

1 **Molecular fingerprints and health risks of home-use incense burning**

2 **smoke**

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28 **Abstract:** The burning of incense for home use is a widespread practice that has been shown to have
29 significant negative impacts on human health and air quality. However, there is a lack of
30 understanding regarding its emission profiles and associated health risks. To address this knowledge
31 gap, we utilized a state-of-the-art thermal desorption comprehensive two-dimensional gas
32 chromatography-mass spectrometer (TD-GC×GC-MS) to (semi-)quantify the emission factors (EFs)
33 of 317 volatile compounds and thoroughly investigate the organic profiles of incense burning smoke
34 across a full-volatility range. Results showed that toluene ($70.8 \pm 35.7 \mu\text{g g}^{-1}$) is the most abundant
35 compound in incensing-burning smoke, followed by benzene, furfural, and phenol. Phenol, toluene,
36 furfural, 2-furanmethanol, benzene, and benzyl alcohol are the main contributors to ozone and
37 secondary organic aerosol (SOA) estimation. Intermediate volatility organic compounds (IVOCs)
38 accounted for 19.2% of the total EFs, but 40.0% of the estimated SOA. Additionally, a novel
39 pixel-based method, combined with aroma analysis, revealed that furfural can act as a key tracer of
40 incense burning, and is responsible for the distinctive flavor of incense smoke. High bioaccumulation
41 potential (BAP) assessment using pixel-based partition coefficient estimation revealed that
42 acenaphthylene, dibenzofuran, and phthalate esters (PAEs) are chemicals of high-risk concern and
43 warrant further control. Our results highlight the critical importance of investigating home-use
44 incense burning and provide new insights into the health impacts of incense burning smoke by novel
45 approaches.

46

47 **1 Introduction**

48 Incense burning is a prevalent custom in many cultures, especially in East and Southeast Asia
49 (Chen et al., 2021). In modern times, incense burning for fragrance has become a frequent practice in
50 households (Manoukian et al., 2013), while functional incense burning, such as mosquito coils, is
51 used for specific purposes. Exposure to incense smoke is linked to adverse health effects like eye
52 irritation, carcinogenicity, genotoxicity, and respiratory system damage (Wong et al., 2020; Yang et
53 al., 2007, 2017). Incense is composed of fragrant materials, aromatic woods, herbs, and adhesive
54 powders, usually available in the form of sticks and coils (Wong et al., 2020; Yadav et al., 2022).
55 Incense burning releases multiple pollutants into the air, including particulate matter (PM), carbon
56 monoxide (CO), volatile organic compounds (VOCs), and intermediate volatility/semi-volatile
57 organic compounds (I/SVOCs) (Wong et al., 2020; Yang et al., 2007; Jetter et al., 2002).

58 Current studies mainly focus on the hazardous VOC and SVOC homologs released from
59 incense-burning smoke. For instance, Lee et al. investigated 8 carbonyls and 11 VOCs emitted from
60 incense burning and found that the emission factors (EFs) of traditional incense burning were higher
61 than aromatic incense (Lee and Wang, 2004). Lu et al. detected 230 kinds of VOCs from
62 mosquito-repellent incense burning, elucidating that alkanes, esters, aldehydes, ketones, and
63 aromatics are predominant (Lu et al., 2020). Staub et al. measured 6 methoxy phenolics, 10
64 monoterpenoids, and other 21 kinds of SVOCs in the burning smoke of incense sticks, and identified
65 cedrol as an important odor source (Staub et al., 2011). However, most of the studies have focused on
66 VOC compounds, with less attention given to gaseous organics in the full volatility range
67 (VOC-IVOC-SVOCs). A full-volatility organic characterization may better evaluate the ozone
68 formation potential (OFP) and SOA formation, as I/SVOCs are potentially important precursors of
69 ozone and secondary organic aerosol (SOA) formation (Zhao et al., 2007; Tang et al., 2021; Guo et
70 al., 2014, 2020). Meanwhile, mapping organics from incense smoke helps to evaluate the potential
71 health risks of toxic compounds.

72 Comprehensive two-dimensional gas chromatography (GC×GC) is a powerful technique dealing
73 with the coelution problem in conventional one-dimensional gas chromatography (1D GC).
74 Pollutants from gasoline exhaust, diesel exhaust, and cooking emissions are well separated and

75 identified (Drozd et al., 2019; Alam et al., 2018; Song et al., 2022a). As much as 50 ~ 98% of the
76 total response in GC×GC chromatograms could be explained (Huo et al., 2021; Song et al., 2022b).
77 Previous work identified 324 compounds from incense smoke by coupling solid-phase
78 microextraction (SPME) with GC×GC, yet chemicals are not quantified (Tran and Marriott, 2007).
79 Thus, a non-targeted and quantitative assessment of incense burning emissions is currently lacking.

80 In this work, two types of incense sticks and three kinds of incense coils were burned in a steel
81 chamber. Gaseous pollutants were trapped by Tenax TA desorption tubes and then analyzed by a
82 thermal desorption comprehensive two-dimensional gas chromatography-mass spectrometer
83 (TD-GC×GC-MS). Pixel-based multiway principal component analysis (MPCA) was utilized to
84 identify markers of incense burning. Risk assessment of pollutants from incense burning emissions
85 was then evaluated by pixel-based approaches and high-risk compounds related to incense burning
86 were assessed.

87 **2 Methodology**

88 **2.1 Sampling and instrumentation**

89 Incenses were purchased from the market, including 4 common incense sticks, 2 Thailand
90 incense sticks, 1 mosquito coil, and 2 incense coils (Figure S1). Incenses could also be classified by
91 their material, containing 2 aromatic coils, 4 aromatic sticks, 1 mosquito coil, 1 sandalwood stick,
92 and 1 smokeless sandalwood stick (Figure S1). Incenses were burned in a stainless combustion
93 chamber (1 m³). After ignition, the burning incense changed from flaming to smoldering. Each kind
94 of incense was burned at least twice. Incenses were weighed before and after combustion.
95 Preconditioned Tenax TA desorption tubes (Gerstel 6 mm 97 OD, 4.5 mm ID glass tube) were
96 utilized to trap organics with a sampling flow of 0.2 L min⁻¹.

97 A comprehensive two-dimensional gas chromatography-quadrupole mass spectrometer
98 (GC×GC-qMS, GC-MS TQ8050, Shimadzu, Japan) coupled with a thermal desorption system (TDS
99 3 C506, Gerstel, Germany) was used for sample analysis. The desorption temperature was 280 °C.
100 The cooled injection system (CIS) with a Tenax TA liner was held at 20 °C and ramped to 320 °C
101 once injecting the gaseous sample into GC columns. The column combination was SH-Rxi-1ms (1st,
102 30 m × 0.25 mm × 0.25 μm) and BPX50 (2nd, 2.5 m × 0.1 mm × 0.1 μm). The modulation period was

103 6s. See Table S1 and elsewhere (Song et al., 2022a) for more information.

104 **2.2 Chemical identification, quantification, and 2D binning**

105 A series of standard mixtures ($2 \mu\text{g mL}^{-1}$, $5 \mu\text{g mL}^{-1}$, $10 \mu\text{g mL}^{-1}$, $20 \mu\text{g mL}^{-1}$, $40 \mu\text{g mL}^{-1}$ in
106 CH_2Cl_2) was injected into Tenax TA tubes ($2 \mu\text{L}$). After purging the solvent with nitrogen gas, the
107 standards were thermally desorbed. The standard mixture contains 26 *n*-alkanes (C7 - C32, CNW
108 Technologies, ANPEL Laboratory Technologies (Shanghai) Inc., China), 16 PAHs, 11 phenolic
109 compounds, 9 alcohols, 4 aldehydes, 8 aromatics, 24 esters, 7 ketones, 5 siloxanes, and 39 other
110 compounds. Gaseous organics are quantified by external calibration curves with most of the R^2
111 between 0.95 and 0.999 (Table S2). Chemicals with the same retention times and mass spectrums
112 were directly qualified and quantified. The unidentified chemicals were qualified by matching their
113 mass spectrum with library spectrums in the National Institute of Standard Technology library (NIST
114 17). Reverse factors of more than 700 were acceptable in this work. As homologs on the
115 two-dimensional chromatogram (contour plot) were eluted with near-equal one-dimensional intervals,
116 chemicals were then qualified by combing the location of the contour plot and the mass spectrums
117 (Song et al., 2023). Compounds without standards were semi-quantified by *n*-alkanes from the same
118 volatility bin (uncertainty 69%) and surrogates from the same chemical class (uncertainty 27%).
119 Instrument detection limits (IDLs) for organics semi-quantified were unknown, as a result, chemicals
120 with negative values calculated by calibration curves were quantified by the volume-to-mass (ng)
121 ratio of the lowest quantification point of standards (Table S2). A total of 317 chemicals were
122 (semi)-quantified, including 10 acids, 34 alcohols, 19 aldehydes, 25 aromatics, 38 esters, 49 ketones,
123 18 *n*-alkanes, 26 nitrogen-containing compounds, and 10 phenols (Table S3).

