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1 Characterizing PM_{2.5} Emissions and Temporal Evolution
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3 California Residence

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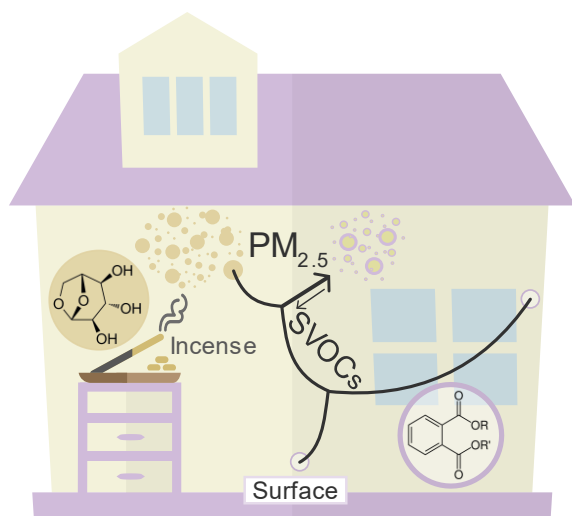
21 ABSTRACT

22 The chemical composition of incense-generated organic aerosol in residential indoor air has
23 received limited attention in Western literature. In this study, we conducted incense burning
24 experiments in a single-family California residence during vacancy. We report the chemical
25 composition of organic fine particulate matter (PM_{2.5}), associated emission factors (EFs), and gas-
26 particle phase partitioning for indoor semivolatile organic compounds (SVOCs). Speciated organic
27 PM_{2.5} measurements were made using two-dimensional gas chromatography coupled with high-
28 resolution time-of-flight mass spectrometry (GC×GC-HR-ToF-MS) and semivolatile thermal
29 desorption aerosol gas chromatography (SV-TAG). Organic PM_{2.5} EFs ranged from 7 to 31 mg g⁻¹
30 for burned incense and were largely comprised of polar and oxygenated species, with high
31 abundance of biomass-burning tracers such as levoglucosan. Differences in PM_{2.5} EFs and
32 chemical profiles were observed in relation to the type of incense burned. Nine indoor SVOCs
33 considered to originate from sources other than incense combustion were enhanced during incense
34 events. Time-resolved concentrations of these SVOCs correlated well with PM_{2.5} mass ($R^2 > 0.75$),
35 suggesting that low-volatility SVOCs such as bis(2-ethylhexyl)phthalate and butyl benzyl
36 phthalate partitioned to incense-generated PM_{2.5}. Both direct emissions and enhanced partitioning
37 of low-volatility indoor SVOCs to incense-generated PM_{2.5} can influence inhalation exposures
38 during and after indoor incense use.

39 **Keywords:** Indoor air, Incense burning, Organics, PM_{2.5}, SVOCs, GC×GC, Chemical speciation

40 **Synopsis:** Incense particle emissions are chemically similar to organic aerosol from biomass-
41 burning. SVOCs in residential indoor air readily transfer to incense-generated PM_{2.5}. Both direct
42 emissions and sorptive partitioning can influence occupant exposures.

43 Abstract graphic



44

45 **1. INTRODUCTION**

46 Exposure to fine particulate matter (PM_{2.5}) is a substantial risk factor for human health.¹ Indoor
47 conditions² and air quality can strongly influence one's personal exposure to PM_{2.5} as studies have
48 shown that indoor PM_{2.5} concentrations can sometimes exceed outdoor levels.³ Given that people
49 spend an average of about two-thirds of their time at home,⁴ combined with the health risks
50 associated with PM_{2.5} exposure, it is crucial to improve our understanding of PM_{2.5} indoors.
51 Incense burning is known to be a significant combustion source of residential indoor particulate
52 matter^{5,6} with emission factors similar to cigarette smoke.⁷ Incense-generated particles are
53 predominantly in the PM_{2.5} size range,^{8,9} most concentrated in the accumulation mode,^{6,10,11} and
54 characterized by large surface area per unit mass, which allows them to sorb gas-phase organic
55 and inorganic compounds, potentially affecting inhalation exposures.

56 Incense burning is a traditional practice in many cultures that serves as an integral part of worship
57 and ceremonial functions.⁸ Beyond its religious significance, incense serves various other
58 purposes, including therapeutic, aesthetic, insect-repelling, and producing pleasant fragrances.¹²
59 Incense use is most prevalent in the Asia-Pacific, Middle East, and Sub-Saharan African regions,
60 which is reflected in the majority of incense studies and associated adverse health effects emerging
61 prominently from these regions.^{8-10,13-20} Incense use is also popular in the West with the US as the
62 largest global importer.²¹ While estimates of US domestic incense use are limited, residential
63 settings likely contribute a significant proportion of total incense consumption. Market research
64 shows that incense products saw a surge in popularity and sales during the COVID-19 pandemic,
65 which was driven by demand for enhancing in-home ambiance amid growing mindfulness
66 practices (e.g., meditation and yoga).²² Despite this increasing trend, incense use remains largely
67 overlooked as a source of indoor PM_{2.5} pollution in Western literature.²³ This oversight is
68 concerning given that a quarter of the US population comprises diverse racial-ethnic and cultural
69 populations whose religions²⁴ incorporate incense burning into worship practices, potentially
70 influencing household incense use. Furthermore, the religiously unaffiliated, making up another
71 sizable portion of the population, may also frequently burn incense at home for aromatherapy or
72 spiritual reasons, a practice especially common in Black²⁵ and Latino²⁶ communities. For instance,
73 one study on polycyclic aromatic hydrocarbons (PAHs) exposure during pregnancy found that
74 28% of Black and Latino women reported burning incense at home.²⁷

