Supplement of Atmos. Chem. Phys., 23, 6633–6646, 2023
https://doi.org/10.5194/acp-23-6633-2023-supplement

Atmospheric Chemistry and Physics Open Access

Supplement of

Measurement report: Underestimated reactive organic gases from residential combustion – insights from a near-complete speciation

Yaqin Gao et al.

Correspondence to: Hongli Wang (wanghl@saes.sh.cn) and Cheng Huang (huangc@saes.sh.cn)

The representativeness of the cited EF of benzene from the literature

The EFs in this study were derived from the reported EF of benzene and the emission ratios (ER) of other species to benzene obtained in this study. Thus, to discuss the representative of EFs used for the estimation of emissions, the representativeness of the cited EF of benzene from the literature should be considered firstly as below.

The major studies of the EF of benzene from residential combustion were reviewed and listed in Table S4. It can be seen the EF of benzene from each type of coal combustion generally reached a reasonable level of agreement and values of anthracite / briquette coal combustion ranged from 2 to 14 mg/kg (Cai et al., 2019; Tsai et al., 2003), which were 1-2 magnitude lower than those of bituminous coal combustion (Liu et al., 2017; Liu et al., 2015; Cai et al., 2019; Tsai et al., 2003; Wang et al., 2013). Considering the coal samples tested in this study were anthracite and briquette coal, the present study cited the latest results of anthracite coal combustion from Cai et al. (2019) study, in which the anthracite coal samples were from the two major coal production regions, i.e. Ningxia and Guizhou, and these coal types were widely used in China (Cai et al., 2019; Li et al., 2016b).

In terms of straw combustion, the EF of benzene in 12 samples from 6 literatures in total were summarized in Table S4 (Stockwell et al., 2015; Wu et al., 2022; Hatch et al., 2017; Inomata et al., 2015; Koss et al., 2018; Tsai et al., 2003) and ranged from 73 mg/kg to 800 mg/kg, which had large variations among different studies probably due to the various types of straws and combustion conditions. Among them, 7 out of 12 samples were from China straw, and their EF of benzene generally reached a reasonable level of agreement expect those of wet straw combustion. The present study used the median value of the reported EF of benzene from straw combustion in China, being of 284 mg/kg, which was derived from the simulated real-world combustion in the FLAM-4 laboratory campaign (Stockwell et al., 2015).

Figure S1. Sampling diagram relates to six solid fuels types, household stoves, sampling port and equipment. The letter n refers to the number of different samples.

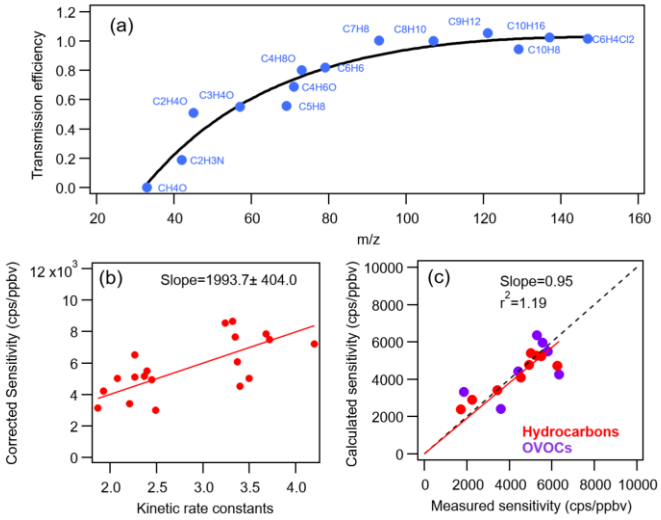

Figure S2. (a) The transmission efficiency of the H_3O^+ PTR-ToF-MS, (b) the relationship between corrected sensitivity and the kinetic rate constants and (c) comparison of calculated and measured calibration factors for standard gases by H_3O^+ PTR-ToF-MS. The black dash line means 1:1. The corrected sensitivity of a given ROG was derived from the measured sensitivity in panel (c) through the correction of its transmission efficiency in panel (a) and fragment proportion obtained from calibration.

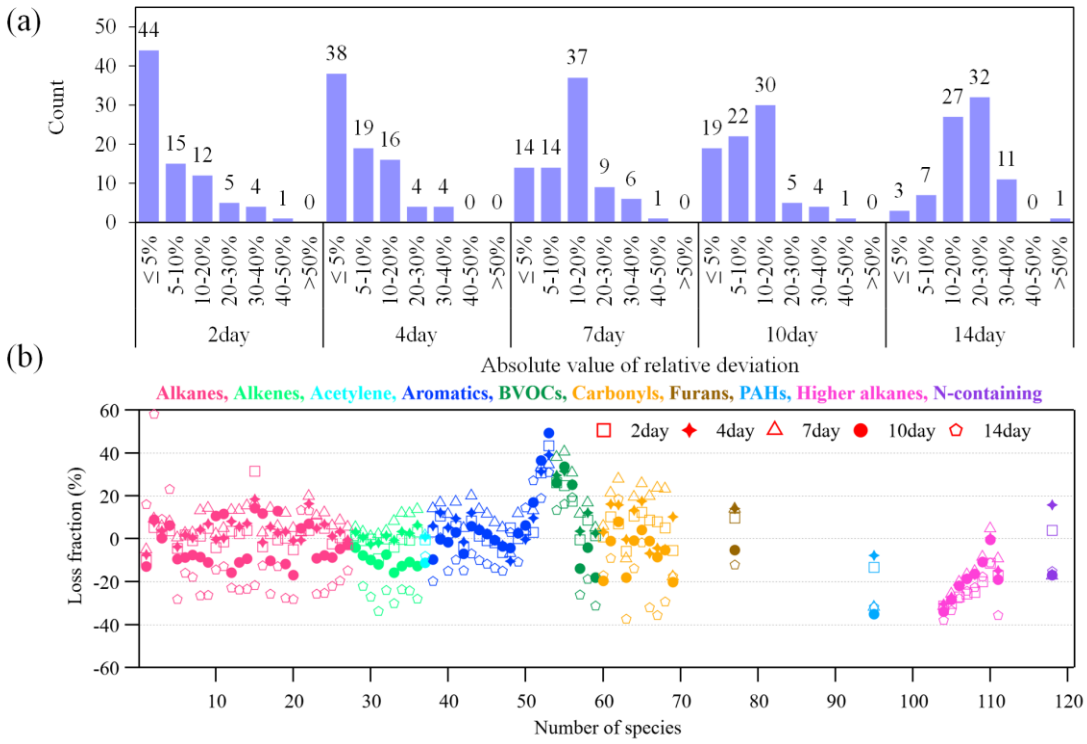

Figure S3. Statistical evaluation on the loss fraction of ROGs in the canisters. (a) Species counts in different loss fraction bins on 2, 4, 7, 10, 14 days (x-axis) of storage in the canisters. (b) The loss fraction of each compound standards on 2, 4, 7, 10, 14 days of storage in the canisters. The measured species corresponding to the numbers of horizontal axis are listed in Table S1.

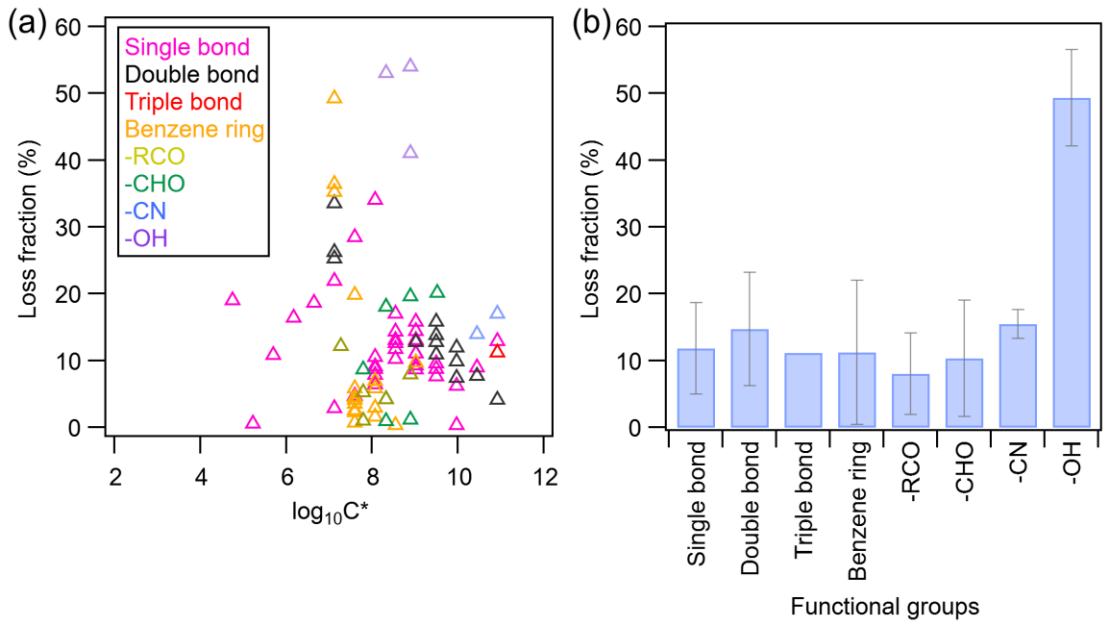

Figure S4. Plots of the loss fraction versus volatility (the logarithmic effective saturation vapor concentration, $\log_{10}C^*$) and polarity (functional groups) of species respectively. (a) The scatter plot of the loss fractions of individual species and $\log_{10}C^*$, colored by functional groups (see legend). (b) The average and standard deviation of loss fraction for species with the same functional groups.

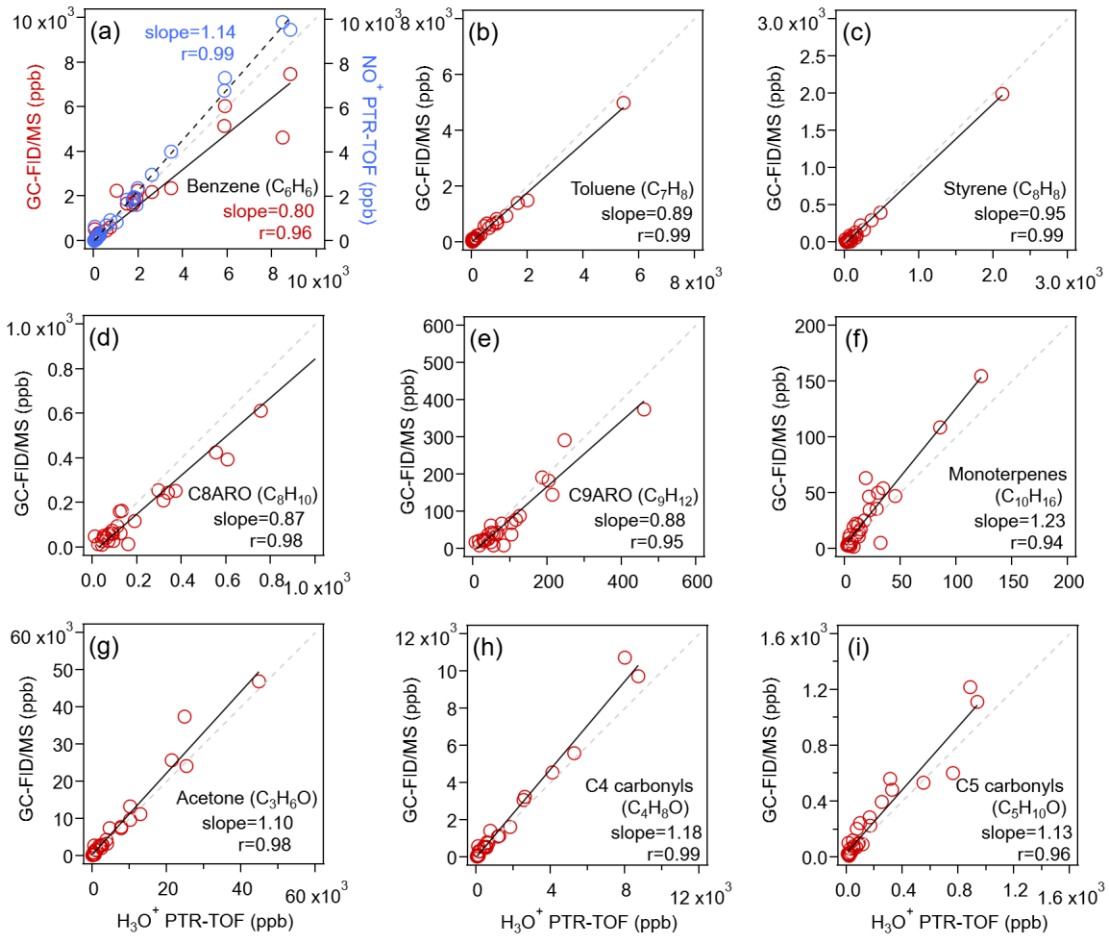

Figure S5. Intercomparisons between species measurement of samples by GC-FID/MS and by H_3O^+/NO^+ Vocus PTR-ToF-MS. C8ARO and C9ARO refer to aromatics containing 8 carbon and 9 carbon atoms, respectively.