124 The compounds identified were sliced into two-dimensional bins (2D bins) (Song et al., 2022a).
125 1st retention times are linked to the volatility of species (B8 to B31 with decreasing volatility) while
126 2nd retention times are associated with polarity (P1 to P8 with increasing polarity). Emission factors
127 of compounds in the same 2D bin were aggregated (Table S3).

128 **2.3 Emission factor (EF), ozone formation potential (OFP), and secondary organic aerosol** 129 **(SOA) estimation**

130 The emission factor (EF, $\mu\text{g g}^{-1}$) was calculated by the following equation:

131
$$EF = \frac{mV}{ftM} \quad (1)$$

132 m is the absolute mass of pollutants (μg) captured by Tenax TA tubes. V is the volume of the
 133 steel chamber (1 m^3). The sampling flow and duration of the Tenax TA tube are f ($0.0002 \text{ m}^3 \text{ min}^{-1}$)
 134 and t (min), respectively. M is the combustion mass (g) of the incense. The sampling volume of
 135 Tenax TA tubes ($0.003 \sim 0.01 \text{ m}^3$) was significantly smaller than the total volume of the steel
 136 chamber (1 m^3) and the volume change of the chamber could be neglected.

137 The ozone formation potential (OFP, $\mu\text{g g}^{-1}$) was calculated using equation (2). EF_i is the
 138 emission factor of precursor i ($\mu\text{g g}^{-1}$) with maximum incremental reactivity (MIR) of MIR_i . The
 139 OFP was calculated inside the FOQAT packages developed by Tianshu Chen
 140 (<https://github.com/tianshu129/foqat>). The MIR used in this work can be found in Table S3.

141
$$OFP = \sum[EF_i] \times MIR_i \quad (2)$$

142 Secondary organic aerosol (SOA) was estimated by equation (3).

143
$$SOA = \sum[EF_i] \times (1 - e^{-k_{OH,i} \times [OH] \times \Delta t}) \times Y_i \quad (3)$$

144 Where $k_{OH,i}$ and Y_i represent the OH reaction rate and SOA yield of precursor i , respectively
 145 (Table S3). The SOA yields of precursors were from literature (Loza et al., 2014; Harvey and
 146 Petrucci, 2015; Tkacik et al., 2012; Shah et al., 2020; McDonald et al., 2018; Chan et al., 2010, 2009;
 147 Wu et al., 2017; Li et al., 2016; Matsunaga et al., 2009; Algrim and Ziemann, 2019, 2016; Liu et al.,
 148 2018; Charan et al., 2020) or surrogates from n -alkanes in the same volatility bins (Zhao et al., 2017).
 149 k_{OH} and Y could be found in Table S3. $[OH] \times \Delta t$ is the OH exposure and was set to be 13×10^{10}
 150 molecules cm^{-3}s (24 hours in OH concentration of 1.5×10^6 molecules cm^{-3}).

151 2.4 Pixel-based risk assessments of incense-burning pollutants

152 Octanol-air partition coefficient (K_{o-a}), air-water partition coefficient (K_{a-w}), and octanol-water
 153 partition coefficient (K_{o-w}) were estimated by a linear free-energy relationship (LFER) model (Nabi
 154 et al., 2014; Zushi et al., 2019). Partition coefficients of chemicals are associated with their
 155 two-dimensional retention times (Song et al., 2022b). Chemicals with high bioaccumulation potential
 156 (BAP) are defined as contaminants with partition coefficients of ($2 < \log K_{o-w} < 11$) and ($6 < \log K_{o-a}$
 157 < 12). See Zushi et al. (Zushi et al., 2019) for more information. The R source code was obtained
 158 from GitHub (<https://github.com/Yasuyuki-Zushi>).

159 3 Results and discussions

160 3.1 Emission profiles of different incense-burning organics

161 Figure S2 is a typical chromatogram of incense burning emissions, which is also set as the
162 reference chromatogram during the pixel-based analysis. As much as 90.2% of the total percent
163 response could be explained. The ratio is similar to a recent study resolving biomass burning
164 emissions (98%) (Huo et al., 2021). The emission factor (EF) of total organics is $791.8 \pm 300.6 \mu\text{g g}^{-1}$,
165 consistent with previous work ($100 \sim 19100 \mu\text{g g}^{-1}$) (Lee and Wang, 2004), and comparable to rice
166 ($475.9 \pm 61.2 \mu\text{g g}^{-1}$), pine ($558.6 \pm 103.6 \mu\text{g g}^{-1}$) and poplar ($564.6 \pm 124.1 \mu\text{g g}^{-1}$) combustions
167 (Zhu et al., 2022), but much lower than coal combustion (6.3 mg g^{-1}) (Huo et al., 2021). The
168 contributions of different chemical categories are displayed in Figure S3. Oxygenated compounds
169 dominate the total EFs, accounting for 48.4%, followed by aromatics (29.8%), *b*-alkanes (5.3%),
170 nitrogen-containing compounds (4.0%), alkenes (4.0%), and *n*-alkanes (2.3%). Unresolved complex
171 mixtures (UCMs) are further separated into aliphatic, cyclic, and oxygenated UCM due to retention
172 times and mass spectrums. The UCM ratio in this work (2.3% in EFs) is comparable to biomass
173 burning (Huo et al., 2021) and diesel exhaust (He et al., 2022) analyzed by GC×GC-MS, and is much
174 smaller than the UCM ratio (>50%) in biomass burning smoke analyzed by 1D GC-MS (Zhu et al.,
175 2022). Ketones are the most abundant oxygenated compounds, accounting for 13.6% of the total EFs,
176 followed by aldehydes (9.7%), esters (8.1%), alcohols (6.9%), phenols (3.6%), and acids (3.1%). The
177 emission profiles are comparable to corncob and wood combustion, which are also dominated by
178 ketones and esters (Huo et al., 2021). However, the abundance of phenol is much lower than in
179 biomass-burning smoke (>15%) (Zhu et al., 2022; Huo et al., 2021), while comparable to coal
180 combustion (5.4%) (Huo et al., 2021).

181 EFs of selected compounds are listed in Table S4, which were comparable with other incense
182 burning studies (Lee and Wang, 2004; Yang et al., 2007; Manoukian et al., 2016), while the EF of
183 benzene ($59.6 \pm 43.1 \mu\text{g g}^{-1}$) is slightly lower than other studies ($188 \sim 1826 \mu\text{g g}^{-1}$) (Lee and Wang,
184 2004; Yang et al., 2007; Manoukian et al., 2016). The Tenax TA liner in the CIS system does not
185 capture benzene at an initial temperature of 20 °C, while it is efficient for the trapping of most
186 I/SVOC compounds. Lower CIS temperature may trap benzene while causing water condensation.

187 As a result, the tailing of benzene on the second column (Figure S2) causes an underestimation of
188 blob integration and results in an underestimation of EF.

189 The top 10 compounds are all VOC compounds (Figure S4), accounting for 35.3% of the total
190 EFs. Toluene ($70.8 \pm 35.7 \mu\text{g g}^{-1}$) is the most abundant compound in incensing-burning smoke,
191 followed by benzene, furfural, phenol, styrene, 2-oxo-propanoic acid methyl ester,
192 3-methyl-2-butanone, ethylbenzene, 1-hydroxy-2-propanone, and benzyl alcohol. Note that VOC
193 compounds discussed here are part of volatile organics captured by Tenax-TA, not the common
194 VOCs detected by SUMMA-GC-MS. The top 5 IVOCs are B17 *b*-alkanes, B16 *b*-alkanes, B18
195 *b*-alkanes, diethyl phthalate, and 1,6-dioxacyclododecane-7,12-dione. The naphthalene (a typical
196 PAH, 2 rings) EF is $3.0 \pm 1.5 \mu\text{g g}^{-1}$, comparable to rice straw combustion (Zhu et al., 2022). SVOCs
197 are all *n*-alkane species and only account for less than 1% of the total EFs.