75 Incense-generated PM_{2.5} has been extensively studied indoors with characterization efforts
76 focusing primarily on the physical characteristics of incense emissions, including emission factors,
77 particle mass concentrations, particle size distributions, and particle-associated PAHs in incense
78 smoke.^{6,7,11,13-15} Conversely, the speciated chemical composition of incense-generated PM_{2.5}
79 remains largely uncharacterized in indoor environments, despite organic aerosol (OA) constituting
80 the majority of emissions.^{8,28-30} Some studies have elucidated the chemical profile of particulate
81 organic matter in incense smoke, particularly from incense sticks, by utilizing chemical
82 characterization techniques such as aerosol mass spectrometry (AMS) and gas chromatography
83 (GC). Yet, such investigations have been restricted to targeted chemical analysis of selected

84 compounds or chemical groups,^{16,18,30-32} qualitative explorations of identified species,³³ and
85 organic compositional analysis with low chemical resolution owing to limitations in the speciation
86 capabilities of the instrumentation used.^{6,34} Furthermore, these studies have only been conducted
87 in laboratory or controlled environments with some results indicating substantial fractions of OA
88 mass that are unidentified or unresolved.^{30,32}

89 Two-dimensional GC coupled with high-resolution mass spectrometry (GC×GC-HR-MS) is a
90 chemical characterization technique that can provide more comprehensive separation and
91 identification of diverse and complex particle-phase organics present in incense smoke.³⁵ GC×GC
92 has been applied to speciate and quantify thousands of individual chemical species spanning a
93 wide range of volatilities and polarities present in atmospheric matrices.^{36,37} Its strengths also lie
94 in separating isomers and several chemically similar compounds that would normally coelute in a
95 one-dimensional GC column. A recent GC×GC-MS laboratory study characterizing total
96 suspended particles from incense emissions could only chemically speciate a small fraction of total
97 particulate organics, owing to quantification challenges that resulted from a lack of chemical
98 derivatization in their analysis approach.³⁸ When applied to augment a characterization technique
99 like GC×GC, chemical derivatization significantly enhances recovery of polar organic
100 compounds³⁹ which dominate incense particulate emissions,^{33-35,38} and serves to adequately
101 resolve separated compounds in a manner essential for reliable quantification. Employing online
102 chemical derivatization coupled with GC×GC to characterize incense-generated PM_{2.5}, as is done
103 in the current work, provides insight into the abundance and behavior of incense-derived particle-
104 phase organics in indoor environments.

105 Assessing air quality impacts of indoor-generated PM_{2.5} requires characterizing common sources.
106 Whereas cooking, candle burning, and smoking have been relatively well studied as indoor
107 combustion sources,⁴⁰⁻⁴² exploring the chemical composition of incense burning and its
108 contributions to indoor air pollution has been more limited.⁴³ The current study focuses on
109 evaluating incense PM_{2.5} emissions and the associated chemistry indoors in a normally occupied
110 residence in the San Francisco Bay Area during a period of vacancy. Incense-generated PM_{2.5} was
111 collected on filters for offline organic compositional analysis by GC×GC with supporting
112 semivolatile organic compound (SVOC) measurements using semivolatile thermal-desorption
113 aerosol gas chromatography (SV-TAG). As this work focuses on incense burning indoors, its
114 significance lies in enhancing our understanding of combustion-generated PM_{2.5} in a residential
115 environment, thus offering insights for exposure assessment and source mitigation.

116 2. METHODS

117 2.1. Incense Experiments and PM_{2.5} Sample Collection

118 The analysis explored in this work was conducted in November 2021 during an unoccupied period
119 in an otherwise normally occupied single-family residence in Oakland, California. During incense
120 experiments, the studied home had interior doors open and exterior doors and windows closed.
121 There was no mechanical ventilation and the central air-handling system was off. Detailed
122 descriptions of this H3 field campaign, incense burning protocols, and the rationale behind
123 choosing the study residence and incense scents are provided in the supporting information (SI).
124 Briefly, five incense burning experiments were carried out in H3, each with two sticks of either
125 lavender or Douglas fir incense. Incense burns occurred twice a day around noon and 5:30 pm with
126 incense sticks ignited in the kitchen and allowed to burn through a ~60-min duration before
127 removing the incense source from the residence (see Figure S1 for an illustration of experimental
128 timing). Indoor incense filter samples were collected in the kitchen over 6-h periods on average,
129 along with three outdoor filters simultaneously sampled in the back yard of the H3 residence during
130 incense experiments. Incense smoke was sampled at 10 L min⁻¹ on 47 mm quartz filters using a
131 custom-designed aerosol sampler³⁷ fitted with a cyclone to exclude particles larger than 2.5 μm.
132 Before incense experiments, an indoor air background sample was collected in the kitchen over a
133 22-h period under closed-home conditions. The H3 occupants reported never burning incense in
134 this residence; thus, the background sample is assumed to be representative of the H3 indoor
135 environment, unperturbed by chemicals related to incense combustion. All H3 samples were
136 collected on heat-treated quartz filters and were stored frozen (-20 °C) prior to chemical analysis.