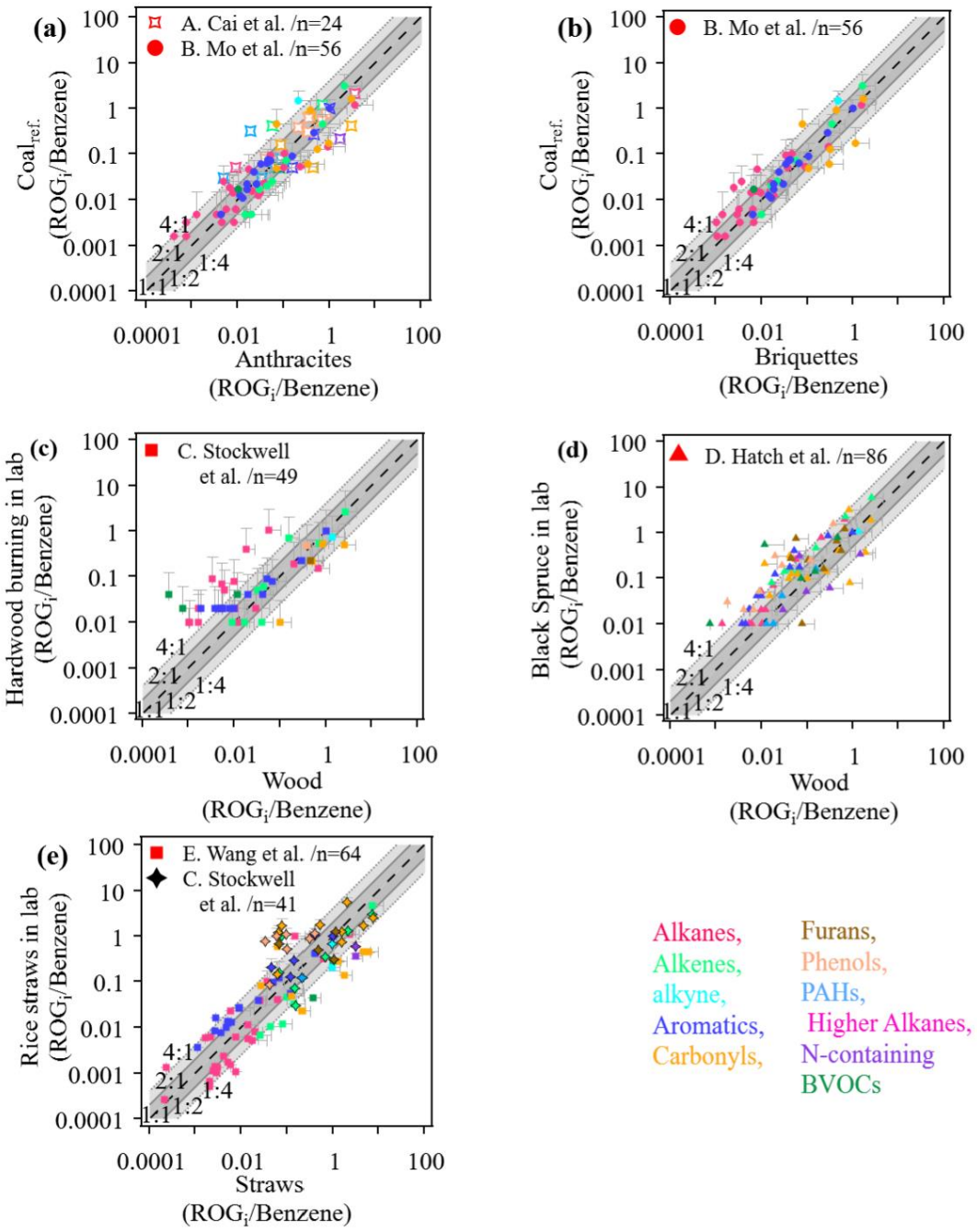

Figure S6. Comparison of emission ratios between this study and the previous studies (Hatch et al., 2017; Mo et al., 2016; Stockwell et al., 2015; Wang et al., 2014; Cai et al., 2019; Stockwell et al., 2016). The black dashed lines indicate the 1:1 relationship, and the gray and light gray areas show agreements within a factor of 2 and 4, respectively. n is the number of compared species with the corresponding reference.

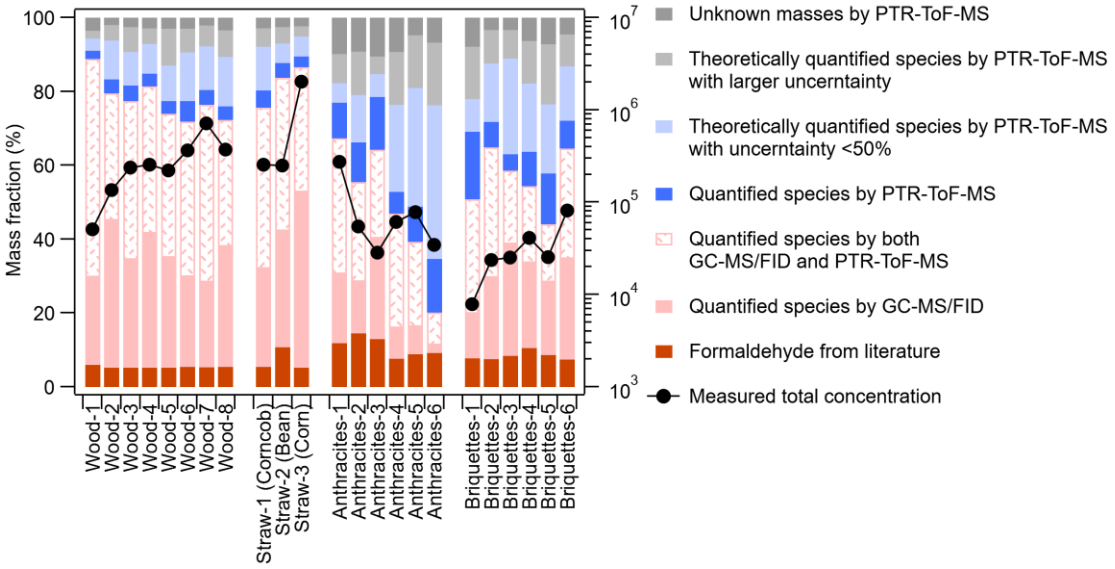

Figure S7. Profile composition of species for different samples measured by GC-MS/FID and Vocus PTR-ToF-MS and the measured total ROG concentration of each sample (black line).

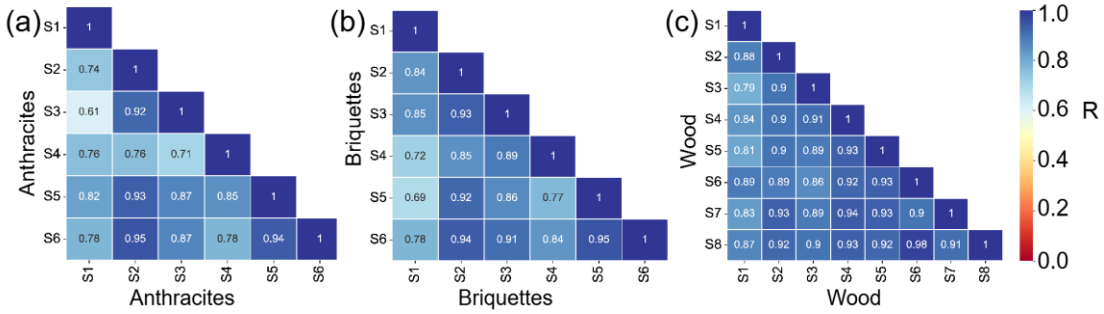

Figure S8. Correlation between ROG source profiles of different samples of the same fuel. The number represents the Spearman correlation coefficient (R).

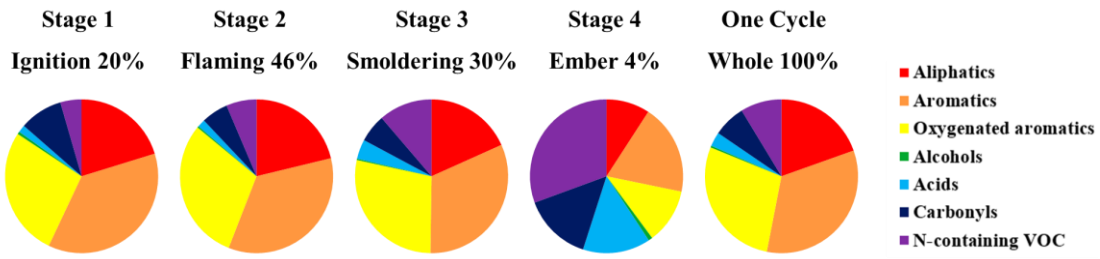

Figure S9. Average ROG compositions for residential coal combustion at each stage and the whole cycle adapted from Cai et al. (2019) (The figure was redrawn using the data from the authors).

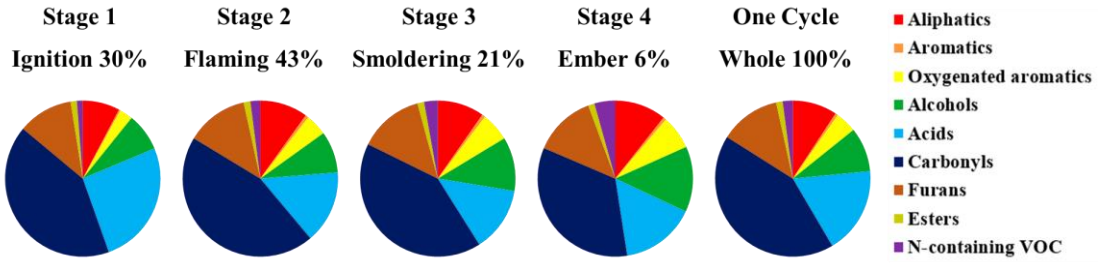

Figure S10. Average ROG compositions for straw combustion experiments at each stage and the whole cycle redrawn using data from Koss et al. (2018) (available data from the CSD NOAA archive at https://esrl.noaa.gov/csd/groups/csd7/measurements/2016firex/FireLab/DataDownload/ (NOAA, 2018)).