198 The average VBS distribution of incense burning is displayed in Figure 1, and the
199 volatility-polarity distribution is exhibited in Figure S5. In general, the EF decreases as the volatility
200 decreases, following the trend of VOC-EF (80.8%) > IVOC-EF(19.2%) >> SVOC-EF (<0.1%). The
201 chemical compositions in the VOC-IVOC range are shown in Figure S6. Oxygenated compounds
202 (53.5% of the total VOC EFs) and aromatics (37.6%) are largely detected in the VOC range, while
203 *b*-alkanes, *n*-alkanes, and oxygenated compounds are the main components of IVOC compounds.
204 The average VBS distribution is similar to cooking emissions (Song et al., 2022a) and wood
205 combustion (Stewart et al., 2021), but less volatile than gasoline exhausts (Lu et al., 2018) and more
206 volatile than diesel emissions (Lu et al., 2018). For example, the proportion of chemicals with
207 saturated vapor concentration (C^*) more than $10^6 \mu\text{g m}^{-3}$ (Figure 1 a) is 80.8% (incense burning),
208 80.7% (cooking emissions) (Song et al., 2022a), 77.6% (wood combustion) (Stewart et al., 2021),
209 94.2% (gasoline exhaust) (Lu et al., 2018), and 41.0% (diesel exhaust) (Lu et al., 2018). The polarity
210 of incense burning is dominated by non-polar and intermediate-polarity organics (P1 ~ P5, Figure
211 S5). The volatility-polarity distribution of incense burning is quite similar to cooking emissions
212 (Song et al., 2022a), dominant by VOCs in the volatility range of before B13 and the polarity range
213 of P1 ~ P5.

214 A similar emission pattern but different EFs of different incense-burning emissions are observed.

215 Similarities among incense burning are more dominant than diversities. First, pixel-based partial
216 least squares-discriminant analysis (PLS-DA) elucidates that there is no systemic difference between
217 different chromatograms of incense burning emission, no matter different incense shapes (Figure S7)
218 or materials (Figure S8). Second, the compositions of different types of incense emissions are indeed
219 quite similar (Figure S9 and Figure S10). Third, the multiway principal component analysis (MPCA)
220 positive loadings are much larger than negative loadings, indicating that the similarities between
221 samples are much more important than the differences (Figure 2).

222 However, the absolute EFs significantly diverge according to different incense forms ($p = 0.03$,
223 Figure S11) and different materials ($p < 0.01$, Figure S12). Incense made in stick form (incense stick:
224 $893.2 \pm 335.6 \mu\text{g g}^{-1}$, Thailand incense stick: $877.5 \pm 123.8 \mu\text{g g}^{-1}$) emits more organics than made in
225 coil form (incense coil: $835.5 \pm 306.0 \mu\text{g g}^{-1}$). The EF of mosquito coil is the smallest (382.5 ± 175.0
226 $\mu\text{g g}^{-1}$). A similar pattern was observed in previous work (Jetter et al., 2002). Concerning the incense
227 materials, we spot that the so-called smokeless sandalwood stick emits more abundant organics
228 ($1195.8 \pm 83.3 \mu\text{g g}^{-1}$) than common sandalwood sticks ($633.7 \pm 6.6 \mu\text{g g}^{-1}$). The emission of
229 smokeless sandalwood sticks is even greater than aromatic sticks ($893.2 \pm 335.6 \mu\text{g g}^{-1}$) and coils
230 ($824.8 \pm 228.5 \mu\text{g g}^{-1}$). Our results demonstrate that although smokeless sandalwood stick is
231 preferred as fewer particulates are generated during the combustion process, the gaseous emissions
232 are enhanced compared to other incenses.

233 **3.2 Contributions of home-use incense burning to ozone and secondary organic aerosols** 234 **(SOA)**

235 The total OFP is $1513.4 \pm 551.0 \mu\text{g g}^{-1}$ which is $1.91 \text{ g O}_3/\text{g VOC-IVOCs}$. The OFP
236 enhancement ratio (OFP per mass of precursor) is much smaller than gasoline exhaust ($3.53 \text{ g O}_3/\text{g}$
237 VOCs) (Wang et al., 2013) and evaporation ($2.3 \sim 4.9 \text{ g O}_3/\text{g VOC}$) (Yue et al., 2017), showing that
238 incense burning is less efficient on ozone formation than gasoline-related sources. The lack of IVOC
239 measurements in previous work could also cause an overestimation of the OFP enhancement ratio as
240 IVOCs are less efficient in ozone formation. Toluene, furfural, *p*-xylene, benzyl alcohol, phenol,
241 2-furanmethanol, *o*-xylene, ethylbenzene, 1-hydroxy-2-propanone, and benzene are top 10 species
242 that contribute most to OFP (Figure S4). Oxygenated compounds take up 48.2% of the total OFP,

243 followed by aromatics (41.0%), and alkenes (6.7%) (Figure S3). VOCs dominate the total OFP,
244 accounting for 92.4% while IVOCs take up 7.6% (Figure 1). Aromandendrene, naphthalene, and
245 α -cedrene are the top 3 IVOC-OFP contributors. The volatility distribution of OFP contribution is
246 comparable to cooking emissions, as VOCs account for 88.8 ~ 99.9% of the total cooking OFP
247 estimation (Song et al., 2022a). Toluene contributes the most OFP in both cooking emissions and
248 incense burning. Short-chain linear aldehydes (pentanal, hexanal, nonanal) originating from the
249 degradation of oils play a more important role in OFP contribution in cooking emissions (Song et al.,
250 2022a), while benzenes, furfural, alcohols, and phenols are non-negligible OFP contributors in
251 incense burning.

252 Figure 1 shows the volatility distribution of estimated SOA estimation, with the top 10
253 contributors displayed in Figure S4. IVOCs contribute 19.2% of the EFs while accounting for 40.0%
254 of the total SOA estimation, highlighting the importance of IVOCs in SOA formation. The
255 contribution of IVOC species to SOA is higher than EFs due to the relatively higher yields and k_{OH} ,
256 which has already been reported in cooking emissions (Song et al., 2022a; Yu et al., 2022), gasoline
257 exhaust (Zhao et al., 2014), diesel exhaust (Zhao et al., 2015), and biomass burning (Stewart et al.,
258 2021). Oxygenated compounds account for 32.9% of the SOA estimation, followed by aromatics
259 (23.7%), and *b*-alkanes (11.5%) (Figure S3). Phenol, benzyl alcohol, styrene, toluene, B18 cyclic
260 UCM, aromandendrene, 2-furanmethanol, B17 *b*-alkanes, benzene, and phenylethyne are the top 10
261 SOA contributors. The incense-burning SOA formation profiles are distinct from cooking emissions
262 (Song et al., 2022a) and biomass burning (Huo et al., 2021). Cooking SOA is largely derived from
263 the oxidation of short-chain acids and aromatics (Song et al., 2022a), while phenols account for more
264 than 65% of the SOA estimation from biomass burning (Huo et al., 2021). Phenols only account for
265 11.0% of SOA estimation in this work. Alcohols (7.3%) and furans (7.6%) are much more important
266 SOA precursors in incense burning compared to biomass burning and cooking emissions. Compared
267 with other sources, we stress the importance of incense-burning benzenes, furfural, alcohols, and
268 phenols in OFP formation and alcohols and furans in SOA formation. The secondary formation
269 potential of mosquito coils is the lowest, while OFP and SOA of burning smokeless sandalwood
270 sticks are the highest. Compared to other incense, the higher aromatic contents of smokeless

271 sandalwood sticks burning fumes result in much more ozone and SOA formation.

