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High-resolution emission inventory of full-volatility organic compounds from cooking in China during 2015–2021

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Text S1. The classification method of restaurant cuisine

We extracted the location, name, and label information of each restaurant nationwide from the POI data on the digital map. The label information consists of 9 major categories and 55 subcategories, as described by Lin et al. (2022). Many of these labels can be used to classify each restaurant into one of the 10 types (the nine cuisines mentioned in Section 2.2.1 and catering services without fume emissions) considered in this study, as described in column 3 of Table S1. However, more than 60% of the restaurants are simply labeled as Chinese food restaurants, which is not conducive to mapping them to the corresponding EFs. Therefore, we re-categorize the unclassified restaurants based on their names. Specifically, we first conduct a frequency analysis of the names of the restaurants which have been classified into a specific cuisine and obtain the keywords that most frequently appear in the names of restaurants of this cuisine. Then, we screen out those keywords unique to this cuisine, i.e., exclude keywords relevant to multiple cuisines. At the same time, we added some specific keywords based on our experience. This process is implemented in R-4.0.3, using the 'jiebaR' package related to Chinese frequency analysis. All keywords are listed in column 4 of Table S1, with English explanations for these Chinese keywords. After that, in the order of the distinctiveness of the cuisine features, we sequentially screen out restaurants with keywords specific to a certain cuisine (as the order in column 5 of Table S1), and they are assigned to this cuisine category. This sequential classification can avoid the rare situation where a restaurant is classified into two cuisines because its name has the keywords of two cuisines simultaneously. The remaining unclassified cuisines are classified as home-style cuisine. Moreover, some restaurants in certain regions have distinctive regional characteristics, such as those located in the provinces of China's eight major cuisines (Shandong, Hunan, Sichuan, Guangdong, Fujian, Jiangsu, Zhejiang, Anhui) and Xinjiang. Therefore, we also classified all homestyle restaurants in these areas as local specialty cuisines. Finally, we removed restaurants with the term "canteen" in their names.

Text S2. Unit conversion of residential and canteen EFs

The gaseous and particulate full-volatility emissions of four typical home-cooked dishes were measured in the laboratory (Song et al., 2022; Yu et al., 2022). The test results of full-volatility EFs are reported in the form of emission rates (EF_r, μg/min). We use the amount of cooking oil used and cooking time recorded in the test studies (Song et al., 2022; Yu et al., 2022) to convert EF_r to the form based on cooking oil consumption (EF_{oil}, g/kg oil):

$$EF_{oil} = EF_r T / V_{oil} / \rho_{oil} \tag{S1}$$

where T is the operation time, the sampling time in the test studies was said to be 15-30 minutes, so we take the median value of 22.5 minutes (Song et al., 2022; Yu et al., 2022). V_{oil} is the amount of cooking oil used, and the values of the four dishes were recorded in the test studies (Song et al., 2022; Yu et al., 2022). ρ_{oil} is the density of the cooking oil, taken as 0.92 g/ml. The average EF_{oil} of the four dishes is used as the EF for residential cooking.

The full-volatility EF for the canteens is determined by Huang (2023) and the literature review (Qian et al., 2022; Wang et al., 2018a). The test results of full-volatility EFs are reported in the form of concentration (EF_c, μg/m^3). We use a few parameters recorded in a previous study (Qian et al., 2022) to convert it to a form based on meals (EF_{meal}, g/meal):

$$EF_{meal} = EF_c Q / f \tag{S2}$$

where Q is the fume gas discharge rate of the canteen, taken as 7178 m^3/h (Qian et al., 2022). f is the number of diners in the canteen per unit of time, taken as 200 persons/h (Qian et al., 2022). These two parameters may exhibit uncertainties, but given the lack of other statistical data currently available, we are obliged to adopt them as the next best option.

Text S3. Collating key policy milestones and implementation transition periods of catering pollution control policies to determine the level of control stringency

We obtained air pollution prevention and control policy documents and local standards for air pollution from the official websites of provincial governments or their departments of ecological and environmental protection. In response to China's Action Plan for the Prevention and Control of Air Pollutants (CPGPRC, 2013) and the Three-Year Action Plan to Win the Battle against the Blue Sky (CPGPRC, 2018), each province successively issued its provincial ordinances, action plans, or implementation plans for air pollution prevention. These documents are regularly revised and serve as instructive guidelines for air quality management within their respective provinces. They set control requirements for key pollutant emission sectors, including the catering industry. The stringency of cooking emission controls specified in provincial policies has varied over different periods. Specific regulations include encouraging certain restaurants (e.g., large-scale restaurants or barbecue establishments) to install fume purifiers, strengthening pollution control in the catering industry, and comprehensive management of restaurant fume emissions. Due to China's Emission Standards for Catering Fumes (MEE, 2001) and China's Action Plan for the Prevention and Control of Air Pollutants (CPGPRC, 2013), all provinces already had some control measures for certain areas or certain restaurants. Thus, the control stringency in each province had reached level C in Table 1 before 2015. Then, we check each version of the policy document for each province to identify the year in which comprehensive control of restaurant emissions was incorporated into policies, thus determining the year each province achieved level B stringency. Additionally, a few provinces, such as Hainan and Shanghai, have issued local standards for restaurant pollutant emissions. Their local standards or policies specify the target year for all restaurants to install purification facilities, enabling us to ascertain the year these provinces reached level A stringency. Transition periods between levels can also be found within these policy documents or standards, or inferred based on assumptions in Table 1.