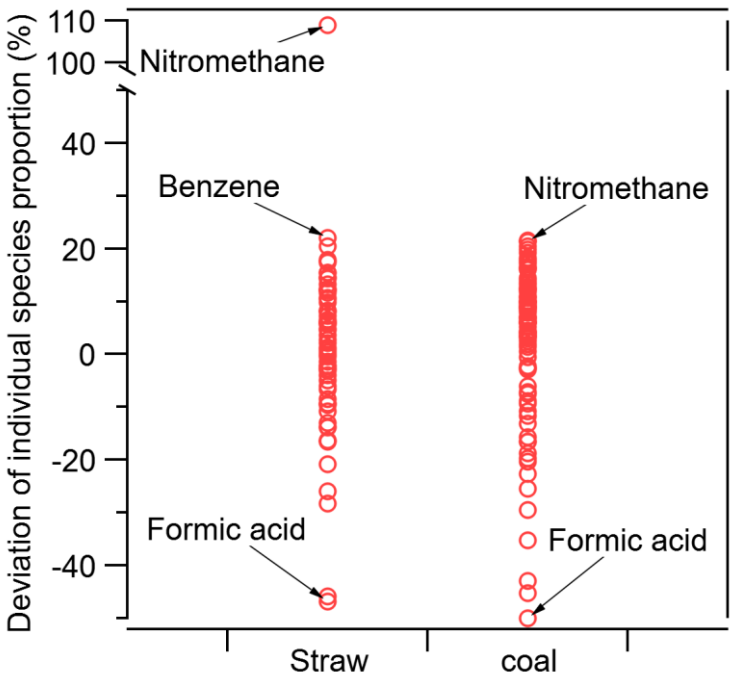

Figure S11. The deviation of the proportion of individual species between the flaming stage and the whole cycle. Only the points with the upper and lower limits of deviation and outlies are marked by the species name.

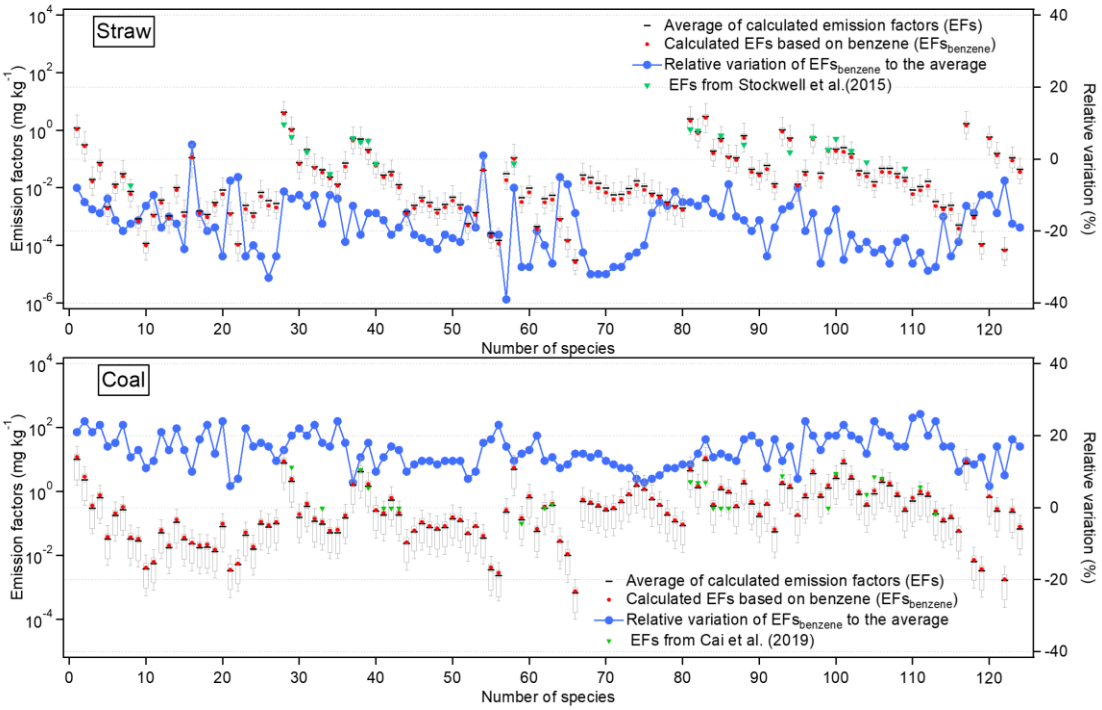

Figure S12. Box plot of estimated emission factors (EFs) of newly identified ROGs based on reported EF of ROGs and the relative variation (blue line) of EFs based on benzene to the average of all tests. The red dot is the calculated EFs based on benzene. The box range is the calculated EFs based on other reported species. The green dot is the EFs from references (Cai et al., 2019; Stockwell et al., 2015) used in calculation.

Table S1. Review on the measurements of ROG emissions from the residential combustion.

Method	Fuel types	Reference	Numbers of species		
			GC-MS/ FID	PTR-ToF-MS	Other instruments
Combustion in stove	Residential coals, biomass (straw and wood) from China	This study	71	84 (84-92% of the overall peak mass)	—
	Corncob from China	(Wu et al., 2022)	—	13	—
	Anthracite, bituminous coal from China	(Cai et al., 2019)	—	79-89 (90-96% of the overall peak intensities)	—
	Beech (Fagus sylvatica) logs	(Bruns et al., 2017)	—	64 (94-97% of the total NMOG mass)	—
	Biomass (peanut shell, maize straw), raw coals from China	(Wang et al., 2013)	60	—	24 (DNPH-HPLC)
Combustion simulation in Lab	Biomass fuels from the western US	(Akherati et al., 2020)	—	150	—
	Burned fuels from the western US	(Koss et al., 2018)	—	172 (~95% of the overall peak intensities)	15 (FTIR), 261(GC-CIMS)
	Four burns: ponderosa pine boughs, Chinese rice straw, Indonesian peat, and black spruce boughs	(Hatch et al., 2017)	~27	~71	~13 (FTIR) ~418 (GC×GC)
	Authentic globally significant fuels	(Stockwell et al., 2015)	—	46-92	—
	Biomass burns of 18 fuel types from 3 geographic regions in the US	(Gilman et al., 2015)	187	Unpublished	Unpublished (OP-FTIR)
	Residential coal, rice, maize, and wheat straw from China	(Mo et al., 2016)	62	—	13 (DNPH-HPLC)
	biomass, residential coal from China	(Liu et al., 2008)	92	—	—

Note:

[a], DNPH-HPLC: 2, 4-Dinitrophenyl hydrazine followed by high performance liquid chromatography (HPLC).

[b], FTIR: Fourier transform infrared spectroscopy.

[c], GC-CIMS: Gas chromatography chemical ionization mass spectrometry.

Table S2. Measurement method, loss fraction in canisters, measurement uncertainty and the total uncertainty for individual species in this study.

Number	Formula	Name (recommended species for Vocus PTR-ToF-MS)	GC-MS /FID[a]	Vocus PTR-ToF-MS[b]	Uncertainty (%)		
					Storage loss on day 10th[d] (avg. ± sd.)	Analysis	Total
Alkanes (27)							
1	C_2H_6	Ethane	Yes	No	-12.9 ± 3.4	4	14
2	C_3H_8	Propane	Yes	No	8.9 ± 13.8	5	10
3	C_4H_{10}	Isobutane	Yes	No	0.3 ± 3.8	4	4
4	C_4H_{10}	n-Butane	Yes	No	6.2 ± 10.3	4	8
5	C_5H_{10}	Cyclopentane	Yes	No	-9.5 ± 7.3	3	10
6	C_5H_{12}	Isopentane	Yes	No	-8.7 ± 6.7	3	9
7	C_5H_{12}	n-Pentane	Yes	No	-7.6 ± 5.4	3	8
8	C_6H_{12}	Methylcyclopentane	Yes	No	-8.6 ± 10.9	6	10
9	C_6H_{12}	Cyclohexane	Yes	No	-11.0 ± 11.3	4	12
10	C_6H_{14}	2,2-Dimethylbutane	Yes	No	-14.4 ± 8.2	3	15
11	C_6H_{14}	2,3-Dimethylbutane	Yes	No	-13.0 ± 9.6	10	16
12	C_6H_{14}	2-Methylpentane	Yes	No	-15.8 ± 8.1	3	16
13	C_6H_{14}	3-Methylpentane	Yes	No	-11.0 ± 10.2	3	11
14	C_6H_{14}	n-Hexane	Yes	No	-9.2 ± 10.2	4	10
15	C_7H_{14}	Methylcyclohexane	Yes	No	14.3 ± 14.8	3	15
16	C_7H_{16}	2,4-Dimethylpentane	Yes	No	-12.6 ± 10.9	7	14
17	C_7H_{16}	2-Methylhexane	Yes	No	-10.2 ± 11.5	7	12
18	C_7H_{16}	2,3-Dimethylpentane	Yes	No	-13.0 ± 11.5	3	13
19	C_7H_{16}	3-Methylhexane	Yes	No	-11.7 ± 11.8	7	14
20	C_7H_{16}	n-Heptane	Yes	No	-17.0 ± 9.6	12	21
21	C_8H_{18}	2,2,4-Trimethylpentane	Yes	No	-10.5 ± 12.0	4	11
22	C_8H_{18}	2,3,4-Trimethylpentane	Yes	No	-6.4 ± 12.1	12	13
23	C_8H_{18}	2-Methylheptane	Yes	No	-9.1 ± 11.9	12	15
24	C_8H_{18}	3-Methylheptane	Yes	No	-7.8 ± 12.2	13	15
25	C_8H_{18}	n-Octane	Yes	No	-8.7 ± 11.3	18	20
26	C_9H_{20}	n-Nonane	Yes	No	-4.7 ± 12.1	15	15
27	$C_{10}H_{22}$	n-Decane	Yes	No	-2.8 ± 12.1	20	20
Alkenes (9)/Alkyne (1)							
28	C_2H_4	Ethylene	Yes	No	-4.1 ± 6.7	5	7
29	C_3H_6	Propylene	Yes	No	-7.7 ± 8.2	6	10
30	C_4H_8	Trans-2-butene	Yes	No	-9.8 ± 7.7	3	10
31	C_4H_8	1-Butene	Yes	No	-11.9 ± 13.4	3	12
32	C_4H_8	Cis-2-butene	Yes	No	-7.4 ± 7.4	3	8
33	C_5H_{10}	1-Pentene	Yes	No	-15.8 ± 9.6	3	16
34	C_5H_{10}	Trans-2-pentene	Yes	No	-12.7 ± 9.3	3	13
35	C_5H_{10}	Cis-2-pentene	Yes	No	-10.9 ± 13.0	3	11
36	C_6H_{12}	1-Hexene	Yes	No	-12.7 ± 9.7	5	14
37	C_2H_2	Acetylene	Yes	No	-11.2 ± 6.5	5	12
Aromatics (16)							
38	C_6H_6	Benzene*	Yes	Yes	-9.7 ± 11.8	5	11
39	C_7H_8	Toluene*	Yes	Yes	-0.3 ± 10.9	1	1
40	C_8H_8	Styrene*	Yes	Yes	-1.6 ± 12.3	6	6
41	C_8H_{10}	Ethylbenzene	Yes	Yes	2.9 ± 12.7	9	9
42	C_8H_{10}	m/p-Xylene*	Yes	Yes	-6.9 ± 11.2	14	16
43	C_8H_{10}	o-Xylene	Yes	Yes	5.8 ± 13.6	9	11
44	C_9H_{12}	iso-Propylbenzene	Yes	Yes	4.1 ± 13.5	4	6
45	C_9H_{12}	n-Propylbenzene	Yes	Yes	2.2 ± 13.2	7	7
46	C_9H_{12}	m-Ethyltoluene	Yes	Yes	-0.7 ± 12.8	4	4

