

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

3 Kai Song<sup>1,2,#</sup>, Rongzhi Tang<sup>3,4,#,\*</sup>, Jingshun Zhang<sup>5</sup>, Zichao Wan<sup>1</sup>, Yuan Zhang<sup>6</sup>, Kun Hu<sup>1</sup>, Yuanzheng  
4 Gong<sup>1</sup>, Daqi Lv<sup>1</sup>, Sihua Lu<sup>1</sup>, Yu Tan<sup>7</sup>, Ruifeng Zhang<sup>3,4</sup>, Ang Li<sup>8</sup>, Shuyuan Yan<sup>8</sup>, Shichao Yan<sup>8</sup>,  
5 Baoming Fan<sup>9</sup>, Wenfei Zhu<sup>10</sup>, Chak K. Chan<sup>3,4</sup>, Song Guo<sup>1,2,\*</sup>

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7 <sup>1</sup> State Key Joint Laboratory of Environmental Simulation and Pollution Control, International Joint  
8 Laboratory for Regional Pollution Control, Ministry of Education (IJRC), College of Environmental  
9 Sciences and Engineering, Peking University, *Beijing* 100871, China

10 <sup>2</sup> Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Nanjing  
11 University of Information Science & Technology, *Nanjing* 210044, China

12 <sup>3</sup> School of Energy and Environment, City University of Hong Kong, *Kowloon* 999077, Hong Kong,  
13 China

14 <sup>4</sup> Shenzhen Research Institute, City University of Hong Kong, *Shenzhen* 518057, China

15 <sup>5</sup> Shanghai Police College, *Shanghai* 200137, China

16 <sup>6</sup> School of Earth Science and Engineering, Hebei University of Engineering, *Handan* 056038, China

17 <sup>7</sup> School of Chemical Engineering and Technology, Sun-Yat-Sen University, *Zhuhai* 519000, China

18 <sup>8</sup> China Automotive Technology and Research Center (CATARC), *Beijing* 100176, China

19 <sup>9</sup> TECHSHIP (Beijing) Technology Co., LTD, *Beijing* 100039, China

20 <sup>10</sup> School of Energy and Power Engineering, University of Shanghai for Science and Technology,  
21 *Shanghai* 200093, China

22

23 # These authors contributed equally to this work.

24 \* **Correspondence:** Rongzhi Tang: rongtang@cityu.edu.hk and Song Guo: songguo@pku.edu.cn

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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 secondary organic aerosol (SOA) formation, as I/SVOCs are  
69 potentially important precursors of ozone and SOA formation (Zhao et al., 2007; Tang et al., 2021;  
70 Guo et al., 2014, 2020). Meanwhile, mapping organics from incense smoke helps to evaluate the  
71 potential 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 m<sup>3</sup>). 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<sup>-1</sup>.

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 (1<sup>st</sup>,  
102 30 m × 0.25 mm × 0.25 μm) and BPX50 (2<sup>nd</sup>, 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  $\text{CH}_2\text{Cl}_2$ ) 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 1<sup>st</sup> retention times are linked to the volatility of species (B8 to B31 with decreasing volatility) while  
126 2<sup>nd</sup> 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 ( $\mu\text{g}$ ) captured by Tenax TA tubes.  $V$  is the volume of the  
133 steel chamber ( $1 \text{ m}^3$ ). 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 ( $1 \text{ m}^3$ ) 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  $13 \times 10^{10}$   
150 molecules  $\text{cm}^{-3}\text{s}$  (24 hours in OH concentration of  $1.5 \times 10^6$  molecules  $\text{cm}^{-3}$ ).

## 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 ( $6.3 \text{ mg g}^{-1}$ ) (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 ( $382.5 \pm 175.0$   
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  $\alpha$ -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-( $\alpha,\beta$ )-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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583 **Figures**