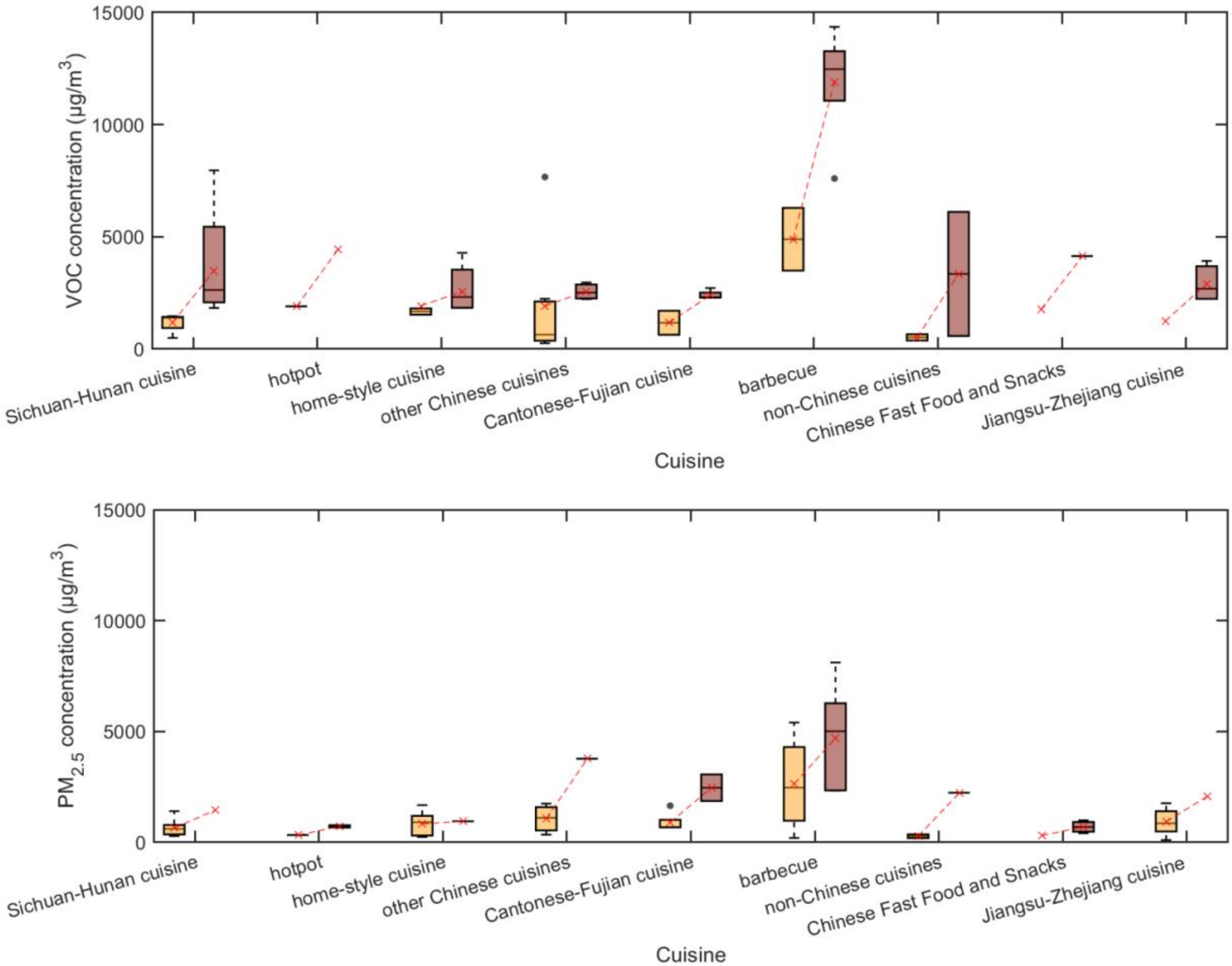

Figure S1: Comparison of uncontrolled and controlled EFs of VOCs and $PM_{2.5}$ in the literature of different cuisines to get the removal efficiencies. Boxes represent the 50th and 25−75th percentiles, and whiskers represent the minimum and maximum values that are not outliers. The red crosses indicate the mean value of each data group. The slope of the red dashed line represents the purification effect for each cuisine after pollution control measures have been implemented. If a certain cuisine lacks controlled EFs, its vacant controlled EFs are estimated based on its uncontrolled EFs and the average removal efficiency of other cuisines. Similarly, if a certain cuisine lacks uncontrolled factors, its vacant uncontrolled factors are calculated based on its controlled factors and the average purification efficiency of other cuisines.