47	C_9H_{12}	p-Ethyltoluene	Yes	Yes	-3.5 ± 12.3	6	7
48	C_9H_{12}	1,3,5-Trimethylbenzene*	Yes	Yes	-4.5 ± 12.0	14	15
49	C_9H_{12}	o-Ethyltoluene	Yes	Yes	2.5 ± 13.2	6	7
50	C_9H_{12}	1,2,4-Trimethylbenzene	Yes	Yes	5.8 ± 13.6	8	10
51	C_9H_{12}	1,2,3-Trimethylbenzene	Yes	Yes	19.8 ± 12.4	8	21
52	$C_{10}H_{14}$	m-Diethylbenzene	Yes	Yes	36.4 ± 16.1	3	37
53	$C_{10}H_{14}$	p-Diethylbenzene	Yes	Yes	49.2 ± 17.0	8	50
		BVOCs (6)					
54	C_5H_8	Isoprene*	Yes	Yes	-13.8 ± 11.1	8	16
55	$C_{10}H_{16}$	alpha-Pinene*	Yes	Yes	26.2 ± 8.2	11	28
56	$C_{10}H_{16}$	beta-Pinene	Yes	Yes	33.5 ± 0.2	11	35
57	$C_{10}H_{16}$	Cinene (Limonene)	Yes	Yes	25.2 ± 2.6	16	30
58	C_4H_6O	Methacrolein	Yes	Yes	-4.2 ± 2.6	12	13
59	C_4H_6O	Methyl vinyl ketone*	Yes	Yes	-18.0 ± 14.6	7	19
		Carbonyls (16)					
60	C_3H_4O	Acrolein*	Yes	Yes	-19.6 ± 5.1	4	20
61	C_3H_6O	Propanal	Yes	Yes	-1.1 ± 6.0	4	4
62	C_3H_6O	Acetone*	Yes	Yes	7.9 ± 7.2	3	9
63	C_4H_6O	Crotonaldehyde	Yes	Yes	-18.0 ± 4.0	16	24
64	C_4H_8O	n-Butanal	Yes	Yes	-0.9 ± 2.5	5	5
65	C_4H_8O	Methyl ethyl ketone*	Yes	Yes	4.2 ± 1.6	3	5
66	$C_5H_{10}O$	2-Pentanone*	Yes	Yes	-1.0 ± 2.3	19	19
67	$C_5H_{10}O$	n-Pentanal	Yes	Yes	-8.6 ± 4.0	5	10
68	$C_5H_{10}O$	3-Pentanone	Yes	Yes	-5.2 ± 3.6	2	6
69	C_2H_4O	Acetaldehyde*	Yes	Yes	-20.1 ± 11.9	5	21
70	CH_2O	Formaldehyde[c]	—	—	—	—	—
71	$C_3H_4O_2$	Methylglyoxal	No	Yes	-20.1[e]	27	34
72	C_5H_4O	Cyclopentadienone	No	Yes	-20.1[e]	21	29
73	C_5H_8O	EVK, cyclopentanone, Dihydromethylfuran	No	Yes	-20.1[e]	21	29
74	$C_6H_{12}O$	C6 carbonyls*	No	Yes	-12.1 ± 5.8	11	16
75	C_7H_6O	Benzaldehyde	No	Yes	-20.1[e]	21	29
		Furans (10)					
76	C_4H_4O	Furan*	No	Yes	-5.3 ± 2.2	10	11
77	C_5H_6O	Methylfuran	No	Yes	-5.3[e]	25	26
78	$C_4H_4O_2$	Furanone	No	Yes	-5.3[e]	27	27
79	$C_5H_4O_2$	Furfural	No	Yes	-5.3[e]	27	27
80	C_6H_8O	Dimethylfuran	No	Yes	-5.3[e]	25	26
81	$C_5H_6O_2$	2-Methanol furanone	No	Yes	-5.3[e]	27	27
82	$C_7H_{10}O$	Trimethylfuran	No	Yes	-5.3[e]	25	26
83	$C_6H_8O_2$	Dimethylfuranone	No	Yes	-5.3[e]	27	27
84	C_8H_6O	Benzofuran	No	Yes	-5.3[e]	25	26
85	$C_8H_{12}O$	Butylfuran	No	Yes	-5.3[e]	25	26
		Phenols (9)					
86	C_6H_6O	Phenol	No	Yes	-20.1[e]	22	30
87	C_7H_8O	Cresol	No	Yes	-20.1[e]	22	30
88	$C_6H_6O_2$	Benzenediols; Methylfurfural	No	Yes	-20.1[e]	27	34
89	$C_8H_{10}O$	C2 phenols	No	Yes	-20.1[e]	22	30
90	$C_7H_8O_2$	Guaiacol	No	Yes	-20.1[e]	27	34
91	$C_9H_{12}O$	Trimethylphenol	No	Yes	-20.1[e]	22	30
92	$C_{10}H_8O$	Naphthalenol	No	Yes	-20.1[e]	22	30
93	$C_{10}H_{12}O$	methyl chavicol	No	Yes	-20.1[e]	22	30
94	$C_8H_{10}O_3$	Syringol	No	Yes	-20.1[e]	39	44
		PAHs (9)					
95	$C_{10}H_8$	Naphthalene*	No	Yes	-35.2 ± 7.4	11	37
96	$C_{10}H_{10}$	Dihydronaphthalene	No	Yes	-35.2[e]	21	41

97	$C_{11}H_{10}$	Methylnaphthalene	No	Yes	-35.2[e]	21	41
98	$C_{12}H_8$	Acenaphthylene	No	Yes	-35.2[e]	21	41
99	$C_{12}H_{10}$	Acenaphthene	No	Yes	-35.2[e]	21	41
100	$C_{12}H_{12}$	Dimethylnaphthalene	No	Yes	-35.2[e]	21	41
101	$C_{13}H_{10}$	Fluorene	No	Yes	-35.2[e]	21	41
102	$C_{14}H_{10}$	Phenanthrene, Anthracene	No	Yes	-35.2[e]	23	42
103	$C_{16}H_{10}$	Pyrene, Fluoranthene	No	Yes	-35.2[e]	23	42
		Higher alkanes (14)					
104	C_8H_{18}	C8 Alkanes*	No	Yes	-34.0 ± 3.2	18	39
105	C_9H_{20}	C9 Alkanes*	No	Yes	-28.4 ± 1.3	12	31
106	$C_{10}H_{22}$	C10 Alkanes*	No	Yes	-21.9 ± 1.4	12	25
107	$C_{11}H_{24}$	C11 Alkanes*	No	Yes	-18.6 ± 1.3	14	23
108	$C_{12}H_{26}$	C12 Alkanes*	No	Yes	-16.4 ± 3.4	15	22
109	$C_{13}H_{28}$	C13 Alkanes*	No	Yes	-10.8 ± 15.9	19	22
110	$C_{14}H_{30}$	C14 Alkanes*	No	Yes	-0.5 ± 30.8	17	17
111	$C_{15}H_{32}$	C15 Alkanes*	No	Yes	-19.0 ± 26.7	12	23
112	$C_{16}H_{34}$	C16 Alkanes	No	Yes	-34.0[e]	27	44
113	$C_{17}H_{36}$	C17 Alkanes	No	Yes	-34.0[e]	27	44
114	$C_{18}H_{38}$	C18 Alkanes	No	Yes	-34.0[e]	27	44
115	$C_{19}H_{40}$	C19 Alkanes	No	Yes	-34.0[e]	27	44
116	$C_{20}H_{42}$	C20 Alkanes	No	Yes	-34.0[e]	27	44
117	$C_{21}H_{44}$	C21 Alkanes	No	Yes	-34.0[e]	27	44
		N-containing (8)					
118	C_2H_3N	Acetonitrile*	No	Yes	-17.0 ± 10.5	15	23
119	C_2H_5N	Ethenamine	No	Yes	-17.0[e]	23	29
120	C_2H_7N	Dimethylamine, ethylamine	No	Yes	-17.0[e]	23	29
121	C_3H_3N	Acrylonitrile*	No	Yes	-13.9 ± 1.4	8	16
122	C_3H_5N	Propanenitrile	No	Yes	-17.0[e]	22	28
123	C_3H_9N	C3 amines	No	Yes	-17.0[e]	23	29
124	C_4H_5N	Pyrrole; Butenenitriles	No	Yes	-17.0[e]	22	28
125	C_4H_7N	Dihydropyrrole; Butanenitriles	No	Yes	-17.0[e]	22	28

[a], The data measured by GC-FID/MS was used in this work for the overlapped ROG species measured by two instruments.

[b], The species with star mark was the standard gas for Vocus PTR-ToF-MS calibration.

[c], Formaldehyde discussed in this study was estimated from previous studies (Cai et al., 2019; Stockwell et al., 2015).

[d], In total, loss fraction of 82 species were determined.

[e], The loss fraction of species was an assumed value as the maximum loss ratio of the same category. The loss ratio of phenol was assumed as the maximum value of all OVOCs in the 125 species.

Table S3. Applied SOA yields, chamber SOA yields, references and the numbers of experiments (N).