137 2.2. PM_{2.5} Filter Analysis: GC×GC

138 H3 PM_{2.5} filters were analyzed by offline thermal desorption two-dimensional gas chromatography
139 with online derivatization coupled with electron ionization high-resolution time-of-flight mass
140 spectrometry (TD-GC×GC-EI-HR-ToF-MS). A detailed description of instrument methods and
141 specifications as well as quantification, uncertainties, and compositional analysis of H3 samples
142 can be found in the SI (Table S1-S4). Briefly, filter punches (0.07-0.82 cm²) from H3 samples
143 were initially heated in the instrument's thermal desorption unit under continuous helium gas flow
144 saturated with a derivatization agent, N-methyl-N-(trimethylsilyl)trifluoroacetamide. Desorbed
145 organics were then separated by volatility and polarity, in sequence, by two serially connected GC
146 columns separated by a thermal modulator followed by subsequent ionization under 70 eV EI and
147 detection by HR-ToF-MS with a resolution of 4000. Analyzed PM_{2.5} organics spanned between
148 C₁₃ and C₃₆ *n*-alkane volatility equivalents. GC×GC chromatograms were analyzed using the GC
149 Image software and quantification of detected compounds was performed using 110 external
150 standards. Compounds were identified and classified into chemical families through matches with
151 authentic external standards, searches against mass spectral libraries (e.g., NIST-20) utilizing
152 linear retention index (RI), and analysis of second dimension retention times (RT2) and specific
153 molecular ions indicating chemical functionality. Henceforth, chemically "speciated" PM_{2.5} mass
154 concentrations reported and discussed throughout the text are based on H3 filter samples analyzed
155 by GC×GC unless otherwise stated.

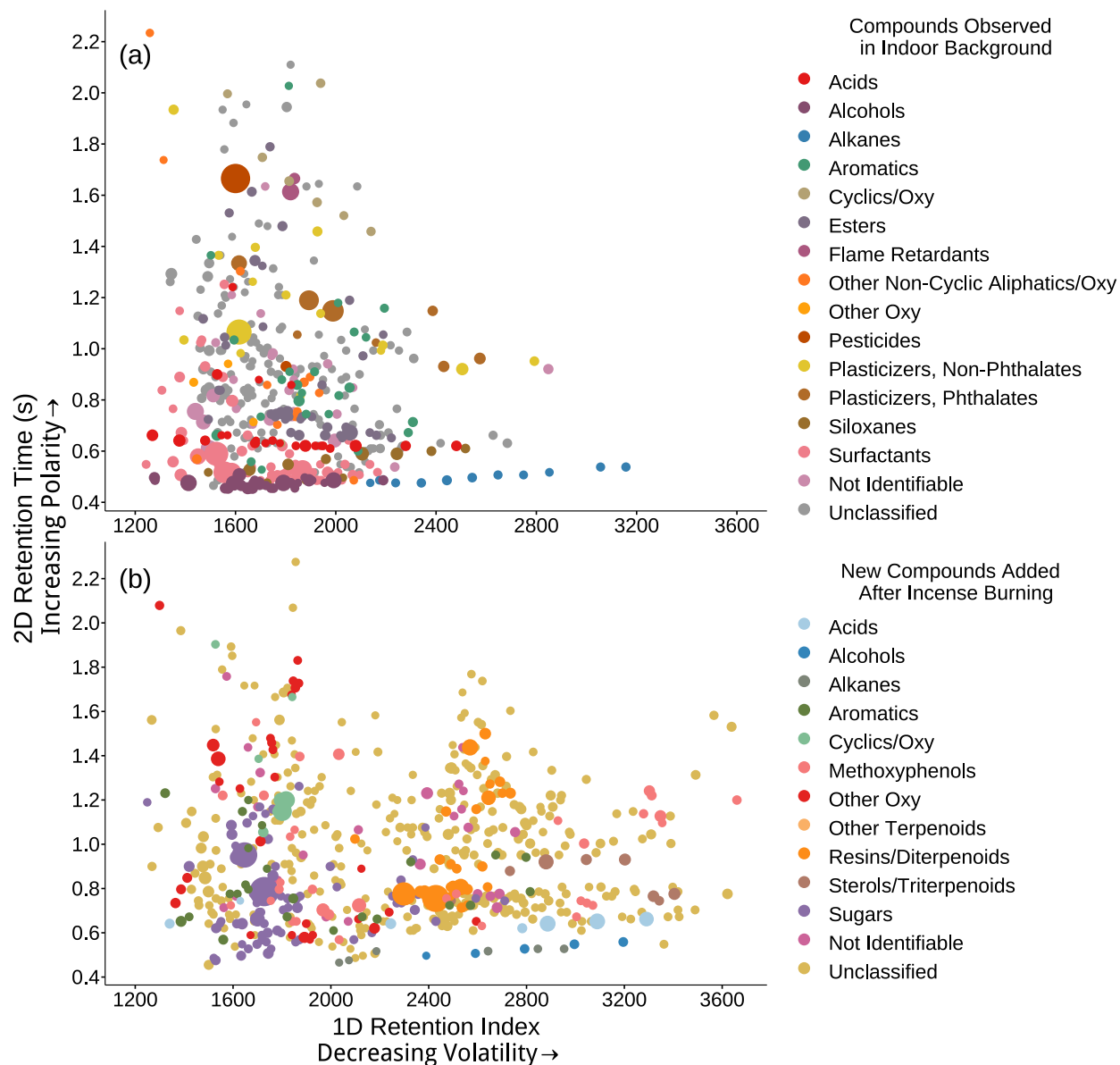
156 **2.3. Differentiating Indoor and Incense-Attributed Compounds in Incense Samples**