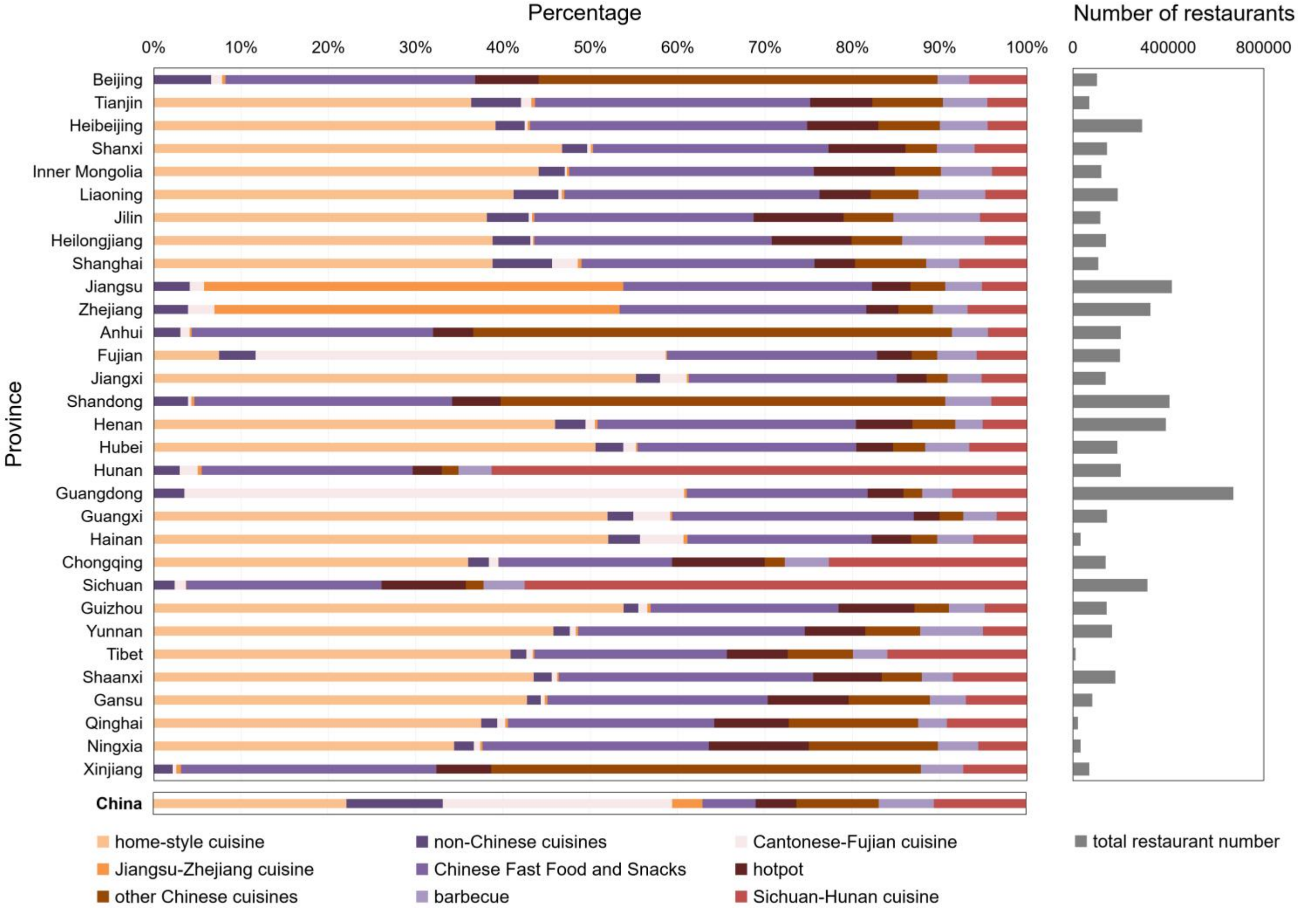

Figure. S2: Average number of commercial restaurants in each province, and provincial and national cuisine distribution from 2015-2021.