272 **3.3 Identification of molecular markers from incense burning**

273 Pixel-based MPCA is utilized to identify tracers of incense burning emissions. In brief, MPCA
274 decomposes a matrix X into a scoring matrix (S) and a loading matrix (L). Similarities and
275 differences in chromatograms are revealed by positive and negative loadings, respectively (Figure 2)
276 (Song et al., 2022b). The similarities of chromatograms could be explained by benzenes (toluene,
277 *p*-xylene, *o*-xylene, and ethylbenzene), ketones (3-methyl-2-cyclopenten-1-one,
278 2-hydroxy-2-cyclopenten-1-one, 3-ethyl-2-pentanone), aldehydes (furfural, succindialdehyde,
279 2-methyl-2-butenal), 2-methyl-propanoic acid, 1-methyl-1H-pyrazole, 2(5H)-furanone, and
280 2-furanmethanol. The differences between samples could be largely explained by 2-methyl-2-butenal,
281 2(5H)-furanone, 3,4-dimethylfuran, 2,3-dihydro-1H-inden-1-one, 2-methoxy-naphthalene, and
282 1,2-dihydro-2,2,4-trimethyl-quinoline. The negative loadings (0.006) are significantly smaller than
283 the positive loadings (0.07), confirming the dominance of similarities among chromatograms. The
284 relationship between the EFs of these compounds among different incense types is displayed in
285 Figure S13. Although the total EFs are significantly different ($p = 0.03$), the EFs of selected
286 compounds (2-hydroxy-2-cyclopenten-1-one, 2-furanmethanol, 3-ethyl-2-pentanone, and furfural are
287 significantly no different ($p > 0.08$). As a result, we recommend these compounds as incense-burning
288 tracers. It is reported that furfural is formed during the thermal degradation of hemicelluloses (Uhde
289 and Salthammer, 2007), while the oxidation of furfural under harsher conditions forms
290 2(5H)-furanone (Depoorter et al., 2021). The formation mechanism of furfural from xylose and
291 D-xylopyranose is displayed in Figure S14 (Ahmad et al., 1995; Bonner and Roth1, 1959; Nimlos et
292 al., 2006). The initiation of the degradation of five-carbon sugars is from the acyclic form of pentoses
293 or directly via a 2,3-(α,β)-unsaturated aldehyde. The dehydrating of the intermediate compounds
294 finally forms furfural (Figure S14). The addressed tracers, furfural, 2-furanmethanol, and
295 2(5H)-furanone, have already been identified in incense burning smoke in previous work (Depoorter
296 et al., 2021; Tran and Marriott, 2007).

297 Furthermore, we compare the chemical profiles with an odor database (Aroma Office 2D,
298 Gerstel). Among the top 20 chemicals contributing to EFs, furfural (bread-like, alcoholic,

299 incense-like), phenol (mushroom, acid, burnt plastics), 1-hydroxy-2-propanone (buttery, caramellic,
300 fruity), benzyl alcohol (burning taste, flower, roasted), limonene (citrus-like, fruity, lemon-like), and
301 2-methyl-propanoic acid (apple-like, cheese-like, sweat) could be the aroma compounds. As for
302 tracers identified above, 2-furanmethanol (burnt sugar, honey, sweet) could also be another aroma
303 compound. Among them, furfural is widely and largely detected which could be the most important
304 molecular marker of incense burning (Silva et al., 2021; Ho and Yu, 2002). Note that
305 aromandendrene, a cucumber-like, woody, and floral compound, is only detected in one incense coil
306 sample (incense coil 2, Figure S1). Aromandendrene is also detected in plants, such as in dry flowers
307 of *Lonicera japonica* (Shang et al., 2011). The emission factor of aromandendrene is rather large (4.3
308 $\mu\text{g g}^{-1}$, 0.7% of the total EFs), and is a significant SOA precursor (2.3 $\mu\text{g g}^{-1}$, 3.9% of the total SOA
309 estimation). The importance of aromandendrene on incense flavor and SOA formation could not be
310 neglected. Aromandendrene could also be responsible for the distinct flavor of a certain incense coil.
311 As above said, we recommend furfural be used as a molecular indicator of incense burning
312 regardless of the incense type or additives, especially responsible for the flavor of incense burning.

313 **3.4 Risk assessment of incense burning organics**

314 The hazardous compounds from incense burning could cause adverse health effects on human
315 health (Wong et al., 2020; Yang et al., 2007; Chen et al., 2021; Yang et al., 2017). To evaluate the
316 potential risks of these compounds, we conducted a pixel-based risk assessment (bioaccumulation
317 potential, BAP) for partition coefficient estimation. Chemicals with high BAP concerns are listed in
318 Figure 3. 2-methoxy-naphthalene, acenaphthylene, dibenzofuran, diethyl phthalate, dibutyl phthalate,
319 benzoic acid 2-ethylhexyl ester, C15 – C19 *n*, and *b*-alkanes are regarded as high BAP concern
320 (Figure 3). Among them, acenaphthylene is a toxic polycyclic aromatic hydrocarbon (PAH) that is
321 widely detected in incense smoke (Yadav et al., 2022). Dibenzofuran, an oxygenated compound with
322 detrimental effects on human health (Suzuki et al., 2021), is also detected in the smoke of incense
323 burning (Tran and Marriott, 2007). Diethyl phthalate and dibutyl phthalate are phthalate esters (PAEs)
324 widely used as plasticizers which are endocrine disruptors (Wang and Qian, 2021). PAEs are
325 abundant in incense smoke (Tran and Marriott, 2007). We propose that acenaphthylene, dibenzofuran,
326 and PAEs could be chemicals of high-risk concern in incense smoke. We also assess the arctic

327 contamination potential (ACP) as shown in Text S1. Further epidemiologic studies should be carried
328 on to demonstrate the health effect of these hazardous compounds.

329 **4 Implication**

330 The non-target approach of GC×GC-MS gives us a full glimpse of incense smoke, spotting a
331 large pool of organics (317 compounds) covering the VOC-IVOC-SVOC range. We have provided a
332 detailed description of both primary emission and secondary estimation of incense burning organics
333 which is ready-to-use in SOA simulation models. IVOCs (130 compounds) are crucial organics
334 accounting for 19.2% of the total EFs and 40.0% of the SOA estimation, highlighting the importance
335 of incorporating IVOCs into SOA models. Further investigation should be carried on to elucidate
336 emission characteristics of short-chain compounds that are lacking in our research, such as alkanes
337 (<C7), alkenes (<C7), and aldehydes (<C5). By combining data obtained from
338 gas-chromatography-flame ionization detector (GC-FID) and proton transfer mass spectrometer
339 (PTR-MS), the emission pattern of incense burning could be well demonstrated. Comparisons of
340 IVOC capture efficiency on different sampling materials should also be taken into account to obtain
341 a reliable quantification result of IVOC species. High-time resolution measurement should also be
342 carried on to understand the time-resolved pattern of incense burning.

343 We also suggest furfural as the molecular marker of incense burning as the EFs of furfural
344 among samples are relatively stable. Pixel-based MPCA also indicates that furfural is responsible for
345 the similarities between chromatograms. Furfural may be the key aroma compound of incense smoke.
346 This key component identified in this work could be implemented in source apportionment. Furfural
347 is also a key component contributing to OFP (rank 2). Phenol, toluene, 2-furanmethanol, benzene,
348 and benzyl alcohol are the main contributors to both OFP and SOA.

349 Surprisingly, we find that the EF of burning smokeless sandalwood sticks is the highest, with a
350 remarkable contribution to OFP and SOA, due to the high aromatic contents. We recommend that
351 both gaseous and particulate organics should also be taken into consideration when burning incense.
352 The single reduction of particles does not mean fewer emissions of gas-phase organics. A
353 comprehensive assessment of incense-burning organics in both gas- and particle-phase should be
354 implemented.

355 Combing pixel-based property estimation and blob identification, the risk assessment analysis of
356 compounds could benefit analysts with less experience with GC×GC. The risk assessment in this
357 work demonstrates that acenaphthylene, dibenzofuran, and PAEs are chemicals of high-risk concern
358 and warrant further control. It was reported that more than half of Chinese residents burn incense
359 every day at home for more than 20 years (Salvi and Apte, 2016). The toxic PAHs detected in indoor
360 air could be 19 times higher than in outdoor air (Salvi and Apte, 2016). Exposure to these hazardous
361 compounds could result in significant health threats. As a result, it is of vital importance to reveal
362 and assess the epidemiological influences of incense burning in future work.