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

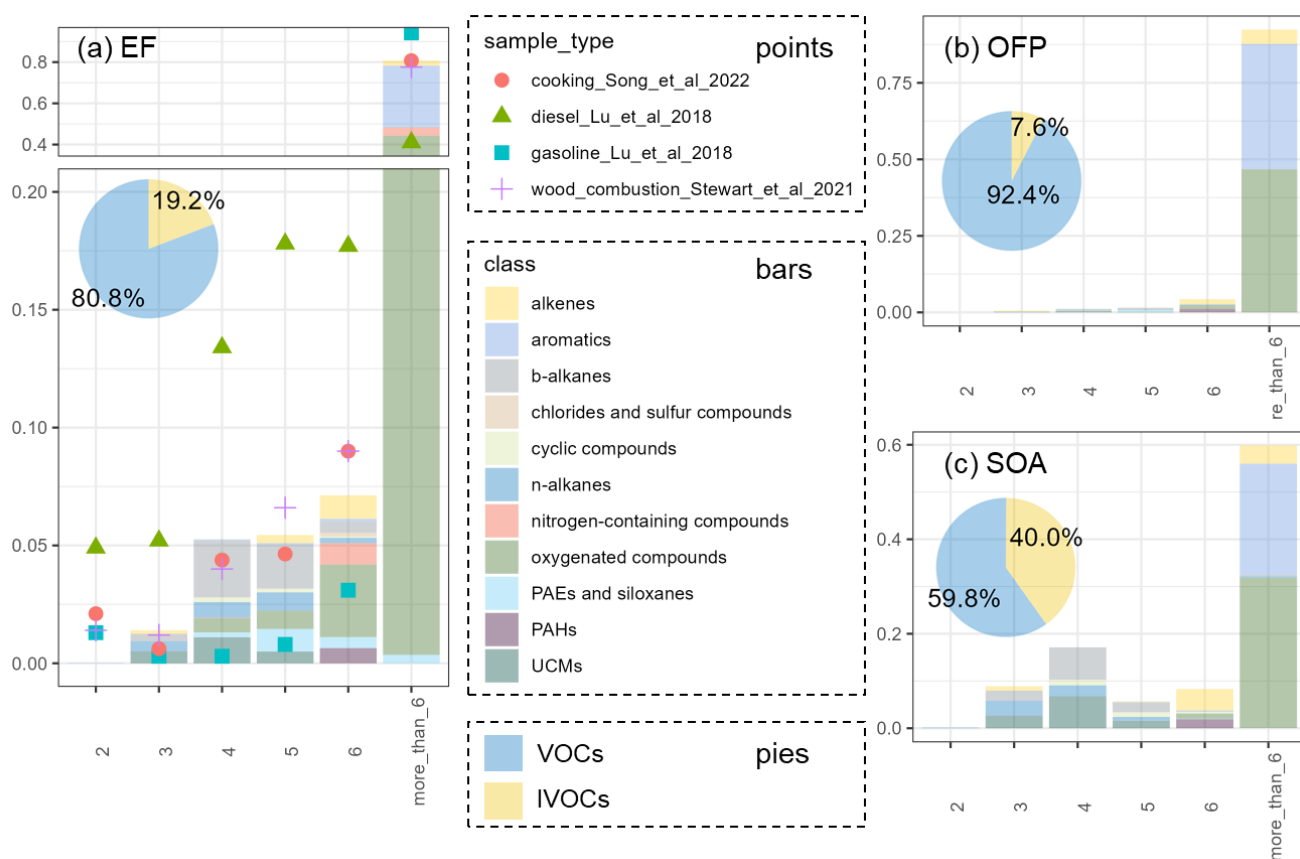
587 **Figure 2.** Positive (a) and negative loadings (b) of incense burning samples describing similarities  
588 and differences between chromatograms. The color bar is the loading.

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

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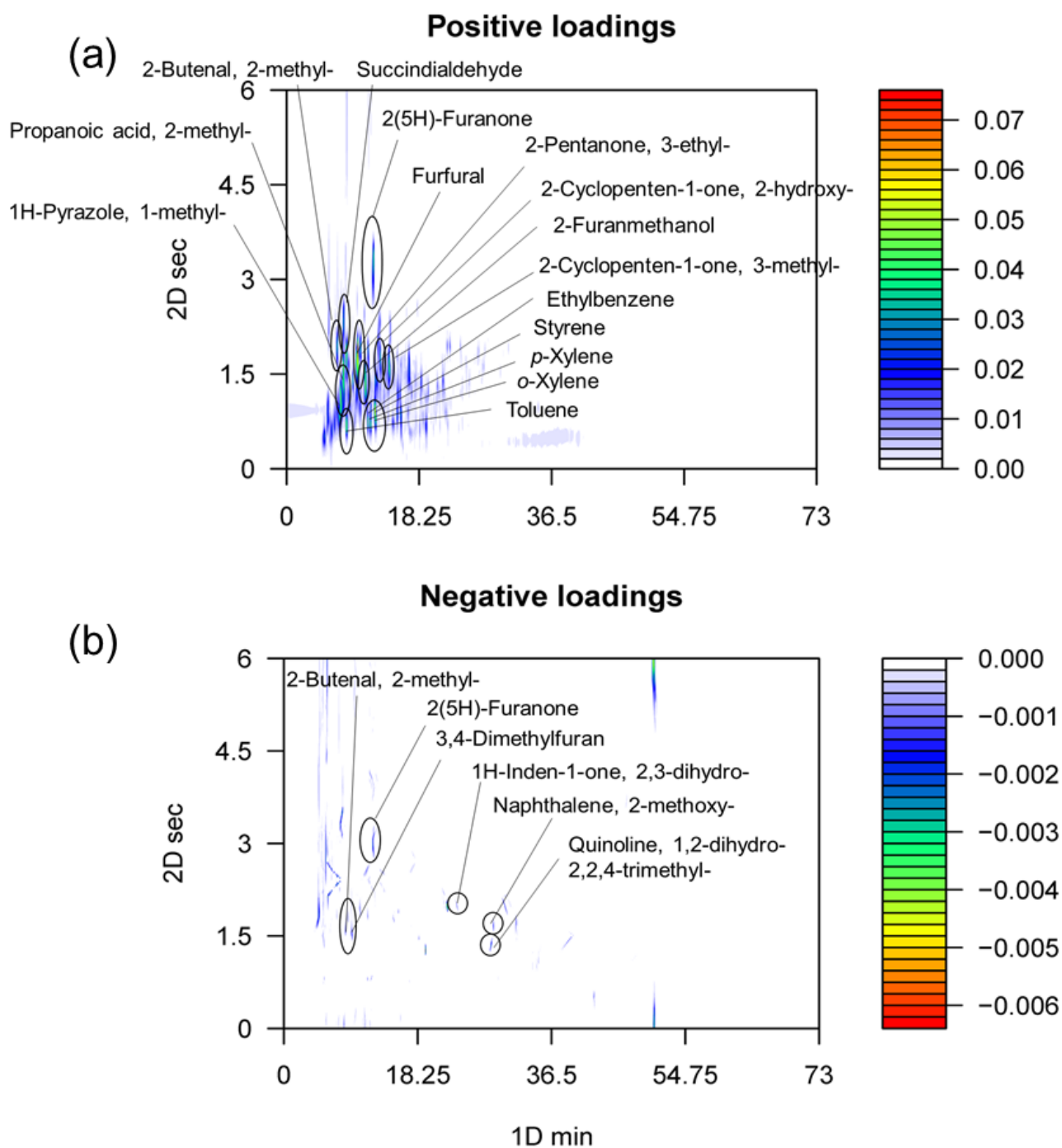