157 The indoor air background sample allowed differentiation between existing conditions at H3 and
158 distinct new compounds observed following incense burns. Compounds detected in the indoor
159 background sample were assigned to a template in GC Image that could be searched against and
160 compared to samples with incense PM_{2.5}, through location in GC×GC space (RI and RT2) and EI
161 mass spectra information. In this way, ubiquitous indoor SVOCs such as phthalate ester
162 plasticizers^{44,45} along with other compounds identified in the indoor background were
163 characterized as particulate organics not (directly) related to incense combustion, despite their
164 detection in samples collected during incense burning events. Some compounds present in the
165 indoor background air at H3 increased substantially during incense experiments and were likely
166 emitted in incense smoke while other species such as indoor SVOCs may be significantly
167 influenced by incense-generated particle mass as a result of partitioning that enhances their
168 particle-phase abundance.^{42,46-49} Compounds observed in the indoor background and the dynamics
169 of their enhancements are discussed in Section 3.3.

170 **2.4. Supporting Analysis for Incense Experiments**

171 Hourly real-time measurements of combined gas and particle-phase organics (gas-plus-particle)
172 smaller than 2.5 μm were collected using an online semivolatile thermal desorption aerosol gas
173 chromatograph (SV-TAG). A detailed description of SV-TAG (e.g., design, operation,
174 uncertainties) can be found elsewhere.^{39,50} SV-TAG separately sampled air from the kitchen and
175 the outdoors with measured SVOC volatilities corresponding roughly to the range C₁₄ to C₃₅ *n*-
176 alkanes. SV-TAG is a GC-based instrument utilized in prior indoor air chemistry campaigns.^{47,51}
177 During the H3 campaign, SV-TAG was housed in a temperature-controlled enclosure in the
178 garage-basement. Real-time PM_{2.5} mass was quantified in the kitchen during incense experiments
179 by a Particles Plus (8306) particle counter. Time-resolved particle number concentrations were
180 measured at 1 Hz in six diameter channels between 0.3 and 25.0 μm and mass concentrations were
181 calculated under a particle density assumption of 1 g cm⁻³. A Sunset Laboratory Model 5L OCEC
182 instrument coupled with the NIOSH870 thermal protocol was used at the Air Quality Research
183 Center at UC Davis to analyze H3 PM_{2.5} filters, including field blanks, for organic carbon (OC)
184 and elemental carbon (EC) content.