363

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370 **Reference**

- 371 Ahmad, T., Kenne, L., Olsson, K., and Theander, O.: The formation of 2-furaldehyde and formic acid
372 from pentoses in slightly acidic deuterium oxide studied by ¹H NMR spectroscopy, *Carbohydr Res*,
373 276, 309–320, [https://doi.org/10.1016/0008-6215\(95\)00176-T](https://doi.org/10.1016/0008-6215(95)00176-T), 1995.
- 374 Alam, M. S., Zeraati-Rezaei, S., Liang, Z., Stark, C., Xu, H., MacKenzie, A. R., and Harrison, R. M.:
375 Mapping and quantifying isomer sets of hydrocarbons ($\geq C_{12}$) in diesel exhaust, lubricating oil and
376 diesel fuel samples using GC \times GC-ToF-MS, *Atmos Meas Tech*, 11, 3047–3058,
377 <https://doi.org/10.5194/amt-11-3047-2018>, 2018.
- 378 Algrim, L. B. and Ziemann, P. J.: Effect of the Keto Group on Yields and Composition of Organic
379 Aerosol Formed from OH Radical-Initiated Reactions of Ketones in the Presence of NO_x, *Journal of*
380 *Physical Chemistry A*, 120, 6978–6989, <https://doi.org/10.1021/acs.jpca.6b05839>, 2016.
- 381 Algrim, L. B. and Ziemann, P. J.: Effect of the Hydroxyl Group on Yields and Composition of Organic
382 Aerosol Formed from OH Radical-Initiated Reactions of Alcohols in the Presence of NO_x, *ACS Earth*
383 *Space Chem*, 3, 413–423, <https://doi.org/10.1021/acsearthspacechem.9b00015>, 2019.
- 384 Bonner, W. A. and Roth1, M. R.: The Conversion of d-Xylose-1-C₁₄ into 2-Furaldehyde- α -C₁₄, *J Am*
385 *Chem Soc*, 81, 5454–5456, <https://doi.org/10.1021/ja01529a051>, 1959.
- 386 Chan, A. W. H., Kautzman, K. E., Chhabra, P. S., Surratt, J. D., Chan, M. N., Crouse, J. D., Kürten, A.,
387 Wennberg, P. O., Flagan, R. C., and Seinfeld, J. H.: Secondary organic aerosol formation from
388 photooxidation of naphthalene and alkylnaphthalenes: Implications for oxidation of intermediate
389 volatility organic compounds (IVOCs), *Atmos Chem Phys*, 9, 3049–3060,
390 <https://doi.org/10.5194/acp-9-3049-2009>, 2009.
- 391 Chan, A. W. H., Chan, M. N., Surratt, J. D., Chhabra, P. S., Loza, C. L., Crouse, J. D., Yee, L. D.,
392 Flagan, R. C., Wennberg, P. O., and Seinfeld, J. H.: Role of aldehyde chemistry and NO_x
393 concentrations in secondary organic aerosol formation, *Atmos Chem Phys*, 10, 7169–7188,
394 <https://doi.org/10.5194/ACP-10-7169-2010>, 2010.
- 395 Charan, S. M., Buenconsejo, R. S., and Seinfeld, J. H.: Secondary organic aerosol yields from the
396 oxidation of benzyl alcohol, *Atmos Chem Phys*, 20, 13167–13190,
397 <https://doi.org/10.5194/acp-20-13167-2020>, 2020.

398 Chen, K. S. F., Tsai, Y. P., Lai, C. H., Xiang, Y. K., Chuang, K. Y., and Zhu, Z. H.: Human health-risk
399 assessment based on chronic exposure to the carbonyl compounds and metals emitted by burning
400 incense at temples, *Environmental Science and Pollution Research*, 28, 40640–40652,
401 <https://doi.org/10.1007/s11356-020-10313-1>, 2021.

402 Depoorter, A., Kalalian, C., Emmelin, C., Lorentz, C., and George, C.: Indoor heterogeneous
403 photochemistry of furfural drives emissions of nitrous acid, *Indoor Air*, 31, 682–692,
404 <https://doi.org/10.1111/INA.12758>, 2021.

405 Drozd, G. T., Zhao, Y., Saliba, G., Frodin, B., Maddox, C., Oliver Chang, M. C., Maldonado, H.,
406 Sardar, S., Weber, R. J., Robinson, A. L., Goldstein, A. H., Chang, M. C. O., Maldonado, H., Sardar, S.,
407 Weber, R. J., Robinson, A. L., Goldstein, A. H., Oliver Chang, M. C., Maldonado, H., Sardar, S.,
408 Weber, R. J., Robinson, A. L., and Goldstein, A. H.: Detailed Speciation of Intermediate Volatility and
409 Semivolatile Organic Compound Emissions from Gasoline Vehicles: Effects of Cold-Starts and
410 Implications for Secondary Organic Aerosol Formation, *Environ Sci Technol*, 53, 1706–1714,
411 <https://doi.org/10.1021/acs.est.8b05600>, 2019.

412 Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., Du, Z., Wu, Z., Shao, M., Zeng, L.,
413 Molina, M. J., and Zhang, R.: Elucidating severe urban haze formation in China, *Proc Natl Acad Sci U*
414 *S A*, 111, 17373–17378, <https://doi.org/10.1073/pnas.1419604111>, 2014.

415 Guo, S., Hu, M., Peng, J., Wu, Z., Zamora, M. L., Shang, D., Du, Z., Zheng, J., Fang, X., Tang, R., Wu,
416 Y., Zeng, L., Shuai, S., Zhang, W., Wang, Y., Ji, Y., Li, Y., Zhang, A. L., Wang, W., Zhang, F., Zhao, J.,
417 Gong, X., Wang, C., Molina, M. J., and Zhang, R.: Remarkable nucleation and growth of ultrafine
418 particles from vehicular exhaust, *Proc Natl Acad Sci U S A*, 117, 3427–3432,
419 <https://doi.org/10.1073/pnas.1916366117>, 2020.

420 Harvey, R. M. and Petrucci, G. A.: Control of ozonolysis kinetics and aerosol yield by nuances in the
421 molecular structure of volatile organic compounds, *Atmos Environ*, 122, 188–195,
422 <https://doi.org/10.1016/j.atmosenv.2015.09.038>, 2015.

423 He, X., Zheng, X., You, Y., Zhang, S., Zhao, B., Wang, X., Huang, G., Chen, T., Cao, Y., He, L., Chang,
424 X., Wang, S., and Wu, Y.: Comprehensive chemical characterization of gaseous I/SVOC emissions
425 from heavy-duty diesel vehicles using two-dimensional gas chromatography time-of-flight mass

426 spectrometry, *Environmental Pollution*, 305, 119284, <https://doi.org/10.1016/j.envpol.2022.119284>,
427 2022.

428 Ho, S. S. H. and Yu, J. Z.: Concentrations of formaldehyde and other carbonyls in environments
429 affected by incense burning, *Journal of Environmental Monitoring*, 4, 728–733,
430 <https://doi.org/10.1039/b200998f>, 2002.

431 Huo, Y., Guo, Z., Liu, Y., Wu, D., Ding, X., Zhao, Z., Wu, M., Wang, L., Feng, Y., Chen, Y., Wang, S.,
432 Li, Q., and Chen, J.: Addressing Unresolved Complex Mixture of I/SVOCs Emitted From Incomplete
433 Combustion of Solid Fuels by Nontarget Analysis, *Journal of Geophysical Research: Atmospheres*,
434 126, e2021JD035835, <https://doi.org/10.1029/2021JD035835>, 2021.

435 Jetter, J. J., Guo, Z., McBrian, J. A., and Flynn, M. R.: Characterization of emissions from burning
436 incense, *Science of the Total Environment*, 295, 51–67,
437 [https://doi.org/10.1016/S0048-9697\(02\)00043-8](https://doi.org/10.1016/S0048-9697(02)00043-8), 2002.

438 Lee, S. C. and Wang, B.: Characteristics of emissions of air pollutants from burning of incense in a
439 large environmental chamber, *Atmos Environ*, 38, 941–951,
440 <https://doi.org/10.1016/j.atmosenv.2003.11.002>, 2004.

441 Li, L., Tang, P., Nakao, S., and Cocker, D. R.: Impact of molecular structure on secondary organic
442 aerosol formation from aromatic hydrocarbon photooxidation under low-NO_x conditions, *Atmos*
443 *Chem Phys*, 16, 10793–10808, <https://doi.org/10.5194/acp-16-10793-2016>, 2016.

444 Liu, T., Wang, Z., Huang, D. D., Wang, X., and Chan, C. K.: Significant Production of Secondary
445 Organic Aerosol from Emissions of Heated Cooking Oils, *Environ Sci Technol Lett*, 5, 32–37,
446 <https://doi.org/10.1021/acs.estlett.7b00530>, 2018.

447 Loza, C. L., Craven, J. S., Yee, L. D., Coggon, M. M., Schwantes, R. H., Shiraiwa, M., Zhang, X.,
448 Schilling, K. A., Ng, N. L., Canagaratna, M. R., Ziemann, P. J., Flagan, R. C., and Seinfeld, J. H.:
449 Secondary organic aerosol yields of 12-carbon alkanes, *Atmos Chem Phys*, 14, 1423–1439,
450 <https://doi.org/10.5194/acp-14-1423-2014>, 2014.

451 Lu, F., Li, S., Shen, B., Zhang, J., Liu, L., Shen, X., and Zhao, R.: The emission characteristic of VOCs
452 and the toxicity of BTEX from different mosquito-repellent incenses, *J Hazard Mater*, 384, 121428,
453 <https://doi.org/10.1016/j.jhazmat.2019.121428>, 2020.