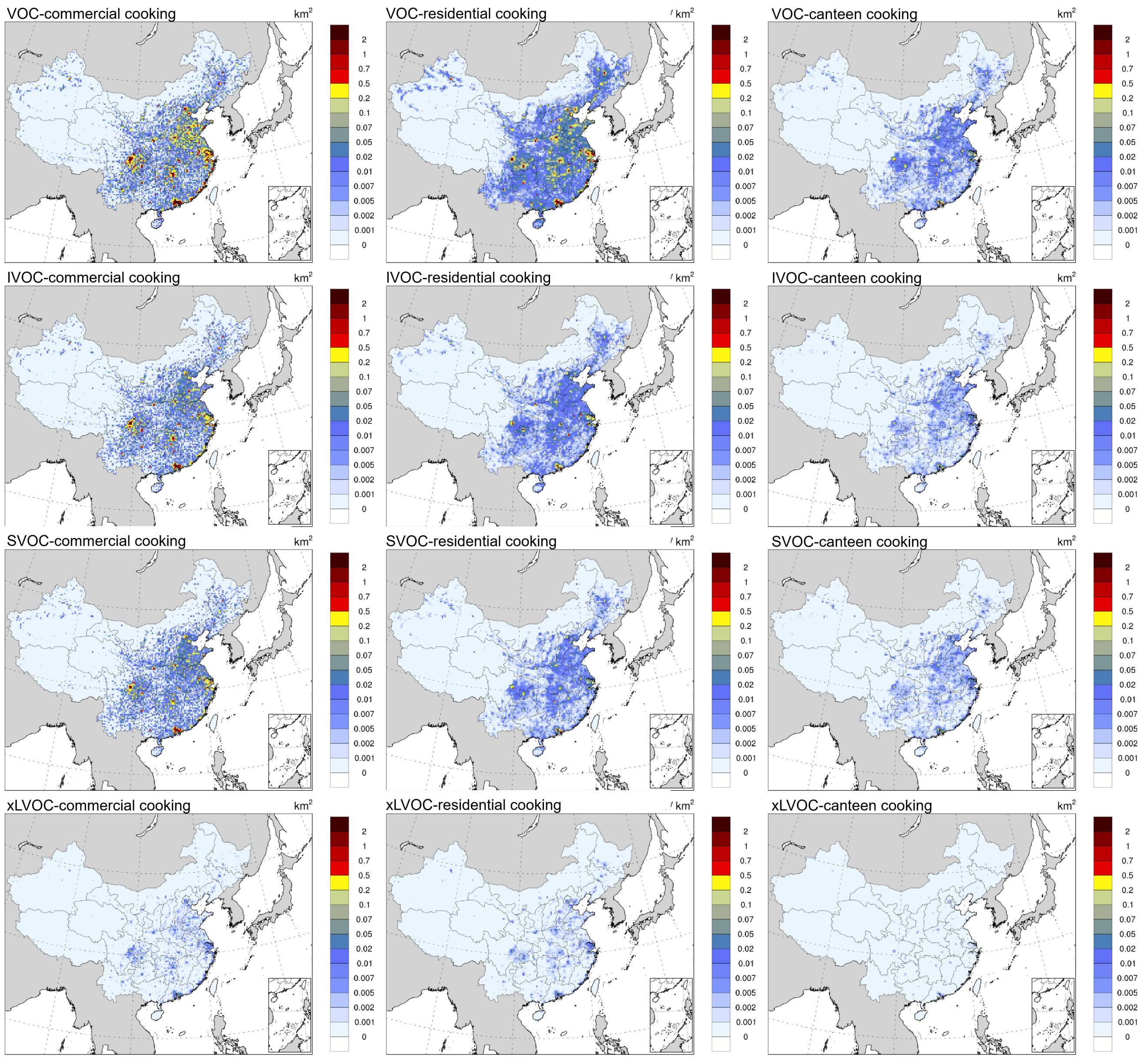

Figure S3: National gridded cooking subsector emissions in the four volatility ranges in 2021. From left to right, the sub-sectors are commercial cooking, residential cooking, and canteen cooking.