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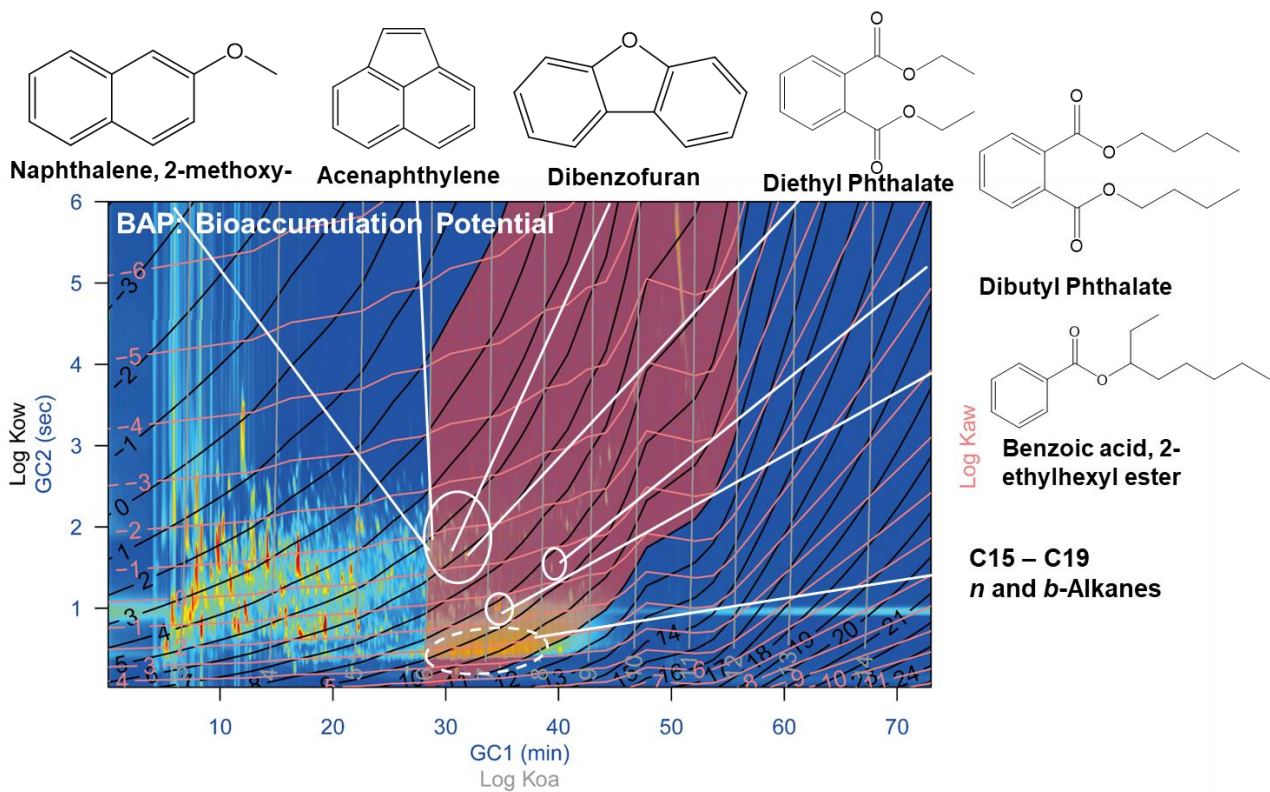




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