454 Lu, Q., Zhao, Y., and Robinson, A. L.: Comprehensive organic emission profiles for gasoline, diesel,
455 and gas-turbine engines including intermediate and semi-volatile organic compound emissions, *Atmos*
456 *Chem Phys*, 18, 17637–17654, <https://doi.org/10.5194/acp-18-17637-2018>, 2018.

457 Manoukian, A., Quivet, E., Temime-Roussel, B., Nicolas, M., Maupetit, F., and Wortham, H.:
458 Emission characteristics of air pollutants from incense and candle burning in indoor atmospheres,
459 *Environmental Science and Pollution Research*, 20, 4659–4670,
460 <https://doi.org/10.1007/s11356-012-1394-y>, 2013.

461 Manoukian, A., Buiron, D., Temime-Roussel, B., Wortham, H., and Quivet, E.: Measurements of
462 VOC/SVOC emission factors from burning incenses in an environmental test chamber: influence of
463 temperature, relative humidity, and air exchange rate, *Environmental Science and Pollution Research*,
464 23, 6300–6311, <https://doi.org/10.1007/s11356-015-5819-2>, 2016.

465 Matsunaga, A., Docherty, K. S., Lim, Y. B., and Ziemann, P. J.: Composition and yields of secondary
466 organic aerosol formed from OH radical-initiated reactions of linear alkenes in the presence of NO_x:
467 Modeling and measurements, *Atmos Environ*, 43, 1349–1357,
468 <https://doi.org/10.1016/j.atmosenv.2008.12.004>, 2009.

469 McDonald, B. C., De Gouw, J. A., Gilman, J. B., Jathar, S. H., Akherati, A., Cappa, C. D., Jimenez, J.
470 L., Lee-Taylor, J., Hayes, P. L., McKeen, S. A., Cui, Y. Y., Kim, S. W., Gentner, D. R.,
471 Isaacman-VanWertz, G., Goldstein, A. H., Harley, R. A., Frost, G. J., Roberts, J. M., Ryerson, T. B.,
472 and Trainer, M.: Volatile chemical products emerging as largest petrochemical source of urban organic
473 emissions, *Science (1979)*, 359, 760–764, <https://doi.org/10.1126/science.aaq0524>, 2018.

474 Nabi, D., Gros, J., Dimitriou-Christidis, P., and Arey, J. S.: Mapping environmental partitioning
475 properties of nonpolar complex mixtures by use of GC × GC, *Environ Sci Technol*, 48, 6814–6826,
476 <https://doi.org/10.1021/es501674p>, 2014.

477 Nimlos, M. R., Qian, X., Davis, M., Himmel, M. E., and Johnson, D. K.: Energetics of xylose
478 decomposition as determined using quantum mechanics modeling, *Journal of Physical Chemistry A*,
479 110, 11824–11838, <https://doi.org/10.1021/jp0626770>, 2006.

480 Salvi, S. and Apte, K.: Household air pollution and its effects on health, *F1000Res*, 5,
481 <https://doi.org/10.12688/f1000research.7552.1>, 2016.

482 Shah, R. U., Coggon, M. M., Gkatzelis, G. I., McDonald, B. C., Tasoglou, A., Huber, H., Gilman, J.,
483 Warneke, C., Robinson, A. L., and Presto, A. A.: Urban Oxidation Flow Reactor Measurements Reveal
484 Significant Secondary Organic Aerosol Contributions from Volatile Emissions of Emerging
485 Importance, *Environ Sci Technol*, 54, 714–725, <https://doi.org/10.1021/acs.est.9b06531>, 2020.

486 Shang, X., Pan, H., Li, M., Miao, X., and Ding, H.: *Lonicera japonica* Thunb.: Ethnopharmacology,
487 phytochemistry and pharmacology of an important traditional Chinese medicine,
488 <https://doi.org/10.1016/j.jep.2011.08.016>, 2011.

489 Silva, G. V., Martins, A. O., and Martins, S. D. S.: Indoor air quality: Assessment of dangerous
490 substances in incense products, *Int J Environ Res Public Health*, 18,
491 <https://doi.org/10.3390/ijerph18158086>, 2021.

492 Song, K., Guo, S., Gong, Y., Lv, D., Zhang, Y., Wan, Z., Li, T., Zhu, W., Wang, H., Yu, Y., Tan, R.,
493 Shen, R., Lu, S., Li, S., Chen, Y., and Hu, M.: Impact of cooking style and oil on semi-volatile and
494 intermediate volatility organic compound emissions from Chinese domestic cooking, *Atmos Chem*
495 *Phys*, 22, 9827–9841, <https://doi.org/10.5194/ACP-22-9827-2022>, 2022a.

496 Song, K., Gong, Y., Guo, S., Lv, D., Wang, H., Wan, Z., Yu, Y., Tang, R., Li, T., Tan, R., Zhu, W., Shen,
497 R., and Lu, S.: Investigation of partition coefficients and fingerprints of atmospheric gas- and
498 particle-phase intermediate volatility and semi-volatile organic compounds using pixel-based
499 approaches, *J Chromatogr A*, 1665, 462808, <https://doi.org/10.1016/j.chroma.2022.462808>, 2022b.

500 Song, K., Guo, S., Gong, Y., Lv, D., Wan, Z., Zhang, Y., Fu, Z., Hu, K., and Lu, S.: Non-target scanning
501 of organics from cooking emissions using comprehensive two-dimensional gas chromatography-mass
502 spectrometer (GC×GC-MS), *Applied Geochemistry*, 151,
503 <https://doi.org/10.1016/j.apgeochem.2023.105601>, 2023.

504 Staub, P. O., Schiestl, F. P., Leonti, M., and Weckerle, C. S.: Chemical analysis of incense smokes used
505 in Shaxi, Southwest China: A novel methodological approach in ethnobotany, *J Ethnopharmacol*, 138,
506 212–218, <https://doi.org/10.1016/j.jep.2011.08.078>, 2011.

507 Stewart, G. J., Nelson, B. S., Acton, W. J. F., Vaughan, A. R., Hopkins, J. R., Yunus, S. S. M., Hewitt, C.
508 N., Nemitz, E., Mandal, T. K., Gadi, R., Sahu, Lokesh. K., Rickard, A. R., Lee, J. D., and Hamilton, J.
509 F.: Comprehensive organic emission profiles, secondary organic aerosol production potential, and OH

510 reactivity of domestic fuel combustion in Delhi, India, *Environmental Science: Atmospheres*, 1, 104–
511 117, <https://doi.org/10.1039/d0ea00009d>, 2021.

512 Suzuki, S., Kiuchi, S., Kinoshita, K., Takeda, Y., Sakaida, S., Konno, M., Tanaka, K., and Oguma, M.:
513 Formation of polycyclic aromatic hydrocarbons, benzofuran, and dibenzofuran in fuel-rich oxidation
514 of toluene using a flow reactor, *Physical Chemistry Chemical Physics*, 23, 6509–6525,
515 <https://doi.org/10.1039/d0cp06615j>, 2021.

516 Tang, R., Lu, Q., Guo, S., Wang, H., Song, K., Yu, Y., Tan, R., Liu, K., Shen, R., Chen, S., Zeng, L.,
517 Jorga, S. D., Zhang, Z., Zhang, W., Shuai, S., and Robinson, A. L.: Measurement report: Distinct
518 emissions and volatility distribution of intermediate-volatility organic compounds from on-road
519 Chinese gasoline vehicles: Implication of high secondary organic aerosol formation potential, *Atmos*
520 *Chem Phys*, 21, 2569–2583, <https://doi.org/10.5194/acp-21-2569-2021>, 2021.

521 Tkacik, D. S., Presto, A. A., Donahue, N. M., and Robinson, A. L.: Secondary organic aerosol
522 formation from intermediate-volatility organic compounds: Cyclic, linear, and branched alkanes,
523 *Environ Sci Technol*, 46, 8773–8781, <https://doi.org/10.1021/es301112c>, 2012.

524 Tran, T. C. and Marriott, P. J.: Characterization of incense smoke by solid phase
525 microextraction-Comprehensive two-dimensional gas chromatography (GC×GC), *Atmos Environ*, 41,
526 5756–5768, <https://doi.org/10.1016/j.atmosenv.2007.02.030>, 2007.

527 Uhde, E. and Salthammer, T.: Impact of reaction products from building materials and furnishings on
528 indoor air quality-A review of recent advances in indoor chemistry, *Atmos Environ*, 41, 3111–3128,
529 <https://doi.org/10.1016/j.atmosenv.2006.05.082>, 2007.