No.	Formula	Species	Applied Yield (g/g)	Reference	Chamber Yield (g/g)	N
1	C_2H_6	Ethane	/			
2	C_3H_8	Propane	/			
3	C_4H_{10}	Isobutane	/			
4	C_4H_{10}	n-Butane	/			
5	C_5H_{10}	Cyclopentane	/			
6	C_5H_{12}	Isopentane	/			
7	C_5H_{12}	n-Pentane	/			
8	C_6H_{12}	Methylcyclopentane	0.017	Assumed as Cyclohexane		
9	C_6H_{12}	Cyclohexane	0.017	(Lim and Ziemann, 2009)	0.040	1
10	C_6H_{14}	2,2-Dimethylbutane	/			
11	C_6H_{14}	2,3-Dimethylbutane	/			
12	C_6H_{14}	2-Methylpentane	/			
13	C_6H_{14}	3-Methylpentane	/			
14	C_6H_{14}	n-Hexane	0.000	(Lim and Ziemann, 2009)	0.000	1
15	C_7H_{14}	Methylcyclohexane	0.017	Assumed as Cyclohexane		
16	C_7H_{16}	2,4-Dimethylpentane	0.010	Assumed as n-Heptane		
17	C_7H_{16}	2-Methylhexane	0.010	Assumed as n-Heptane		
18	C_7H_{16}	2,3-Dimethylpentane	0.010	Assumed as n-Heptane		
19	C_7H_{16}	3-Methylhexane	0.010	Assumed as n-Heptane		
20	C_7H_{16}	n-Heptane	0.010	(Lim and Ziemann, 2009)	0.009	1
21	C_8H_{18}	2,2,4-Trimethylpentane	0.017	Assumed as n-Octane		
22	C_8H_{18}	2,3,4-Trimethylpentane	0.017	Assumed as n-Octane		
23	C_8H_{18}	2-Methylheptane	0.017	Assumed as n-Octane		
24	C_8H_{18}	3-Methylheptane	0.017	Assumed as n-Octane		
25	C_8H_{18}	n-Octane	0.017	(Lim and Ziemann, 2009; Presto et al., 2010)	0.041	1
26	C_9H_{20}	n-Nonane	0.021		0.070	1
27	$C_{10}H_{22}$	n-Decane	0.033		0.030-0.140	3
28	C_2H_4	Ethylene	/			
29	C_3H_6	Propylene	/			
30	C_4H_8	Trans-2-butene	/			
31	C_4H_8	1-Butene	/			
32	C_4H_8	Cis-2-butene	/			
33	C_5H_{10}	1-Pentene	/			
34	C_5H_{10}	Trans-2-pentene	/			
35	C_5H_{10}	Cis-2-pentene	/			
36	C_6H_{12}	1-Hexene	/			
37	C_2H_2	Acetylene	/			
38	C_6H_6	Benzene	0.096	(Li et al., 2016a; Ng et al., 2007)	0.078-0.349	8
39	C_7H_8	Toluene	0.200	(Li et al., 2016a; Ng et al., 2007)	0.078-0.196	12
40	C_8H_8	Styrene	0.016	(Tajuelo et al., 2019)	0.018-0.064	24
41	C_8H_{10}	Ethylbenzene	0.057	(Li et al., 2016a)	0.013-0.167	7
42	C_8H_{10}	m/p-Xylene	0.057	(Li et al., 2016a; Ng et al., 2007)	0.035-0.154	44
43	C_8H_{10}	o-Xylene	0.057	(Li et al., 2016a)	0.035-0.108	11
44	C_9H_{12}	iso-Propylbenzene	0.074	(Li et al., 2016a)	0.031-0.110	4
45	C_9H_{12}	n-Propylbenzene	0.074	(Li et al., 2016a)	0.051-0.054	2
46	C_9H_{12}	m-Ethyltoluene	0.074	(Li et al., 2016a)	0.020-0.167	9
47	C_9H_{12}	p-Ethyltoluene	0.060	(Li et al., 2016a)	0.039-0.122	6
48	C_9H_{12}	1,3,5-Trimethylbenzene	0.074	(Li et al., 2016a)	0.007-0.065	5
49	C_9H_{12}	o-Ethyltoluene	0.074	(Li et al., 2016a)	0.141-0.237	6
50	C_9H_{12}	1,2,4-Trimethylbenzene	0.074	(Li et al., 2016a)	0.028-0.065	9
51	C_9H_{12}	1,2,3-Trimethylbenzene	0.074	(Li et al., 2016a)	0.075-0.119	4
52	$C_{10}H_{14}$	m-Diethylbenzene	0.048	(Li et al., 2016a) (C10aromatics)	0.005-0.034	5
53	$C_{10}H_{14}$	p-Diethylbenzene	0.048		0.005-0.034	5
54	C_5H_8	Isoprene	0.440	(Kleindienst et al., 2006; Carlton et al., 2009)	0.003-0.017	11
55	$C_{10}H_{16}$	alpha-Pinene	0.346	(Ahlberg et al., 2017)	0.010-0.530	12
56	$C_{10}H_{16}$	beta-Pinene	0.346	Assumed as alpha-Pinene		
57	$C_{10}H_{16}$	Limonene	0.346	Assumed as alpha-Pinene		
58	C_4H_6O	Methacrolein	/			
59	C_4H_6O	Methyl vinyl ketone	/			
60	C_3H_4O	Acrolein	/			
61	C_3H_6O	Propanal	/			
62	C_3H_6O	Acetone	/			
63	C_4H_6O	Crotonaldehyde	/			
64	C_4H_8O	n-Butanal	/			

65	C_4H_8O	Methyl ethyl ketone	/			
66	$C_5H_{10}O$	2-Pentanone	/			
67	$C_5H_{10}O$	n-Pentanal	/			
68	$C_5H_{10}O$	3-Pentanone	/			
69	C_2H_4O	Acetaldehyde	/			
70	CH_2O	Formaldehyde	/			
71	$C_3H_4O_2$	Methylglyoxal	/			
72	C_5H_4O	Cyclopentadienone	/			
73	C_5H_8O	EVK, cyclopentanone, dihydromethylfuran	/			
74	$C_6H_{12}O$	C6 carbonyls	/			
75	C_7H_6O	Benzaldehyde	0.200	Assumed as toluene		
76	C_4H_4O	Furan*	0.050	(Gómez Alvarez et al., 2009)	0.019-0.072	2
77	C_5H_6O	Methyl furan	0.070	(Gómez Alvarez et al., 2009)	0.055-0.085	2
78	$C_4H_4O_2$	Furanone	0.050	Assumed as furan		
79	$C_5H_4O_2$	Furfural	0.050	Assumed as furan		
80	C_6H_8O	Dimethylfuran	0.070	Assumed as Methyl furan		
81	$C_5H_6O_2$	2-Methanol furanone	/			
82	$C_7H_{10}O$	TriMetfuran	0.070	Assumed as Methyl furan		
83	$C_6H_8O_2$	DiMetfuranone	0.070	Assumed as Methyl furan		
84	C_8H_6O	Benzofuran	0.156	Assumed as Styrene		
85	$C_8H_{12}O$	Butylfuran	0.070	Assumed as Methyl furan		
86	C_6H_6O	Phenol	0.440	(Yee et al., 2013)	0.240-0.540	5
87	C_7H_8O	Cresols	0.360	(Henry et al., 2008)	0.000-0.420	25
88	$C_6H_6O_2$	Benzenediols, methylfurfural	0.370	(Nakao et al., 2011)[b]	0.390	1
89	$C_8H_{10}O$	C2 phenols	0.440	(Nakao et al., 2011)[b]	0.130-0.730	7
90	$C_7H_8O_2$	Guaiacol, methyl benzenediols	0.500	(Yee et al., 2013)	0.340-0.530	11
91	$C_9H_{12}O$	Trimethylphenol	0.440	Assumed as C2 phenols		
92	$C_{10}H_8O$	Naphthalenol	0.440	Assumed as C2 phenols		
93	$C_{10}H_{12}O$	Methyl chavicol	0.440	Assumed as C2 phenols		
94	$C_8H_{10}O_3$	Syringol	0.370	(Yee et al., 2013)	0.110-0.370	7
95	$C_{10}H_8$	Naphthalene*	0.263	(Chan et al., 2009)	0.190-0.300	5
96	$C_{10}H_{10}$	Dihydronaphthalene	0.348	Assumed as MeNap		
97	$C_{11}H_{10}$	Methylnaphthalene (MetNap)	0.348	(Chan et al., 2009)	0.190-0.450	8
98	$C_{12}H_8$	Acenaphthalene	0.072	(Shakya et al., 2010)	0.030-0.110	10
99	$C_{12}H_{10}$	Acenaphthene	0.280	(Shakya et al., 2010)	0.040-0.130	8
100	$C_{12}H_{12}$	Dimethylnaphthalene (diMetNap)	0.372	(Chan et al., 2009)	0.300-0.310	3
101	$C_{13}H_{10}$	Fluorene	0.372	Assumed as diMetNap		
102	$C_{14}H_{10}$	Phenanthrene, Anthracene	0.372	Assumed as diMetNap		
103	$C_{16}H_{10}$	Pyrene, Fluoranthene	0.372	Assumed as diMetNap		
104	C_8H_{18}	C8 Alkanes	0.017		~0.40	1
105	C_9H_{20}	C9 Alkanes	0.021	(Lim and Ziemann, 2009; Presto	0.070	1
106	$C_{10}H_{22}$	C10 Alkanes	0.033	et al., 2010)	0.010-0.150	3
107	$C_{11}H_{24}$	C11 Alkanes	0.050		0.270	1
108	$C_{12}H_{26}$	C12 Alkanes	0.090	(Presto et al., 2010)	~0.01-0.09	8
109	$C_{13}H_{28}$	C13 Alkanes	0.220	(Presto et al., 2010)[a]		
110	$C_{14}H_{30}$	C14 Alkanes	0.300	(Presto et al., 2010)[a]		
111	$C_{15}H_{32}$	C15 Alkanes	0.340	(Presto et al., 2010)	~0.10-0.60	10
112	$C_{16}H_{34}$	C16 Alkanes	0.390	(Presto et al., 2010)[a]		
113	$C_{17}H_{36}$	C17 Alkanes	0.430	(Presto et al., 2010)	0.090-0.510	10
114	$C_{18}H_{38}$	C18 Alkanes	0.430	Assumed as C17 Alkanes		
115	$C_{19}H_{40}$	C19 Alkanes	0.430	Assumed as C17 Alkanes		
116	$C_{20}H_{42}$	C20 Alkanes	0.430	Assumed as C17 Alkanes		
117	$C_{21}H_{44}$	C21 Alkanes	0.430	Assumed as C17 Alkanes		
118	C_2H_3N	Acetonitrile	/			
119	C_2H_5N	Ethenamine	/			
120	C_2H_7N	C2 amines	/			
121	C_3H_3N	Acrylonitrile	/			
122	C_3H_5N	Propanenitrile	/			
123	C_3H_9N	C3 amines	/			
124	C_4H_5N	Pyrrole	/			
125	C_4H_7N	Dihydropyrrole, butane	/			

[a], SOA yields was estimated using the reported two-product parameters (Presto et al., 2010) which derived from the experimental yields of C12 alkanes and C17 alkanes.

[b], Only SOA yields in the absence of NO_x were reviewed, which probably underestimate the SOA formation potential (Nakao et al., 2011; Yee et al., 2013).

[c], "/" in the column "Yield" denotes that these species are not the potential SOA precursors.

Table S4. The emission factors (EFs, mg/kg) of benzene for coals and straws reported by other studies.

Fuel	Combustion facility	Combustion Stage	N[a]	EFs (mg/kg)	Reference
Coal					
Anthracite coal (Ningxia/Guizhou)	commercial stove widely used in northern China	a complete burn cycle	5	2-4.8	Cai et al. (2019)
Briquette coal (honeycomb)	metal coal stove with/without a flue	a complete burn cycle	3	~2.7-14	Tsai et al. (2003)
Briquette coal	metal coal stove without flue	a complete burn cycle	1	7.4	Tsai et al. (2003)
Anthracite and bituminous coal	commercial stove widely used in northern China	residential burning condition	5	21.5	Wang et al. (2013)
Bituminous coal (Shenmu/ Neimeng/ Unknown)	commercial stove widely used in northern China	a complete burn cycle	8	94-156	Cai et al. (2019)
Washed coal	metal coal stove with a flue	a complete burn cycle	1	440	Tsai et al. (2003)
Pulverized coal	metal coal stove or brick stove with a flue	a complete burn cycle	2	25.8-1050	Tsai et al. (2003)
Bituminous coal	commercial stove widely used in northern China	flaming or smoldering stage	10	58.2-622.2	Liu et al. (2017)
Bituminous coal	domestic cooking stoves	flaming or smoldering stage	/	71-724	Liu et al. (2015)
Straw					
Rice Straw (China)	a large indoor combustion room	simulated real-world conditions	9	284±115	Stockwell et al. (2015)
Corncob (China)	combustion chamber	simulated real-world conditions	5	190	Wu et al. (2022)
Rice Straw (China)	combustion chamber	mix of flaming and smoldering	1	167	Hatch & al. (2017)
Rice Straw (China)	a heat-resistant combustion box	flaming	6	250±100	Inomata et al. (2015)
Rice Straw (China)	a heat-resistant combustion box	smoldering	8	400±100	Inomata et al. (2015)
Rice Straw (China)	a heat-resistant combustion box	smoldering (wet fuel)	4	800±500	Inomata et al. (2015)
Rape Plant (China)	a heat-resistant combustion box	flaming	2	220	Inomata et al. (2015)
Rape Plant (China)	a heat-resistant combustion box	smoldering	4	300±100	Inomata et al. (2015)
Wheat Straw	a large indoor combustion room	simulated real-world conditions	6	142±40	Stockwell et al. (2015)
wheat residue	brick stove with a flue	a complete burn cycle	1	512	Tsai et al. (2003)
maize residue	brick stove with a flue	a complete burn cycle	2	102-194	Tsai et al. (2003)
Rice Straw	Fire Sciences Laboratory facility	mix of flaming and smoldering	1	72.6	Koss et al. (2018)

[a], The number of samples.