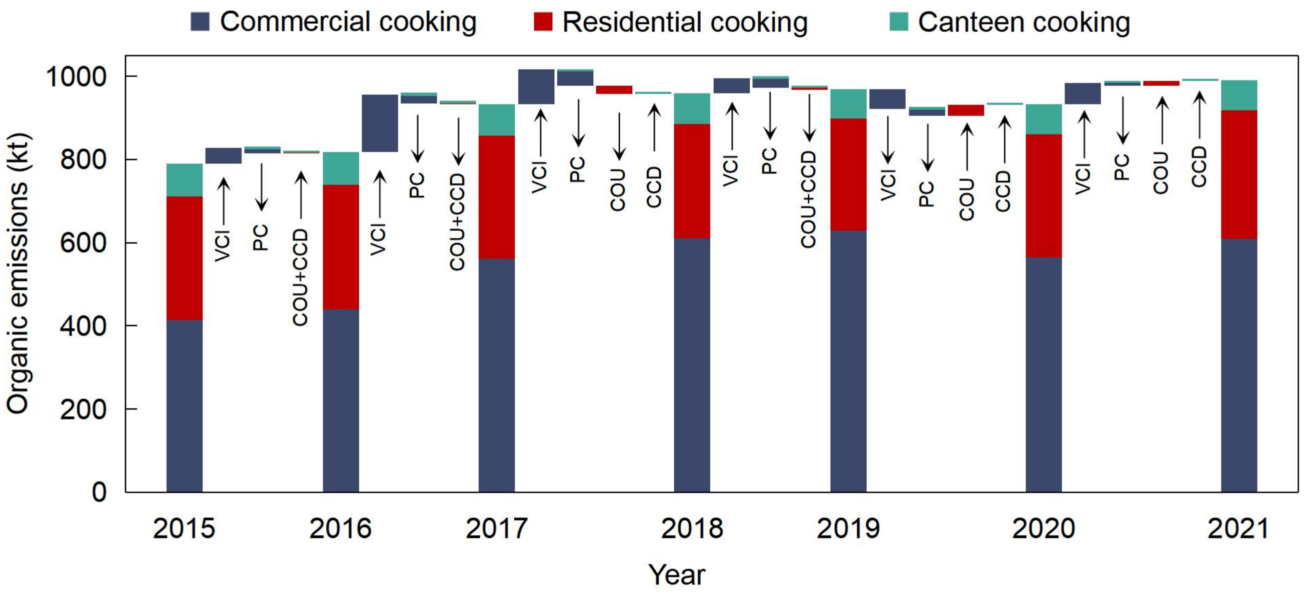

Figure S4: Cooking emissions from various sources in 2015-2021 and the yearly contributions of different influencing factors. The factors include variations of the catering industry (VCI), pollution control (PC), changes in edible oil usage (COU), and changes in canteen diners (CCD). The factors contributing less than 1 % are summed up together.

Table S1: Cuisine description and classification information

cuisine	characteristics of cuisine	labels in POI data that can be used to classify cuisines	high-frequency keywords used to identify dishes for uncategorized restaurants[a]	order[b]
Catering services without oil fume emissions	Beverages, dessert	Coffee House, Tea House, Icecream Shop, Bakery, Dessert House	奶茶/咖啡/冷饮/冰淇淋/饮品/星巴克/酸奶/水吧 (beverages), 味多美/蛋糕/烘焙/甜品/糕点/面包/西饼/稻香村/好利来 (dessert), 茶楼/茶馆/茶艺/茶坊/凉茶/茶庄/茶园 (tea-related venues), 水果 (fruits)	1
barbecue	grilled meats and vegetables, smoky flavor, high cooking oil and spice use	-	铁板烧/串烧 (various barbecue), 烤 (a verb for barbecue), 炭火/果木 (common barbecue fuels)	2
hotpot	communal dining, customizable, simmering broth, fresh ingredients	Hotpot Restaurant, Xiabu xiabu	火锅/串串香/铜锅/麻辣烫 (various hotpots), 涮 (a verb for cooking hotpot), 海底捞 (famous cuisine brand)	3
Sichuan-Hunan cuisine	spicy, use of chili and peper, oil-rich	Sichuan Food, Hunan Food	川/蜀/重庆/渝/湘/湖南/长沙/浏阳/湘西/成都 (related location name), 麻辣/香辣 (spicy), 小面/鸡公煲/酸菜鱼/酸辣粉(specialty foods)	4
Cantonese-Fujian cuisine	mild and fresh flavors, light sauces, seafood-rich	Cantonese Food, Fujin Food, Chaozhou Food, Teahouse	粤/广东/潮汕/闽/沙县/潮州/客家/莆田 (related location name), 砂锅粥/烧腊/肠粉/烧鹅/早茶 (specialty foods), 潮味/港式 (cuisine adjectives), 原味汤粉王(famous cuisine brand)	5
Jiangsu-Zhejiang cuisine	delicate, slightly sweet, use of vinegars and wines	Jiangsu Food, Zhejiang Food, Shanghai Food	杭州/无锡/淮扬/浙 (related location name), 绿茶餐厅 (famous cuisine brand)	6
non-Chinese cuisines[c]	global flavors, diverse styles, varying complexity	Foreign Food Restaurant, KFC, McDonald's, Pizza Hut	寿司/披萨/料理/炸鸡/比萨/牛排/汉堡/沙拉 (Foreign specialties such as pizza, sushi, burgers, salads), 外国/日式/韩式/西餐/国际/意式 (Foreign-related adjectives)	7
Chinese fast food and snacks	quick, convenient, street food, regional varieties	Fast Food Restaurant, Yon ho, Cafe de Coral, Fairwood, Maxim's, Yoshinoya, Saint's Alp Teahouse	饺/馄饨/抄手 (dumpling), 面粉/拉面/面馆/凉皮/粉馆/米线/米粉/刀削面 (various noodles), 包子/肉夹馍/煎饼/烧饼/馒头/肉饼/大饼 (Chinese snack similar to buns and pancakes), 熟食/粥/炒饭/豆浆 (other snacks), 快餐/小吃/早餐/早点 (related terms)	8
other Chinese cuisines	localized flavors, regional specialties	Shandong Food, Anhui Food, Beijing Food, Hubei Food, Northeastern Chinese Food, Yunnan & Guizhou Food, Northwestern Chinese Food, Islamic Food, Taiwan Food	山东/北京/鲁/济南/胶东/徽/淮南/皖北/新疆/上海/沪/湖北/鄂/东北/云贵/云南/贵州/滇/台湾 (related location name). 烤鸭/葱烧/酱爆/扒鸡/锅塌/夹饼/板面 (specialty foods), 清真/回族/回民/京味/西北菜 (cuisine adjectives)	9
home-style cuisine	broadly appealing, diverse flavors, traditional Chinese cooking style	-	the remaining unclassified restaurants	10