185 **3. RESULTS and DISCUSSION**

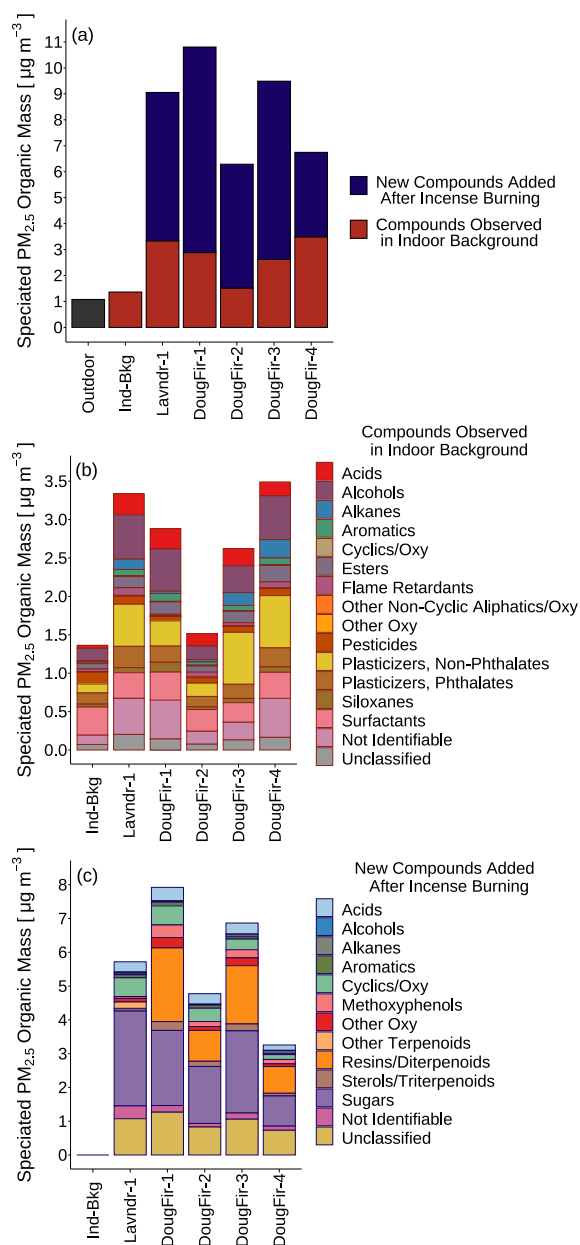


186
 187 **Figure 1.** GCxGC chromatograms of (a) the indoor background sample and (b) an incense smoke
 188 sample collected from a Douglas fir incense burn event. Compounds are separated by volatility on
 189 the *x*-axis and by polarity on the *y*-axis. Each point (panel (a) total = ~460; panel (b) total = 590)
 190 corresponds to a unique compound with a full mass spectrum (*m/z* ~35-650). Point size
 191 approximately scales with quantified organic aerosol mass concentrations ($\mu\text{g m}^{-3}$) and colors
 192 identify the compound's classification. Differing colors between the same classification (e.g.,
 193 acids, alcohols, etc.) in both chromatograms highlight indoor background compounds in panel (a)
 194 distinct from incense-attributed compounds shown in panel (b) (see Section 2.3).

3.1. Chemical Composition of Particulate Organics from Incense Burning

195 Incense-attributed compounds from both lavender and Douglas fir incense burns exhibited
196 diversity in both structural and chemical properties as shown for a representative incense burn
197 sample in Figure 1b. New compounds following incense burns in H3—i.e., distinct “incense-
198 attributed” compounds not including the indoor background (see Section 2.3)—were distributed
199 over the range of measured species with more compounds inhabiting higher mass (lower volatility)
200 and more oxidized (higher polarity) regions in GC×GC space compared to the indoor background
201 (Figure 1a). Approximately 1600 distinct incense-attributed compounds were separated from
202 incense-generated PM_{2.5} OA samples, of which ~300 compounds were classified into chemical
203 families with 86 of those compounds being positively identified across all five incense burns. The
204 chemical families include acids (carboxylic acids), alcohols, alkanes, aromatics (compounds with
205 at least one aromatic ring), cyclics/oxygenates (non-aromatic/cyclic aliphatics), methoxyphenols,
206 other oxygenates (with two or more -OH groups), other terpenoids (mono- and sesquiterpenoids),
207 resins/diterpenoids, sterols/triterpenoids, and sugars (with sugar derivatives including
208 anhydrosugars and sugar alcohols). Compounds with signal responses above the selected intensity
209 cutoff that could not be identified or classified during analysis were categorized as not identifiable
210 while the remainder of the compounds under this limit were grouped as unclassified.
211

212 Incense-attributed compounds were closely related to smoke particles found in biomass-burning
213 organic aerosol (BBOA).^{37,52} These findings were consistent with previous studies,^{32,34,38} as the
214 composition of incense sticks (e.g., aromatic woods, flowers, resins, etc.) supports the observation
215 of wood pyrolysis products as found in BBOA. The range of observed BBOA compounds
216 demonstrated the elevated presence of polar and oxygenated organic compounds in incense smoke.
217 This finding was confirmed by estimating the incidence of derivatization in GC×GC, which
218 accounted for more than 88% of all incense-attributed compounds across incense burn samples.
219 The process for determining the fraction of separated compounds that were derivatized is discussed
220 in the SI (see Figure S2). Due to the derivatization process used in this work, many polar organics
221 were both recovered and well resolved, making it possible to reliably integrate and quantify these
222 speciated compounds. However, speciated compounds differ chemically from their original forms
223 with derivatization, which can create some challenges for identification and classification as
224 derivatized mass spectra may not be available or published in MS libraries or literature.^{37,53}
225 Overall, 29–39% of incense-attributed compounds were classified within each analyzed incense
226 burn sample.



227
 228 **Figure 2.** GCxGC speciated $PM_{2.5}$ organic aerosol mass concentrations for (a) total quantified
 229 mass in H3 filter samples, with designated mass fractions in incense samples, (b) indoor
 230 background mass fractions classified by chemical family in each sample, and (c) incense-attributed
 231 mass fractions classified by chemical family in incense samples. Note the different y-axis scales
 232 in (b) and (c) in contrast to (a), and that the sum of (b) and (c) equals (a) for incense samples. Each
 233 stacked bar in (b) and (c) shows the sum of concentrations of classified compounds in each sample
 234 (see Table S6 and S7). Colors that differ between common chemical families (e.g., acids, alcohols,
 235 etc.) in (b) and (c) highlight that compounds within those chemical families are distinct between
 236 indoor background and incense-attributed masses. “Ind-Bkg” refers to the indoor air background
 237 sample, “Lavndr” refers to a sample with lavender incense burned, and “DougFir” refers to a
 238 sample with Douglas fir incense burned.