Table S5. Emission ratio relative to benzene of individual species in different fuels.

Number	Formula	Name	Emission ratio (μg mg^{-1})					
			Anthracites	Briquettes	Wood	Corncob	Corn straw	Bean straw
1	C_2H_6	Ethane	2713.8 ± 1519.3	1708.6 ± 695.7	1049.9 ± 1125.1	1047.5	2168.9	5022.1
2	C_3H_8	Propane	829.2 ± 389.7	356.6 ± 222.4	336.3 ± 390.0	392.9	453.1	1277.8
3	C_4H_{10}	Isobutane	139.3 ± 84.7	65.5 ± 61.4	28.5 ± 26.3	27.4	37.4	61.8
4	C_4H_{10}	n-Butane	265.4 ± 93.6	122.2 ± 77.3	92.4 ± 92.6	117.6	106.7	263.6
5	C_5H_{12}	Cyclopentane	8.7 ± 2.0	8.5 ± 6.7	2.3 ± 2.7	2.6	2.2	9.7
6	C_5H_{12}	Isopentane	79.1 ± 73.4	53.3 ± 64.3	16.1 ± 16.3	22.4	20.3	40.3
7	C_5H_{12}	n-Pentane	94.9 ± 55.0	52.5 ± 37.2	44.4 ± 45.3	63.9	32.7	94.3
8	C_6H_{12}	Methylcyclopentane	19.4 ± 15.7	10.3 ± 4.7	9.4 ± 6.5	12.9	14.6	18.0
9	C_6H_{12}	Cyclohexane	7.1 ± 3.9	6.1 ± 2.5	1.8 ± 1.9	1.5	1.2	2.6
10	C_6H_{14}	2,2-Dimethylbutane	0.9 ± 0.7	0.9 ± 0.3	0.2 ± 0.2	0.2	0.2	0.4
11	C_6H_{14}	2,3-Dimethylbutane	1.3 ± 0.7	1.8 ± 1.5	1.4 ± 2.7	0.8	5.9	1.3
12	C_6H_{14}	2-Methylpentane	15.1 ± 11.1	10.4 ± 6.0	5.1 ± 4.7	7.2	4.9	10.7
13	C_6H_{14}	3-Methylpentane	6.1 ± 3.5	4.8 ± 3.6	1.8 ± 2.1	1.9	0.2	4.6
14	C_6H_{14}	n-Hexane	34.2 ± 24.5	22.0 ± 12.4	17.3 ± 21.6	18.5	14.4	30.7
15	C_7H_{14}	Methylcyclohexane	7.8 ± 3.7	7.0 ± 3.0	2.4 ± 2.3	3.5	1.7	2.7
16	C_7H_{16}	2,4-Dimethylpentane	14.1 ± 14.4	11.7 ± 17.1	46.5 ± 119.1	0.6	16.5	856.5
17	C_7H_{16}	2-Methylhexane	6.1 ± 4.5	4.3 ± 3.4	1.2 ± 0.8	2.4	2.3	5.4
18	C_7H_{16}	2,3-Dimethylpentane	5.0 ± 4.9	3.3 ± 3.2	1.3 ± 1.4	2.5	1.3	3.4
19	C_7H_{16}	3-Methylhexane	3.7 ± 1.9	3.8 ± 3.7	1.7 ± 1.1	4.8	13.0	1.6
20	C_7H_{16}	n-Heptane	27.6 ± 26.0	12.9 ± 12.6	16.5 ± 13.4	22.0	8.3	15.3
21	C_8H_{18}	2,2,4-Trimethylpentane	0.9 ± 0.9	1.5 ± 2.9	0.5 ± 0.8	0.1	9.1	0.2

22	C_8H_{18}	2,3,4-Trimethylpentane	1.9 ± 1.8	2.2 ± 2.8	0.3 ± 0.3	0.1	0.1	0.6
23	C_8H_{18}	2-Methylheptane	12.3 ± 11.0	8.2 ± 6.9	4.9 ± 3.9	6.6	3.1	4.0
24	C_8H_{18}	3-Methylheptane	9.4 ± 7.8	4.6 ± 3.7	3.2 ± 2.1	3.1	2.1	2.5
25	C_8H_{18}	n-Octane	34.7 ± 23.2	25.2 ± 14.6	15.2 ± 11.6	18.2	9.6	10.2
26	C_9H_{20}	n-Nonane	26.8 ± 18.7	21.7 ± 15.4	9.0 ± 8.1	11.4	4.3	2.4
27	$C_{10}H_{22}$	n-Decane	34.0 ± 21.9	35.4 ± 28.3	7.6 ± 6.2	7.5	3.9	4.4
28	C_2H_4	Ethylene	1944.1 ± 957.8	2019.3 ± 1089.0	3019.6 ± 1283.7	2429.3	20434.6	5954.7
29	C_3H_6	Propylene	845.8 ± 567.7	465.8 ± 338.0	993.0 ± 670.6	1052.1	3463.9	3077.6
30	C_4H_8	Trans-2-butene	86.6 ± 68.6	33.3 ± 36.9	72.7 ± 82.1	79.1	126.2	303.6
31	C_4H_8	1-Butene	170.3 ± 131.3	85.6 ± 75.4	221.8 ± 162.6	277.3	513.5	627.0
32	C_4H_8	Cis-2-butene	61.3 ± 46.2	24.2 ± 26.8	52.4 ± 58.0	56.9	93.4	218.9
33	C_5H_{10}	1-Pentene	43.1 ± 35.9	26.0 ± 20.1	60.4 ± 57.0	73.8	76.9	109.5
34	C_5H_{10}	Trans-2-pentene	30.2 ± 25.3	15.3 ± 12.7	25.9 ± 28.8	25.6	42.2	92.1
35	C_5H_{10}	Cis-2-pentene	26.2 ± 19.3	9.7 ± 6.6	14.8 ± 16.4	15.9	20.7	52.8
36	C_6H_{12}	1-Hexene	65.6 ± 71.6	41.0 ± 30.4	92.4 ± 73.3	157.8	149.1	110.2
37	C_2H_2	Acetylene	259.2 ± 181.4	631.5 ± 422.2	1259.7 ± 598.9	590.4	1751.7	1026.2
38	C_6H_6	Benzene	1000.0 ± 0.0	1000.0 ± 0.0	1000.0 ± 0.0	1000.0	1000.0	1000.0
39	C_7H_8	Toluene	567.3 ± 233.2	356.9 ± 146.8	362.3 ± 183.2	267.8	786.0	317.7
40	C_8H_8	Styrene	129.0 ± 123.4	83.8 ± 39.0	80.9 ± 50.7	74.5	355.4	16.7
41	C_8H_{10}	Ethylbenzene	79.3 ± 51.2	58.0 ± 24.5	53.1 ± 26.3	37.3	123.3	16.3
42	C_8H_{10}	m/p-Xylene	238.5 ± 136.0	144.3 ± 72.4	76.8 ± 54.2	68.1	97.0	49.2
43	C_8H_{10}	o-Xylene	82.2 ± 47.5	53.9 ± 26.9	28.9 ± 21.4	21.0	40.7	16.0
44	C_9H_{12}	iso-Propylbenzene	7.1 ± 4.6	9.0 ± 9.1	2.5 ± 1.2	1.7	7.1	1.1
45	C_9H_{12}	n-Propylbenzene	18.9 ± 12.7	19.5 ± 15.4	6.2 ± 4.2	4.8	7.8	2.2
46	C_9H_{12}	m-Ethyltoluene	42.6 ± 31.4	32.8 ± 20.4	11.1 ± 7.6	9.1	12.6	5.3
47	C_9H_{12}	p-Ethyltoluene	30.5 ± 22.5	26.5 ± 20.0	7.4 ± 4.9	6.6	7.1	4.1
48	C_9H_{12}	1,3,5-Trimethylbenzene	23.7 ± 16.6	21.9 ± 16.8	5.3 ± 4.3	4.3	3.0	2.7
49	C_9H_{12}	o-Ethyltoluene	28.1 ± 19.9	25.7 ± 19.7	7.8 ± 5.6	5.0	7.8	3.2
50	C_9H_{12}	1,2,4-Trimethylbenzene	70.0 ± 56.8	48.1 ± 31.8	14.5 ± 11.8	9.9	10.0	7.3

51	C_9H_{12}	1,2,3-Trimethylbenzene	48.4 ± 39.4	41.9 ± 33.2	8.3 ± 6.2	5.9	4.5	4.6
52	$C_{10}H_{114}$	m-Diethylbenzene	12.2 ± 8.5	20.2 ± 26.7	1.5 ± 0.9	0.8	1.0	1.9
53	$C_{10}H_{14}$	p-Diethylbenzene	29.2 ± 23.4	30.6 ± 29.6	4.1 ± 2.9	2.6	2.4	3.7
54	C_5H_8	Isoprene	24.7 ± 21.0	11.7 ± 17.4	24.5 ± 42.5	7.7	11.5	291.9
55	$C_{10}H_{16}$	alpha-Pinene	3.7 ± 4.4	1.0 ± 0.7	1.0 ± 1.3	0.5	0.7	0.3
56	$C_{10}H_{16}$	beta-Pinene	2.8 ± 4.3	0.5 ± 0.5	0.5 ± 0.5	0.3	0.2	0.3
57	$C_{10}H_{16}$	Cinene (Limonene)	193.6 ± 264.8	69.3 ± 58.5	86.2 ± 115.7	119.1	6.9	13.5
58	C_4H_6O	Methacrolein	189.6 ± 162.7	122.8 ± 86.7	220.5 ± 156.1	266.3	525.3	414.1
59	C_4H_6O	Methyl vinyl ketone	933.7 ± 1094.1	377.8 ± 315.3	592.0 ± 304.9	785.5	1469.5	1072.1
60	C_3H_4O	Acrolein	2653.4 ± 2492.5	1664.7 ± 1313.5	2492.8 ± 1229.3	2683.4	7437.6	6116.1
61	C_3H_6O	Propanal	838.9 ± 646.7	464.9 ± 420.5	969.7 ± 502.8	1151.0	1792.8	2980.5
62	C_3H_6O	Acetone	8404.5 ± 8112.2	2526.9 ± 1872.0	3826.5 ± 3651.0	3681.0	4654.4	12189.5
63	C_4H_6O	Crotonaldehyde	676.5 ± 755.0	327.2 ± 324.3	233.7 ± 131.9	61.1	531.1	274.7
64	C_4H_8O	n-Butanal	165.6 ± 121.6	131.8 ± 159.0	136.0 ± 94.9	177.5	229.6	301.0
65	C_4H_8O	Methyl ethyl ketone	1746.3 ± 1795.9	502.6 ± 467.5	762.5 ± 729.0	1086.5	1093.7	1858.9
66	$C_5H_{10}O$	2-Pentanone	164.7 ± 162.1	47.4 ± 44.2	58.5 ± 51.5	53.8	47.9	100.9
67	$C_5H_{10}O$	n-Pentanal	197.1 ± 186.5	170.2 ± 208.4	108.2 ± 53.2	156.3	109.7	74.0
68	$C_5H_{10}O$	3-Pentanone	55.8 ± 53.2	15.7 ± 14.7	22.5 ± 19.0	26.2	21.9	35.7
69	C_2H_4O	Acetaldehyde	942.7 ± 748.7	605.1 ± 389.0	1054.3 ± 569.9	1432.2	1825.6	3554.3
70	CH_2O	Formaldehyde	2125 ± 581.1	2125 ± 581.1	2856± 532.9	2848 ± 555.3	2848 ± 555.3	2848 ± 555.3
71	$C_3H_4O_2$	Methylglyoxal	78.9 ± 85.1	70.5 ± 66.7	13.9 ± 8.8	12.3	18.0	62.2
72	C_5H_4O	Cyclopentadienone	1336.1 ± 2106.0	112.3 ± 138.7	66.8 ± 96.9	65.3	121.2	33.0
73	C_5H_8O	EVK, Dihydromethylfuran, cyclopentanone	1839.1 ± 2062.5	330.1 ± 408.8	414.2 ± 357.3	457.6	409.2	550.7
74	$C_6H_{12}O$	C6 carbonyls	515.1 ± 616.9	96.3 ±71.1	99.6 ± 53.8	79.5	81.3	88.0
75	C_7H_6O	Benzaldehyde	337.9 ± 380.3	103.4 ± 51.1	71.2 ± 36.1	65.3	113.1	8.8
76	C_4H_4O	Furan	1489.0 ± 1726.1	451.8 ± 780.5	741.1 ± 835.3	713.8	920.7	1872.7
77	C_5H_6O	Methylfuran	5654.4 ± 7399.9	954.4 ± 1275.5	987.4 ± 1258.0	883.3	763.2	2035.8
78	$C_4H_4O_2$	Furanone	744.7 ± 873.2	176.1 ± 115.8	58.1 ± 50.8	87.4	66.1	17.9