[a] As the majority of restaurant names in the POI (point of interest) data are in Chinese, Chinese keywords are used for search classification, with explanatory notes provided for each Chinese word.

[b] The high-ranked cuisines have more distinctive characteristics, thus providing a more substantial basis for classification; therefore, their classification should be determined as a priority.

[c] Non-Chinese cuisines refer to cuisines from countries outside of China. While there are many types, their total quantity is small, so they are classified as one category.

Table S2: Calculation parameters for activity data of commercial cooking

type of cuisine	cuisines other than Chinese fast food and snack			Chinese fast food and snack	reference
scale	large	middle	small	small	
the proportion of restaurants of different scales	12.0%	28.4%	59.6%	100%	(Lin et al., 2022; Wang et al., 2018a; Yuan et al., 2023)
the average number of stoves in a restaurant	8.40	4.30	2.42	2.21	(Lin et al., 2022; Wang et al., 2018a; Yuan et al., 2023)
oil fumes gas discharge rate of each stove (m^3/h)	2864	2245	1962	1962	(Yuan et al., 2023)
annual total operating time of restaurants (h/y)	2464	2102	1911	1911	(Yuan et al., 2023)

Table S3: Calculation parameters for activity data of canteen cooking

type of diners	the average annual number of days in school or at work (d/y)	the average number of meals per day in the canteen (times/d)	the proportion of people dining in canteens
preschool and kindergarten students	190	1	100%
primary school students	190	1	80%
junior high school students	190	2	70%
high school students	190	2	70%
undergraduate and graduate students	270	3	90%
employees of enterprises and institutions	250	1.5	70%

Table S4: Detailed methods and data source for full-volatility EF estimates from different cooking sources

Cuisine/source	VOC EFs	volatility distribution of gaseou organics	POA EFs[a]	volatility distribution of particle-phase organics
home-style cuisine (HS)	testing of full-volatility emissions of gaseous organics (Huang, 2023)		literature review (Jiang et al., 2021; Huang et al., 2020; Sun et al., 2022)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
Sichuan-Hunan cuisine (SH)	simultaneous testing of full-volatility emissions of both particle- and gaseous-phase organics (Huang, 2023)			
Chinese fast Food and snacks (CFFS)	literature review (Zhang et al., 2016; Lin et al., 2019)	average distribution of HS and canteen (Huang, 2023)	literature review (Zheng, 2018)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
non-Chinese cuisines[c]	testing of full-volatility emissions of gaseous organics (Huang, 2023)		literature review (Wang et al., 2018a; Huang et al., 2020)	average distribution of fried chicken and barbecue (Huang, 2023; Song et al., 2023)
hotpot	simultaneous testing of full-volatility emissions of both particle- and gaseous-phase organics (Huang, 2023)			
barbecue (BBQ)	simultaneous testing of full-volatility emissions of both particle- and gaseous-phase organics (Huang, 2023), and adjusting EFs based on the results of literature review[a]			
Cantonese-Fujian cuisine (CF)	literature review (Zhao et al., 2007; Lin et al., 2019; He et al., 2004; Wang et al., 2018b)	average distribution of HS and canteen (Huang, 2023)	literature review (Wang et al., 2018a; Huang et al., 2020)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
Jiangsu-Zhejiang cuisine (JZ)	literature review (Wang et al., 2018b; Lin et al., 2019; Pei et al., 2016)	average distribution of HS and Beijing cuisine (Huang, 2023)	literature review (Zhang et al., 2023; Tong, 2019; He et al., 2020; Cui et al., 2015; Zheng, 2018)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
other Chinese cuisines	literature review (Wang et al., 2015; Lin et al., 2019; Zhao et al., 2007)	average distribution of HS and Beijing cuisine (Huang, 2023)	literature review (Sun et al., 2022; Cheng et al., 2016; Huang et al., 2020; Wang et al., 2018a)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
residential cooking	testing of full-volatility emissions of gaseous organics (Song et al., 2022) and unit conversion		POA testing (Yu et al., 2022)	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)
canteen cooking	testing of full-volatility emissions of gaseous organics (Huang, 2023), adjusting EFs[d] (Liang et al., 2022; Huang, 2023; Wang et al., 2018a) and unit conversion		literature review (Zhao et al., 2020) and unit conversion	average distribution of SC, HP, BBQ and Xingjiang cuisine (Huang, 2023)