239 3.2. Speciated Organic PM_{2.5} Mass Contributions from Incense Emissions

240 Total GC×GC speciated PM_{2.5} OA concentrations are shown in Figure 2a for incense samples,
241 with mass fraction contributions from both indoor background and incense-attributed compounds.
242 Incense samples contained mass concentrations 4.6–7.9 times higher than the indoor background.
243 Incense-attributed compounds shown in Figure 1b accounted for 3.3–7.9 μg m⁻³ (48–73%) of total
244 speciated mass in incense samples (Figure 2a). The lower limit of the incense-attributed mass
245 fraction is likely related to incomplete incense combustion for the DougFir-4 sample (see SI). The
246 total outdoor mass concentration, 1.1 μg m⁻³, is the average of the three outdoor filter samples
247 collected at H3. The incense-attributed mass fraction for each incense sample is summarized by
248 chemical family in Figure 2c. Classified compounds accounted for 74–82% of incense-attributed
249 mass across burns while the not identifiable and unclassified compounds represented on average
250 about a fifth (18–26%). Sugars contributed the highest proportion (27–49%) to incense-attributed
251 mass for all burns with levoglucosan, an unequivocal BBOA tracer, being the most abundant sugar
252 compound emitted (41–62%). Levoglucosan was also the highest mass contributor across all
253 incense-attributed compounds with concentrations ranging from 0.4 to 1.3 μg m⁻³. This finding
254 aligns with reported high levoglucosan emissions from incense burning³⁸ and as pyrolysis products
255 of primarily cellulose-rich plant materials⁵⁴ such as those used in producing incense. Other
256 important BBOA tracers such as resins/diterpenoids were also abundant (19–28%) in Douglas fir
257 burn samples as the second highest contributing incense-attributed chemical family. These
258 compounds are indicative of conifer species^{37,55–57} such as the Douglas fir incense burned in H3.
259 Emissions of dehydroabietic acid, which is an identified marker of conifer combustion,⁵⁶ was also
260 in agreement with BBOA studies^{56,57} as the most abundant resin/diterpenoid (27–33%) with
261 speciated mass concentrations of 0.2–0.7 μg m⁻³ for the four Douglas fir burn samples. Palustric
262 acid was the second highest mass contributor of the resins/diterpenoids chemical family (17–26%)
263 in Douglas fir samples with concentrations of 0.1–0.5 μg m⁻³. This compound is distinct to pine
264 species^{37,55} and likely originated from the addition of “piñon pine” highlighted in the list of
265 ingredients for Douglas fir incense.

266 For the single burn sample of lavender incense (non-conifer), resins/diterpenoids only made up
267 0.2% of the incense-attributed mass with a concentration < 0.01 μg m⁻³. Furthermore, only the
268 lavender burn exhibited other terpenoid compounds such as mono- and sesquiterpenoids. These
269 compounds accounted for 3.3% of incense-attributed speciated mass and are distinctive to fragrant
270 plants like lavender. Also, compared to Douglas fir samples, lavender incense emitted much less
271 mass of methoxyphenols (3.1–4.7% vs 0.9%). Since methoxyphenols are pyrolysis products of
272 lignin and indicative of burned wood in fine aerosol,⁵⁶ this difference is likely a result of more
273 woody biomass components being present in Douglas fir incense compared to the higher floral
274 content used in producing lavender incense. These variations in the organic chemical composition
275 of incense-generated PM_{2.5} are likely influenced by components of the incense materials used,^{10,38}
276 and are relevant given that the toxicity of BBOA, and incense by proxy, depends partly on chemical
277 composition.⁵⁸ The vast majority of these compounds have unknown health impacts,⁵² nonetheless,
278 some BBOA-related compounds with hazard codes outlined in the SI of Liang et al.⁵² were

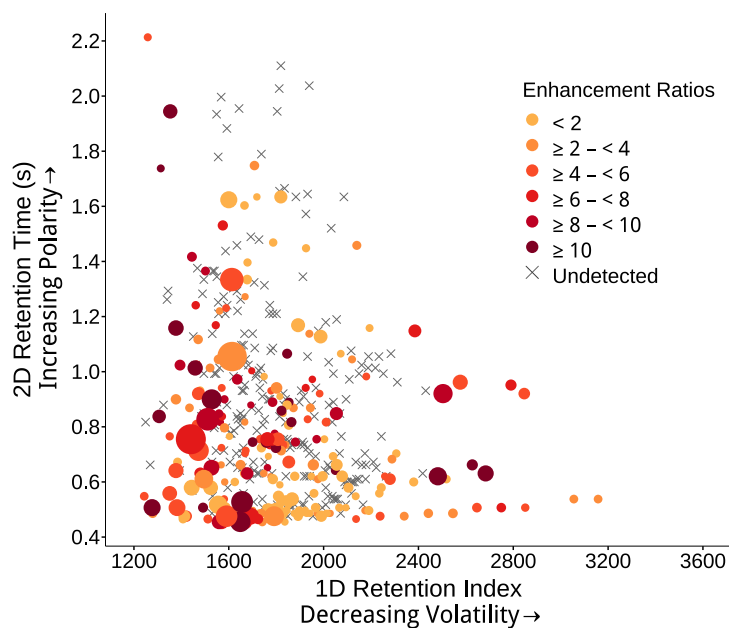
279 positively identified in this work as summarized in Table S5. Additional BBOA-related chemical
280 families contributing to incense-attributed mass fractions in Figure 2c are provided in Table S6.