79	$C_5H_4O_2$	Furfural	14120.4 ± 18694.4	1457.6 ± 1830.3	920.7 ± 987.8	662.8	495.6	187.6
80	C_6H_8O	Dimethylfuran	3903.1 ± 5098.9	569.7 ± 513.1	373.3 ± 428.7	312.8	229.0	345.1
81	$C_5H_6O_2$	2-Methanol furanone	1188.0 ± 1534.8	197.4 ± 133.5	86.8 ± 91.8	90.8	99.9	30.8
82	$C_7H_{10}O$	Trimethylfuran	2317.1 ± 3058.2	347.4 ± 284.7	165.2 ± 188.9	134.2	69.8	55.2
83	$C_6H_8O_2$	Dimethylfuranone	944.6 ± 1281.7	187.2 ± 132.9	67.7 ± 62.9	65.2	93.2	22.2
84	C_8H_6O	Benzofuran	231.3 ± 246.8	67.5 ± 54.5	59.1 ± 44.3	41.6	87.8	4.7
85	$C_8H_{12}O$	Butylfuran	1083.4 ± 1458.3	167.0 ± 139.4	67.2 ± 74.8	51.7	22.5	13.2
86	C_6H_6O	Phenol	3762.9 ± 5889.4	574.3 ± 526.1	443.5 ± 451.8	258.1	908.1	281.9
87	C_7H_8O	Cresols	2017.8 ± 3924.1	166.0 ± 277.1	76.9 ± 150.0	41.5	24.5	25.3
88	$C_6H_6O_2$	Benzenediols, methylfurfural	3372.0 ± 4703.2	407.2 ± 292.3	175.9 ± 196.4	114.2	118.2	38.5
89	$C_8H_{10}O$	C2 phenols	1248.1 ± 2563.9	94.9 ± 151.4	35.1 ± 54.5	24.3	12.6	8.5
90	$C_7H_8O_2$	Guaiacol	1995.4 ± 4089.5	128.8 ± 143.4	41.2 ± 43.9	26.3	26.8	8.7
91	$C_9H_{12}O$	Trimethylphenol	432.0 ± 795.3	36.5 ± 42.0	14.6 ± 19.3	10.0	4.8	3.0
92	$C_{10}H_8O$	Naphthalenol	132.5 ± 185.6	32.5 ± 22.6	5.9 ± 7.2	3.5	2.8	7.2
93	$C_{10}H_{12}O$	methyl chavicol	173.9 ± 230.0	40.3 ± 29.1	10.4 ± 11.9	6.7	2.7	4.3
94	$C_8H_{10}O_3$	Syringol	40.7 ± 50.8	21.2 ± 18.8	2.6 ± 2.8	1.1	1.3	0.5
95	$C_{10}H_8$	naphthalene	2325.2 ± 1892.3	1790.4 ± 1896.7	176.4 ± 105.6	107.0	126.8	540.0
96	$C_{10}H_{10}$	Dihydronaphthalene	94.6 ± 92.4	40.3 ± 39.3	18.0 ± 20.5	12.8	9.0	2.5
97	$C_{11}H_{10}$	Methylnaphthalene	560.8 ± 625.0	188.8 ± 271.0	42.6 ± 49.9	28.8	9.2	14.0
98	$C_{12}H_8$	Acenaphthylene	109.4 ± 217.4	13.2 ± 15.9	2.7 ± 5.2	0.9	0.6	1.3
99	$C_{12}H_{10}$	Acenaphthene	250.6 ± 313.4	95.7 ± 74.7	18.9 ± 20.5	9.7	8.4	5.8
100	$C_{12}H_{12}$	Dimethylnaphthalene	308.7 ± 370.9	115.3 ± 178.4	29.5 ± 37.8	15.9	4.1	9.5
101	$C_{13}H_{10}$	Fluorene	20.5 ± 30.7	9.7 ± 13.2	1.6 ± 1.4	0.6	0.6	4.7
102	$C_{14}H_{10}$	Phenanthrene, Anthracene	6.4 ± 6.6	3.6 ± 3.1	0.6 ± 0.5	0.1	0.3	0.7
103	$C_{16}H_{10}$	Pyrene, Fluoranthene	0.6 ± 0.7	0.2 ± 0.1	0.1 ± 0.1	0.0	0.1	0.0
104	C_8H_{18}	C8 Alkanes	161.2 ± 109.4	169.3 ± 151.2	58.1 ± 39.3	72.0	35.0	48.7
105	C_9H_{20}	C9 Alkanes	134.1 ± 97.6	141.0 ± 128.4	49.4 ± 32.2	70.8	23.0	22.5
106	$C_{10}H_{22}$	C10 Alkanes	106.5 ± 73.9	111.6 ± 101.2	36.3 ± 28.2	45.4	16.2	12.6
107	$C_{11}H_{24}$	C11 Alkanes	84.3 ± 65.3	93.9 ± 91.0	28.2 ± 21.4	31.3	9.6	10.5

108	$C_{12}H_{26}$	C12 Alkanes	96.5 ± 86.3	107.4 ± 95.3	23.0 ± 17.5	16.9	3.4	9.6
109	$C_{13}H_{28}$	C13 Alkanes	164.5 ± 151.8	176.6 ± 153.1	29.0 ± 24.5	18.3	1.3	11.4
110	$C_{14}H_{30}$	C14 Alkanes	298.0 ± 300.5	306.3 ± 288.7	43.0 ± 45.3	26.0	4.6	21.3
111	$C_{15}H_{32}$	C15 Alkanes	497.7 ± 515.5	723.1 ± 933.1	73.1 ± 78.4	46.3	6.7	42.3
112	$C_{16}H_{34}$	C16 Alkanes	354.9 ± 370.6	562.7 ± 783.3	46.3 ± 47.1	28.6	2.9	32.7
113	$C_{17}H_{36}$	C17 Alkanes	216.9 ± 210.3	265.8 ± 327.3	24.1 ± 20.0	10.8	1.5	29.5
114	$C_{18}H_{38}$	C18 Alkanes	161.7 ± 156.8	153.5 ± 147.5	17.9 ± 14.2	7.9	0.9	27.4
115	$C_{19}H_{40}$	C19 Alkanes	96.7 ± 91.4	72.4 ± 55.9	10.8 ± 8.5	4.9	0.5	15.4
116	$C_{20}H_{42}$	C20 Alkanes	57.0 ± 49.4	44.1 ± 44.2	6.4 ± 4.9	2.7	0.2	13.3
117	$C_{21}H_{44}$	C21 Alkanes	41.0 ± 34.3	33.6 ± 38.6	4.2 ± 3.0	2.8	0.1	9.9
118	C_2H_3N	Acetonitrile	3273.2 ± 2921.0	2628.6 ± 1550.5	1879.6 ± 1117.9	2003.1	5377.2	3826.7
119	C_2H_5N	Ethenamine	4.8 ± 5.5	2.3 ± 1.5	1.1 ± 0.6	1.6	2.0	3.3
120	C_2H_7N	Dimethylamine, Ethylamine	2.2 ± 2.2	1.2 ± 0.8	1.5 ± 3.5	0.1	0.4	0.3
121	C_3H_3N	Acrylonitrile	163.7 ± 153.7	315.3 ± 301.7	386.6 ± 344.1	301.1	3491.1	146.9
122	C_3H_5N	Propanenitrile	170.5 ± 232.1	69.9 ± 54.8	144.3 ± 141.0	188.6	685.1	144.0
123	C_3H_9N	C3 amines	1.0 ± 1.2	0.6 ± 0.6	0.1 ± 0.1	0.0	0.2	0.2
124	C_4H_5N	Pyrrole	326.8 ± 425.7	70.4 ± 135.3	104.9 ± 96.0	163.5	474.6	38.7
125	C_4H_7N	Dihydropyrrole, butane nitrile, pyrroline	47.7 ± 62.8	21.2 ± 17.7	47.4 ± 49.6	68.7	168.4	31.8

Table S6. Annual consumption of residential coal and biomass combustion in China mainland.

Year	Residential coal consumption (10^4 t)	Biomass combustion (10^8 t)
2010	9159	3.1
2011	9212	3.1
2012	9253	3.0
2013	9290	2.9
2014	9303	2.8
2015	9627	2.7
2016	9492	2.6
2017	9283	2.2
2018	7714	2.3
2019	6547	2.2

Table S7. Annual consumption of residential coal and biomass combustion by province in 2019 and 2017, respectively.

NO.	Region	Residential coal consumption (10^4 t)	Biomass combustion (10^4 t)
1	Beijing	48.7	5.1
2	Tianjin	38.2	60.1
3	Hebei[a]	1313.3	178.8
4	Shanxi	422.7	288.2
5	Inner Mongolia	333.7	60.1
6	Liaoning[a]	413.6	244.4
7	Jilin	188.5	1242.9
8	Heilongjiang	273.2	2845.7
9	Shanghai	4.1	20.2
10	Jiangsu	-	1470.1
11	Zhejiang	28.2	163.9
12	Anhui	35.0	1480.3
13	Fujian	21.4	104.1
14	Jiangxi	250.1	894.1
15	Shandong	478.7	1600.0
16	Henan	331.6	1700.0
17	Hubei	501.5	1138.1
18	Hunan	408.4	1488.5
19	Guangdong	65.9	862.7
20	Guangxi	0.9	970.0
21	Hainan	-	101.4
22	Chongqing	48.1	208.8
23	Sichuan	72.1	800.0
24	Guizhou	494.0	144.0
25	Yunnan	327.7	500.0
26	Tibet	-	-
27	Shaanxi	284.7	244.1
28	Gansu	327.5	210.2
29	Qinghai	65.0	23.3
30	Ningxia	40.3	78.6
31	Xinjiang	465.9	642.0
32	National	6547.0	22000.0

[a], Consumption from biomass combustion in Hebei and Liaoning are from 2020 statistic data.