Note: We determine full-volatility EFs for different cooking sources based on available testing data: (1) For cuisines with simultaneous testing of full-volatility emissions of both particle- and gaseous-phase organics, we prioritize using the tested full-volatility EFs unless their EFs are considered not representative for the cuisine. In such cases, we correct the EFs using literature review results. (2) For cuisines lacking gaseous full-volatility testing, we adopt the average VOC EF of the corresponding cuisines from the previous study and estimate the EFs for other gaseous organics proportionally based on the volatility distribution of similar cuisines with full-volatility EF data. (3) For cuisines lacking particle full-volatility testing, we use the average POA EF of the corresponding cuisines from previous studies as the overall particulate organic EFs, and distribute the total particulate EF to different volatility bins according to the volatility distribution of similar cuisines with full-volatility EF data.

All data sources for the literature review are labeled in the table above, and the specific data are in Table S5. Note that the EFs in Table S4 are all measured after pollution control. The uncontrolled EFs are inferred by the removal efficiencies of different sources listed in Table S5-6.

[a] Previous study rarely reports POA EFs directly, so we use POA = 81.5% $PM_{2.5}$ to calculate POA EFs, as discussed in the main text.

[b] The sampled and tested barbecue restaurant uses ovens to grill the food, which is considered not representative of the common barbecue methods in China, which mainly use charcoal or iron plate to grill the food. Therefore, the tested VOC and POA concentrations are much lower than those in other studies. We use the VOC and POA EFs from literature reviews to correct the gaseous and particulate EFs for barbecue, while the volatility distribution still uses the full-volatility test results from Huang (2023).

[c] The original test EFs are usually in the form of concentration or emission rate. For convenience in calculating emissions, the EFs for residential and canteen cooking are transformed into the corresponding forms, as described above in the SI.

[d] The gaseous organic emission test results in a canteen from Huang (2023) differ greatly from the other studies (Qian et al., 2022; Wang et al., 2018a), probably due to differences between canteens. Therefore, to reduce the uncertainty, we take the average of Huang (2023)'s results and other literature (Qian et al., 2022; Wang et al., 2018a) results as the EF for gaseous organics.

Table S5: Summary of uncontrolled and controlled EFs of VOCs and $PM_{2.5}$ in the literature