530 Wang, J., Jin, L., Gao, J., Shi, J., Zhao, Y., Liu, S., Jin, T., Bai, Z., and Wu, C. Y.: Investigation of
531 speciated VOC in gasoline vehicular exhaust under ECE and EUDC test cycles, *Science of the Total*
532 *Environment*, 445–446, 110–116, <https://doi.org/10.1016/j.scitotenv.2012.12.044>, 2013.

533 Wang, Y. and Qian, H.: Phthalates and their impacts on human health,
534 <https://doi.org/10.3390/healthcare9050603>, 2021.

535 Wong, A., Lou, W., Ho, K. fai K., Yiu, B. K. fung, Lin, S., Chu, W. C. wing, Abrigo, J., Lee, D., Lam,
536 B. Y. ka, Au, L. W. chi, Soo, Y. O. yan, Lau, A. Y. lun, Kwok, T. C. yui, Leung, T. W. hong, Lam, L. C.
537 wa, Ho, K. fai K., and Mok, V. C. tong: Indoor incense burning impacts cognitive functions and brain

538 functional connectivity in community older adults, *Sci Rep*, 10, 1–11,
539 <https://doi.org/10.1038/s41598-020-63568-6>, 2020.

540 Wu, W., Zhao, B., Wang, S., and Hao, J.: Ozone and secondary organic aerosol formation potential
541 from anthropogenic volatile organic compounds emissions in China, *J Environ Sci (China)*, 53, 224–
542 237, <https://doi.org/10.1016/j.jes.2016.03.025>, 2017.

543 Yadav, V. K., Malik, P., Tirth, V., Khan, S. H., Yadav, K. K., Islam, S., Choudhary, N., Inwati, G. K.,
544 Arabi, A., Kim, D. H., and Jeon, B. H.: Health and Environmental Risks of Incense Smoke:
545 Mechanistic Insights and Cumulative Evidence, *J Inflamm Res*, 15, 2665–2693,
546 <https://doi.org/10.2147/JIR.S347489>, 2022.

547 Yang, T. T., Lin, T. S., and Chang, M.: Characteristics of emissions of volatile organic compounds
548 from smoldering incense, *Bull Environ Contam Toxicol*, 78, 308–313,
549 <https://doi.org/10.1007/s00128-007-9184-9>, 2007.

550 Yang, T. T., Ho, S. C., Chuang, L. te, Chuang, H. C., Li, Y. T., and Wu, J. J.: Characterization of
551 particulate-phase polycyclic aromatic hydrocarbons emitted from incense burning and their
552 bioreactivity in RAW264.7 macrophage, *Environmental Pollution*, 220, 1190–1198,
553 <https://doi.org/10.1016/j.envpol.2016.11.016>, 2017.

554 Yu, Y., Guo, S., Wang, H., Shen, R., Zhu, W., Tan, R., Song, K., Zhang, Z., Li, S., Chen, Y., and Hu, M.:
555 Importance of Semivolatile/Intermediate-Volatility Organic Compounds to Secondary Organic
556 Aerosol Formation from Chinese Domestic Cooking Emissions, *Environ Sci Technol Lett*,
557 <https://doi.org/10.1021/acs.estlett.2c00207>, 2022.

558 Yue, T., Yue, X., Chai, F., Hu, J., Lai, Y., He, L., and Zhu, R.: Characteristics of volatile organic
559 compounds (VOCs) from the evaporative emissions of modern passenger cars, *Atmos Environ*, 151,
560 62–69, <https://doi.org/10.1016/j.atmosenv.2016.12.008>, 2017.

561 Zhao, Y., Hu, M., Slanina, S., and Zhang, Y.: Chemical compositions of fine particulate organic matter
562 emitted from Chinese cooking, *Environ Sci Technol*, 41, 99–105, <https://doi.org/10.1021/es0614518>,
563 2007.

564 Zhao, Y., Hennigan, C. J., May, A. A., Tkacik, D. S., de Gouw, J. A., Gilman, J. B., Kuster, W. C.,
565 Borbon, A., and Robinson, A. L.: Intermediate-volatility organic compounds: A large source of

566 secondary organic aerosol, *Environ Sci Technol*, 48, 13743–13750, <https://doi.org/10.1021/es5035188>,
567 2014.

568 Zhao, Y., Nguyen, N. T., Presto, A. A., Hennigan, C. J., May, A. A., and Robinson, A. L.: Intermediate
569 Volatility Organic Compound Emissions from On-Road Diesel Vehicles: Chemical Composition,
570 Emission Factors, and Estimated Secondary Organic Aerosol Production, *Environ Sci Technol*, 49,
571 11516–11526, <https://doi.org/10.1021/acs.est.5b02841>, 2015.

572 Zhao, Y., Saleh, R., Saliba, G., Presto, A. A., Gordon, T. D., Drozd, G. T., Goldstein, A. H., Donahue,
573 N. M., and Robinson, A. L.: Reducing secondary organic aerosol formation from gasoline vehicle
574 exhaust, *Proc Natl Acad Sci U S A*, 114, 6984–6989, <https://doi.org/10.1073/pnas.1620911114>, 2017.

575 Zhu, X., Han, Y., Feng, Y., Cheng, P., Peng, Y., Wang, J., Cai, J., and Chen, Y.: Formation and emission
576 characteristics of intermediate volatile organic compounds (IVOCs) from the combustion of biomass
577 and their cellulose, hemicellulose, and lignin, *Atmos Environ*, 286, 119217,
578 <https://doi.org/10.1016/j.atmosenv.2022.119217>, 2022.

579 Zushi, Y., Yamatori, Y., Nagata, J., and Nabi, D.: Comprehensive two-dimensional
580 gas-chromatography-based property estimation to assess the fate and behavior of complex mixtures: A
581 case study of vehicle engine oil, *Science of the Total Environment*, 669, 739–745,
582 <https://doi.org/10.1016/j.scitotenv.2019.03.157>, 2019.

583

584 **Figures**

585 **Figure 1.** Volatility distributions of EF, OFP, and SOA with chemical class in each volatility bin. The
586 *x*-axis is the unsaturated vapor concentration in logarithmic form ($\log C^*$, $\mu\text{g m}^{-3}$). The *y*-axis is the
587 normalized mass emission factor (100%).

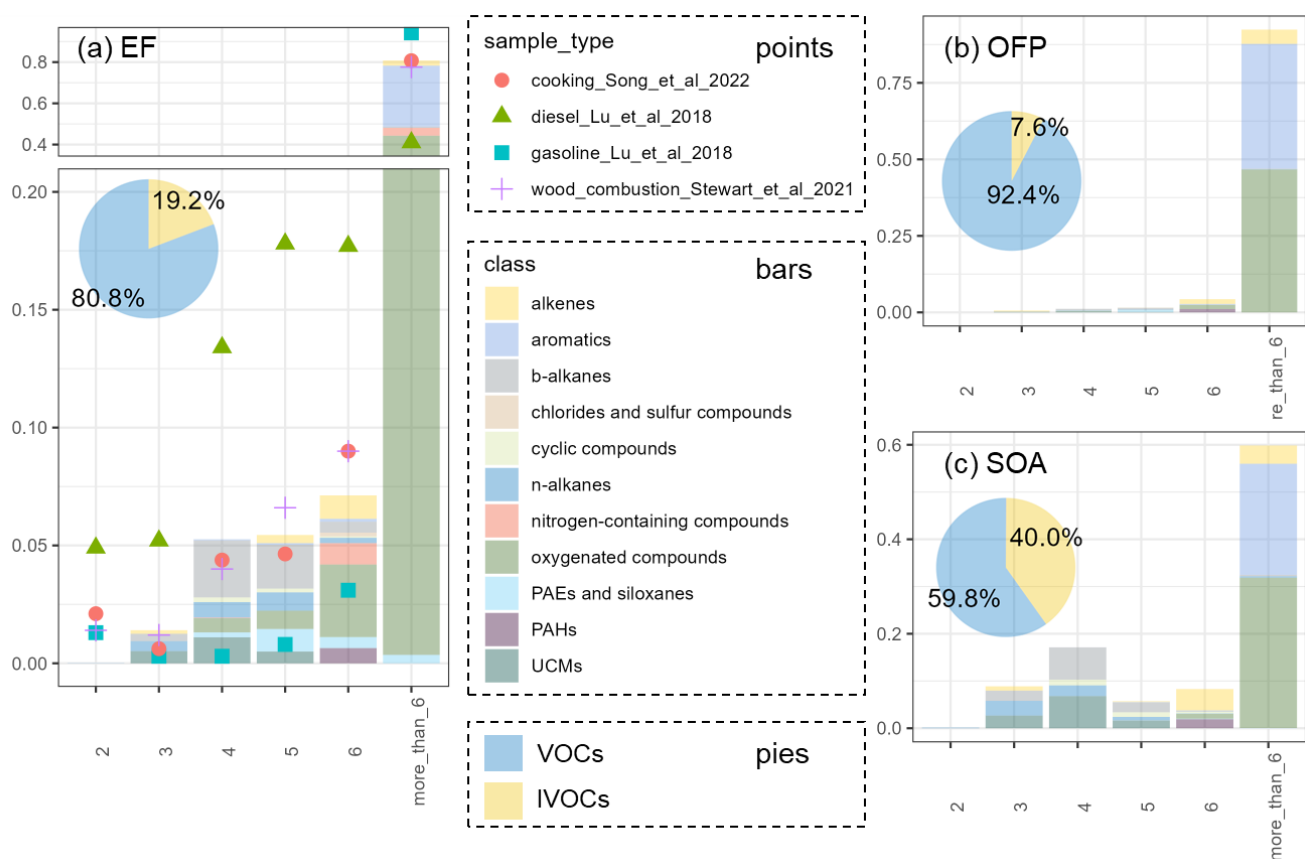
588 **Figure 2.** Positive (a) and negative loadings (b) of incense burning samples describing similarities
589 and differences between chromatograms. The color bar is the loading.