Reference

Ahlberg, E., Falk, J., Eriksson, A., Holst, T., Brune, W. H., Kristensson, A., Roldin, P., and Svenningsson, B.: Secondary organic aerosol from VOC mixtures in an oxidation flow reactor, Atmospheric Environment, 161, 210-220, 10.1016/j.atmosenv.2017.05.005, 2017.

Akherati, A., He, Y., Coggon, M. M., Koss, A. R., Hodshire, A. L., Sekimoto, K., Warneke, C., de Gouw, J., Yee, L., Seinfeld, J. H., Onasch, T. B., Herndon, S. C., Knighton, W. B., Cappa, C. D., Kleeman, M. J., Lim, C. Y., Kroll, J. H., Pierce, J. R., and Jathar, S. H.: Oxygenated aromatic compounds are important precursors of secondary organic aerosol in biomass-burning emissions, Environ Sci Technol, doi.10.1021/acs.est.1020c01345, 10.1021/acs.est.0c01345, 2020.

Bruns, E. A., Slowik, J. G., El Haddad, I., Kilic, D., Klein, F., Dommen, J., Temime-Roussel, B., Marchand, N., Baltensperger, U., and Prevot, A. S. H.: Characterization of gas-phase organics using proton transfer reaction time-of-flight mass spectrometry: fresh and aged residential wood combustion emissions, Atmospheric Chemistry and Physics, 17, 705-720, 10.5194/acp-17-705-2017, 2017.

Cai, S., Zhu, L., Wang, S., Wisthaler, A., Li, Q., Jiang, J., and Hao, J.: Time-Resolved Intermediate-Volatility and Semivolatile Organic Compound Emissions from Household Coal Combustion in Northern China, Environmental Science & Technology, 53, 9269-9278, 10.1021/acs.est.9b00734, 2019.

Carlton, A. G., Wiedinmyer, C., and Kroll, J. H.: A review of Secondary Organic Aerosol (SOA) formation from isoprene, Atmospheric Chemistry and Physics, 9, 4987-5005, 2009.

Chan, A. W. H., Kautzman, K. E., Chhabra, P. S., Surratt, J. D., Chan, M. N., Crounse, J. D., Kuerten, A., Wennberg, P. O., Flagan, R. C., and Seinfeld, J. H.: Secondary organic aerosol formation from photooxidation of naphthalene and alkylnaphthalenes: implications for oxidation of intermediate volatility organic compounds (IVOCs), Atmospheric Chemistry and Physics, 9, 3049-3060, 10.5194/acp-9-3049-2009, 2009.

Gilman, J. B., Lerner, B. M., Kuster, W. C., Goldan, P. D., Warneke, C., Veres, P. R., Roberts, J. M., de Gouw, J. A., Burling, I. R., and Yokelson, R. J.: Biomass burning emissions and potential air quality impacts of volatile organic compounds and other trace gases from fuels common in the US, Atmospheric Chemistry and Physics, 15, 13915-13938, 10.5194/acp-15-13915-2015, 2015.

Gómez Alvarez, E., Borrás, E., Viidanoja, J., and Hjorth, J.: Unsaturated dicarbonyl products from the OH-initiated photo-oxidation of furan, 2-methylfuran and 3-methylfuran, Atmospheric Environment, 43, 1603-1612, https://doi.org/10.1016/j.atmosenv.2008.12.019, 2009.

Hatch, L. E., Yokelson, R. J., Stockwell, C. E., Veres, P. R., Simpson, I. J., Blake, D. R., Orlando, J. J., and Barsanti, K. C.: Multi-instrument comparison and compilation of non-methane organic gas emissions from biomass burning and implications for smoke-derived secondary organic aerosol precursors, Atmospheric Chemistry and Physics, 17, 1471-1489, 10.5194/acp-17-1471-2017, 2017.

Henry, F., Coeur-Tourneur, C., Ledoux, F., Tomas, A., and Menu, D.: Secondary organic aerosol formation from the gas phase reaction of hydroxyl radicals with m-, o- and p-cresol, Atmospheric Environment, 42, 3035-3045, https://doi.org/10.1016/j.atmosenv.2007.12.043, 2008.

Inomata, S., Tanimoto, H., Pan, X., Taketani, F., Komazaki, Y., Miyakawa, T., Kanaya, Y., and Wang, Z.: Laboratory measurements of emission factors of nonmethane volatile organic compounds from burning of Chinese crop residues, Journal of Geophysical Research: Atmospheres, 120, 5237-5252, 10.1002/2014jd022761, 2015.

Kleindienst, T. E., Edney, E. O., Lewandowski, M., Offenberg, J. H., and Jaoui, M.: Secondary organic carbon and aerosol yields from the irradiations of isoprene and alpha-pinene in the presence of NOx and SO2, Environmental Science & Technology, 40, 3807-3812, 10.1021/es052446r, 2006.

Koss, A. R., Sekimoto, K., Gilman, J. B., Selimovic, V., Coggon, M. M., Zarzana, K. J., Yuan, B., Lerner, B. M., Brown, S. S., Jimenez, J. L., Krechmer, J., Roberts, J. M., Warneke, C., Yokelson, R. J., and de Gouw, J.: Non-methane organic gas emissions from biomass burning: identification, quantification, and emission factors from PTR-ToF during the FIREX 2016 laboratory experiment, Atmospheric Chemistry and Physics, 18, 3299-3319, 10.5194/acp-18-3299-2018, 2018.

Li, L., Tang, P., Nakao, S., Kacarab, M., and Cocker, D. R., III: Novel Approach for Evaluating Secondary

Organic Aerosol from Aromatic Hydrocarbons: Unified Method for Predicting Aerosol Composition and Formation, Environmental Science & Technology, 50, 6249-6256, 10.1021/acs.est.5b05778, 2016a.

Li, Q., Jiang, J., Zhang, Q., Zhou, W., Cai, S., Duan, L., Ge, S., and Hao, J.: Influences of coal size, volatile matter content, and additive on primary particulate matter emissions from household stove combustion, Fuel, 182, 780-787, https://doi.org/10.1016/j.fuel.2016.06.059, 2016b.

Lim, Y. B. and Ziemann, P. J.: Effects of Molecular Structure on Aerosol Yields from OH Radical-Initiated Reactions of Linear, Branched, and Cyclic Alkanes in the Presence of NOx, Environmental Science & Technology, 43, 2328-2334, 10.1021/es803389s, 2009.

Liu, C., Zhang, C., Zhang, Y., and Mu, Y.: Preliminary study on volatile organic compounds emission from domestic cooking stoves under different coal combustion modes, The 16th Annual Academic Meeting of Chinese Society for Mineralogy Petrology and Geochemistry, Changchun, China, 2015.

Liu, C., Zhang, C., Mu, Y., Liu, J., and Zhang, Y.: Emission of volatile organic compounds from domestic coal stove with the actual alternation of flaming and smoldering combustion processes, Environmental pollution, 221, 385-391, 10.1016/j.envpol.2016.11.089, 2017.

Liu, Y., Shao, M., Fu, L., Lu, S., Zeng, L., and Tang, D.: Source profiles of volatile organic compounds (VOCs) measured in China: Part I, Atmospheric Environment, 42, 6247-6260, 10.1016/j.atmosenv.2008.01.070, 2008.

Mo, Z., Shao, M., and Lu, S.: Compilation of a source profile database for hydrocarbon and OVOC emissions in China, Atmospheric Environment, 143, 209-217, 10.1016/j.atmosenv.2016.08.025, 2016.

Nakao, S., Clark, C. H., Tang, P., Sato, K., and Cocker, D. R.: Secondary organic aerosol formation from phenolic compounds in the absence of NOx, Atmospheric Chemistry and Physics, 11, 10649-10660, 2011.

Ng, N. L., Kroll, J. H., Chan, A. W. H., Chhabra, P. S., Flagan, R. C., and Seinfeld, J. H.: Secondary organic aerosol formation from m-xylene, toluene, and benzene, Atmospheric Chemistry and Physics, 7, 3909-3922, 2007.

Presto, A. A., Miracolo, M. A., Donahue, N. M., and Robinson, A. L.: Secondary Organic Aerosol Formation from High-NOx Photo-Oxidation of Low Volatility Precursors: n-Alkanes, Environmental Science & Technology, 44, 2029-2034, 10.1021/es903712r, 2010.

Stockwell, C. E., Veres, P. R., Williams, J., and Yokelson, R. J.: Characterization of biomass burning emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-reaction time-of-flight mass spectrometry, Atmospheric Chemistry and Physics, 15, 845-865, 10.5194/acp-15-845-2015, 2015.

Stockwell, C. E., Christian, T. J., Goetz, J. D., Jayarathne, T., Bhave, P. V., Praveen, P. S., Adhikari, S., Maharjan, R., DeCarlo, P. F., Stone, E. A., Saikawa, E., Blake, D. R., Simpson, I. J., Yokelson, R. J., and Panday, A. K.: Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): emissions of trace gases and light-absorbing carbon from wood and dung cooking fires, garbage and crop residue burning, brick kilns, and other sources, Atmos. Chem. Phys., 16, 11043-11081, 10.5194/acp-16-11043-2016, 2016.

Tajuelo, M., Rodriguez, D., Teresa Baeza-Romero, M., Diaz-de-Mera, Y., Aranda, A., and Rodriguez, A.: Secondary organic aerosol formation from styrene photolysis and photooxidation with hydroxyl radicals, Chemosphere, 231, 276-286, 10.1016/j.chemosphere.2019.05.136, 2019.

Tsai, S. M., Zhang, J. J., Smith, K. R., Ma, Y., Rasmussen, R. A., and Khalil, M. A.: Characterization of non-methane hydrocarbons emitted from various cookstoves used in China, Environ Sci Technol, 37, 2869-2877, 10.1021/es026232a, 2003.

Wang, H., Lou, S., Huang, C., Qiao, L., Tang, X., Chen, C., Zeng, L., Wang, Q., Zhou, M., Lu, S., and Yu, X.: Source Profiles of Volatile Organic Compounds from Biomass Burning in Yangtze River Delta, China, Aerosol and Air Quality Research, 14, 818-828, 10.4209/aaqr.2013.05.0174, 2014.

Wang, Q., Geng, C., Lu, S., Chen, W., and Shao, M.: Emission factors of gaseous carbonaceous species from residential combustion of coal and crop residue briquettes, Frontiers of Environmental Science & Engineering, 7, 66-76, 10.1007/s11783-012-0428-5, 2013.

Wu, J., Kong, S., Yan, Y., Yao, L., Yan, Q., Liu, D., Shen, G., Zhang, X., and Qi, S.: Neglected biomass burning emissions of air pollutants in China-views from the corncob burning test, emission estimation, and simulations, Atmospheric Environment, 10.1016/j.atmosenv.2022.119082, 2022.

Yee, L. D., Kautzman, K. E., Loza, C. L., Schilling, K. A., Coggon, M. M., Chhabra, P. S., Chan, M. N., Chan, A. W. H., Hersey, S. P., Crounse, J. D., Wennberg, P. O., Flagan, R. C., and Seinfeld, J. H.: Secondary organic aerosol formation from biomass burning intermediates: phenol and methoxyphenols, Atmospheric Chemistry and Physics, 13, 8019-8043, 10.5194/acp-13-8019-2013, 2013.