281 In this study, PAHs were not detected in PM_{2.5} organic aerosol collected on incense filter samples
282 analyzed by GC×GC, including lower volatility PAHs with four rings or more (e.g., fluoranthene),
283 which are generally found in the particle phase.⁵⁹ This observation was surprising given the
284 prominent role of PAHs as products of incomplete combustion of carbonaceous fuels as is
285 characteristic of incense burning. While some studies have explored particle-associated PAHs in
286 incense emissions,^{13,14,16} others have encountered challenges in measuring these compounds
287 indoors, such as in Lung et al.¹⁵ who estimated household incense PAHs emissions through
288 laboratory combustion.⁶⁰ Observed mass loadings of PAHs from their laboratory experiments were
289 less than 0.1% of total particle mass, with similar ratios reported in later studies in a controlled
290 experimental house⁶ and during chamber combustion.¹⁶ Yang et al.¹⁶ reported that emission factors
291 of gas-phase PAHs were about three times higher than particle-associated PAHs and Lin et al.¹⁴
292 found that 90% of indoor airborne PAHs from incense burning were in the gas phase. These studies
293 suggest that open combustion indoors, incense composition, particle loading, and PAH abundance
294 in the gas phase may have impeded detection of particle-bound PAHs in H3 incense samples.

295 **3.3. Influence of Incense Burning on Indoor Compounds and SVOCs** 296 **Concentrations**

297 The speciated chemical composition of compounds observed in the indoor background sample is
298 depicted in Figure 1a. Approximately 460 background compounds observed in H3 were largely
299 concentrated within more volatile regions (95th percentile RI < C₂₄) in GC×GC space compared to
300 compounds attributed to incense in Figure 1b. This finding indicates that indoor background
301 compounds were predominantly higher volatility SVOCs species such as plasticizers (e.g., from
302 floor coverings and personal care products) and surfactants (e.g., in detergents and cleaners), which
303 are abundant and persist in indoor air from stable or recurring indoor sources.⁴⁴ Analysis of the
304 indoor background sample resulted in 58% of observed compounds classified into broad chemical
305 families: esters, flame retardants, other non-cyclic aliphatics/oxygenates, pesticides, plasticizers
306 (non-phthalates and phthalates), and surfactants (non-ionic, alcohol ethoxylates). Chemical
307 families of indoor background compounds matching those illustrated in Figure 1b for incense are
308 described in Section 3.1. Compounds observed in the indoor background sample had a total mass
309 concentration of 1.4 μg m⁻³ (Figure 2a) and accounted for 1.5–3.5 μg m⁻³ (24–52%) of total
310 speciated mass in incense samples. Figure 2b displays the speciated mass concentrations of
311 chemical families, describing the range of observed indoor background compounds and their
312 abundance with respect to incense samples (Table S7). Classified compounds accounted for 75–
313 86% of the indoor background mass fraction across all samples shown in Figure 2b. For indoor
314 background compounds detected in incense samples, we treated the indoor air background sample
315 as the baseline for these non-incense-attributed compounds. This approach allows for broad
316 observations of changes in the abundance and enhancements of indoor background compounds
317 across incense samples.

318 Using GC×GC speciated mass, enhancement ratios (ERs) were calculated from the increases in
319 the time-averaged concentrations of indoor background compounds detected in incense samples
320 relative to (i.e., divided by) the indoor background sample. In this study, ERs for a given compound
321 had to be consistently greater than two (2) across all incense samples to be considered “enhanced”.
322 Additionally, compounds detected in incense samples that were completely absent from the indoor
323 background sample were manually searched at levels below normal analytical limits of detection
324 (LOD) in the background sample to ensure that they were not misattributed due to changes in LOD
325 from differing sampling volumes. Figure 3 illustrates the range of ERs calculated for indoor
326 background compounds detected in the DougFir-1 incense sample. Table S8 reports all indoor
327 background compounds that were consistently enhanced across incense samples and were
328 positively identified. Background indoor compounds within acid, alkane, alcohol, aromatic, ester,
329 and plasticizer chemical families were found to be consistently enhanced across incense samples,
330 with variability in ER values. The enhancements of acids, alcohols, and alkanes most likely relate
331 to direct OA emissions from incense burns. Observed background compounds such as C₂₀ acid
332 (eicosanoic acid) and C₂₇ alkane (heptacosane) were previously shown to be constituents of
333 primary BBOA, emitted abundantly in samples collected during wildfires.⁵² This evidence is
334 consistent with high mean and median ERs for eicosanoic acid (14.5 and 16.0) and heptacosane
335 (46.5 and 42.8) in incense samples. Both eicosanoic acid and heptacosane as well as other
336 enhanced indoor background acids, alkanes, and alcohols have been previously reported in incense
337 emissions.^{35,38}



338
339 **Figure 3.** Enhancement ratios of indoor background compounds detected in DougFir-1 incense
340 sample. Point size indicates the quantified organic aerosol mass concentration ($\mu\text{g m}^{-3}$) in GC×GC,
341 and the color scale identifies the enhancement ratio compared to the indoor background sample.
342 “Undetected” refers to indoor background compounds not detected in DougFir-1.