type of source		uncontrolled $PM_{2.5}$	controlled $PM_{2.5}$	uncontrolled VOCs	controlled VOCs
Commercial cooking (μg/m³)	home-style cuisine	948 (Lin et al., 2019)	328 (Wang, 2013), 241 (Wang, 2013), 1032 (Li et al., 2021), 1678 (Li et al., 2021), 905 (Lin et al., 2014)	2783 (Tong, 2019), 1843 (He et al., 2020), 4283 (Cui et al., 2015), 1828 (Zhang et al., 2023)	1404 (Huang et al., 2020), 1806 (Sun et al., 2022), 1529 (Jiang et al., 2021)
	Sichuan-Hunan cuisine	1457[a]	364 (Pei et al., 2016), 1406 (He et al., 2004), 733 (Wang et al., 2018b), 582 (Wang, 2013), 352 (Wang, 2013), 639 (Zhao et al., 2007), 832 (Zhao et al., 2007), 283 (Wang et al., 2015)	2077 (Tong, 2019), 2582 (Tong, 2019), 1828 (He et al., 2020), 5446 (Cui et al., 2015), 7960 (Zheng, 2018), 2680 (Zhang et al., 2023)	494 (Cheng et al., 2016), 1462 (Wang et al., 2018a), 1373 (Sun et al., 2022)
	Chinese fast Food and snacks	692 (Lin et al., 2019), 410 (Zhang et al., 2016)	311[a]	4140 (Zheng, 2018)	1773[a]
	non-Chinese cuisines[c]	2238 (Li et al., 2020)	358 (Pei et al., 2016), 189 (Wang et al., 2018b)	578 (Cui et al., 2015), 6110 (Zheng, 2018)	656 (Huang et al., 2020), 377 (Wang et al., 2018a)
	hotpot	772 (Lin et al., 2019), 666 (Zhang et al., 2016)	330 (Li et al., 2021)	4438[a]	1900 (Huang et al., 2020)
	barbecue	8112 (Lin et al., 2019), 2332 (Lin et al., 2019), 5010 (Lin et al., 2019), 5660 (Zhang et al., 2016), 2455 (Li et al., 2020)	5403 (Lin et al., 2019), 3189 (Lin et al., 2019), 198 (Wang, 2013), 1751 (Wang et al., 2015)	12471 (He et al., 2020), 12220 (Cui et al., 2015), 7600 (Xu et al., 2017), 12910 (Zheng, 2018), 14355 (Zhang et al., 2023)	3494 (Cheng et al., 2016), 6287 (Sun et al., 2022)
	Cantonese-Fujian cuisine	3063 (Lin et al., 2019), 1862 (Li et al., 2020)	1651 (Lin et al., 2019),672 (He et al., 2004), 803 (Wang et al., 2018b), 687 (Wang et al., 2018b), 678 (Zhao et al., 2007)	2714 (Tong, 2019), 2311 (Tong, 2019), 2297 (He et al., 2020), 2283 (Zhang et al., 2023)	633 (Huang et al., 2020), 1702 (Wang et al., 2018a)
	Jiangsu-Zhejiang cuisine	2079[a]	860 (Lin et al., 2019), 623 (Pei et al., 2016), 1764 (Wang et al., 2018b), 101 (Wang et al., 2018b), 1284 (Wang et al., 2018b)	2288 (Tong, 2019), 2231 (Tong, 2019), 2233 (He et al., 2020), 3925 (Cui et al., 2015), 3690 (Zheng, 2018), 3079 (Zhang et al., 2023)	1245[a]
	other Chinese cuisines	3772 (Lin et al., 2019), 992 (Shu et al., 2014)	1749 (Lin et al., 2019), 1105 (Zhao et al., 2007), 346 (Wang et al., 2015)	2260 (Tong, 2019), 2510 (Tong, 2019), 2845 (Tong, 2019), 2966 (He et al., 2020), 2223 (Zhang et al., 2023)	258 (Cheng et al., 2016), 639 (Huang et al., 2020), 612 (Huang et al., 2020), 7666 (Wang et al., 2018a), 1745, 2238, 288 (Sun et al., 2022)
Canteen Cooking (g/meal)		0.61 (Zhao et al., 2020)	0.27[a]	0.656[a]	0.043 (Huang, 2023), 0.01 (Wang et al., 2018a), 0.79 (Liang et al., 2022)

Note: residential cooking already has gaseous full-volatility EFs or POA EFs, so its VOC and POA EFs are not required.

[a] These cuisines lack corresponding EFs, we derive the missing EFs from the removal efficiency of the cuisine in Table S6 and the other related EFs.

Table S6: Removal efficiencies of for particulate and gaseous organics for different cooking source.

type of source		removal efficiencies of particulate organics	removal efficiencies of gaseous organics
commercial Cooking	home-style cuisine	11.7%	25.0%
	Sichuan-Hunan cuisine	55.4%[a]	66.1%
	Chinese fast Food and snacks	55.4%[a]	57.2%[b]
	non-Chinese cuisines[c]	87.8%	84.6%
	hotpot	54.1%	57.2%[b]
	barbecue	43.8%	58.9%
	Cantonese-Fujian cuisine	63.5%	51.4%
	Jiangsu-Zhejiang cuisine	55.4%[a]	57.2%[b]
	other Chinese cuisines	71.7%	25.0%
residential Cooking		-	-
canteen Cooking		55.4%[a]	57.2%[b]

Note: The removal efficiency of each cuisine is obtained from the reduction ratio of the average controlled EF relative to the average uncontrolled EFs in Table S5, since the measured removal efficiency data for each cuisine is lacking. We assume that the removal efficiency for gaseous and particle-phase organics is equivalent to that for $PM_{2.5}$ and VOCs, respectively.

[a] These cuisines do not have $PM_{2.5}$ EFs for both pre- and post-pollution control conditions. Therefore, their particulate removal efficiency is taken as the average of other cuisines, which is 55.4%.

[b] These cuisines do not have VOC EFs for both pre- and post-pollution control conditions. Therefore, their particulate removal efficiency is taken as the average of other cuisines, which is 57.2%.

Table S7: The pollutant removal efficiency of the purification equipment in the local standards of Beijing (Beijing Environmental Protection Bureau, 2018)

pollutants	the pollutant removal efficiency of the purification facility for restaurants of different scale			the removal efficiency weighted by scale proportion
	large	middle	small	
non-methane hydrocarbon	≥85%	≥75%	≥65%	≥68.7%
particulate matter	≥95%	≥85%	≥80%	≥82.3%

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