590 **Figure 3.** Chemicals with high bioaccumulation potential (BAP) assessed by pixel-based approaches.

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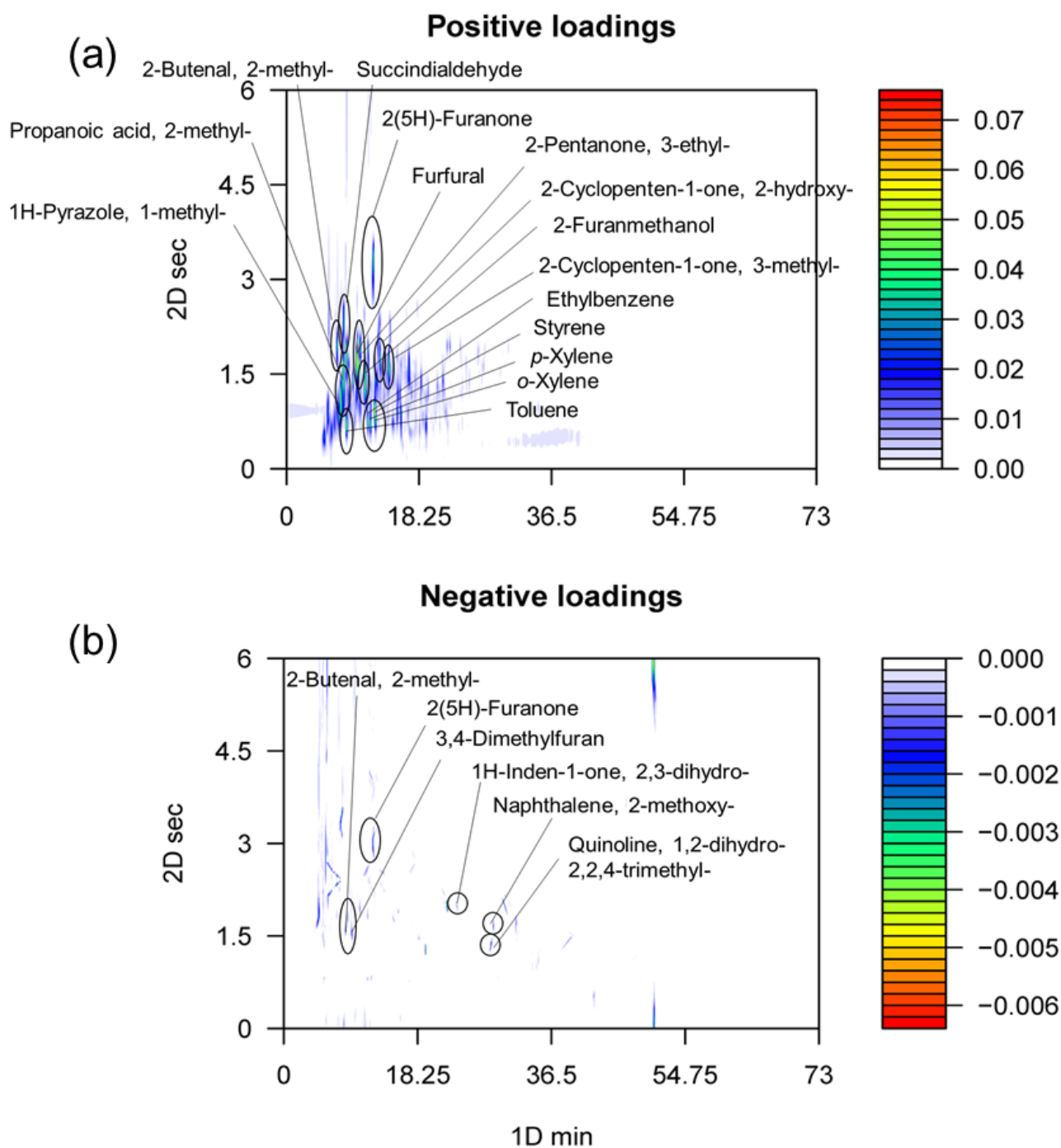
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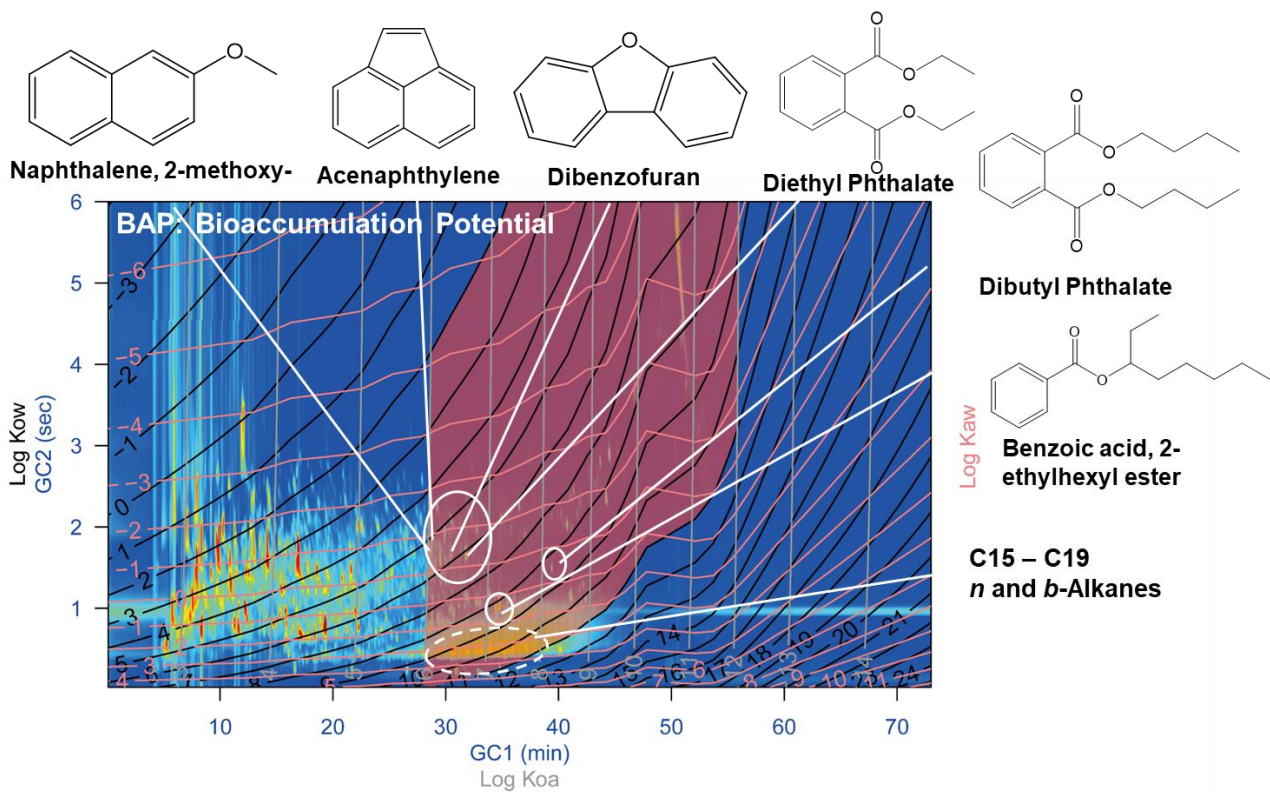
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