non-carcinogenic and carcinogenic risk.

Author contributions

Xiaohui Hua: writing—review & editing, data curation. Jian Zhang: investigation. Xinyu Zhang: writing—original draft. Houjian Yang: investigation. Meng Wang: data curation. Zhiyun Luo: conceptualization, methodology, writing—review & editing. Hailin Wang: supervision.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data supporting the findings of this study are available in the Supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5va00320b.

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