343 The enhanced aromatic, ester, and plasticizer compounds we observed in incense samples were
344 mostly SVOC species related to building materials and consumer items such as personal care
345 products. For example, homosalate is an SVOC used in the production of sunscreen,⁶¹ which has
346 been found in residential indoor air during occupancy independent of cooking or cleaning
347 activities.⁵¹ Isopropyl myristate, commonly used as a cosmetic ingredient in personal care
348 products, was detected in 100% of household dust samples collected in a study in northern
349 California.⁶² Bis(2-ethylhexyl) phthalate (DEHP) and butyl benzyl phthalate (BBzP) are widely
350 used as plasticizers that make up large mass fractions of several construction and furnishing
351 materials.⁶³ They have also been measured extensively in residential indoor environments.⁶⁴
352 Diethyl phthalate (DEP) is an abundant plasticizer present in furnishings as well as in personal
353 care products.⁶³ Bis(2-ethylhexyl) terephthalate (DEHT) is a high production volume non-
354 phthalate plasticizer, often used as a replacement for DEHP, in consumer products and building
355 materials.⁶⁵ 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (trade name TXIB; Eastman Chemical)
356 is another non-phthalate plasticizer that is used largely in vinyl products such as flooring and wall
357 coverings.⁶⁶ TXIB, DEP, and isopropyl myristate were also shown in one study to dominate SVOC
358 peak abundances in residential indoor air under closed conditions prior to window opening.⁶⁷ To
359 better understand the dynamic behavior of these assumed indoor originating SVOCs detected and
360 enhanced in incense filter samples, we provide relative abundances of gas-plus-particle samples
361 of these compounds during incense burns using SV-TAG.

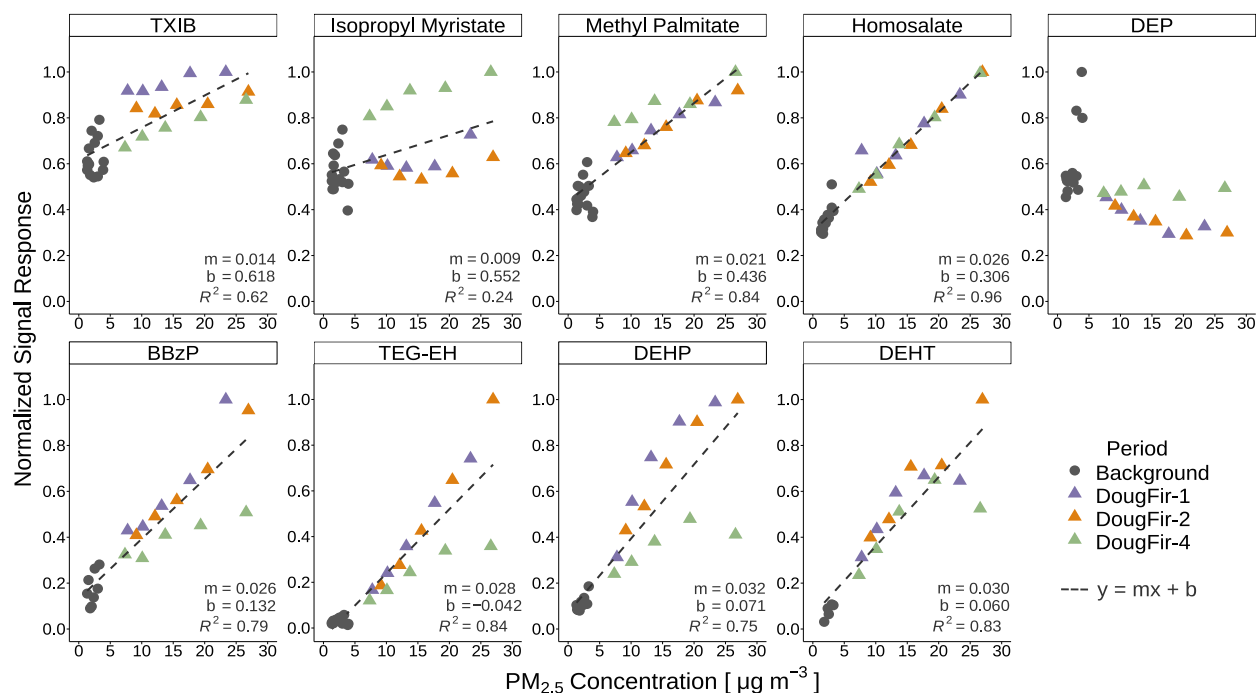
362 **3.4. Influence of Incense-Generated PM_{2.5} on Gas- and Particle-Phase Partitioning** 363 **of Indoor SVOCs**

364 Nine indoor SVOCs were compared to particle mass at hourly resolution during incense burning
365 events using the SV-TAG and Particles Plus instruments respectively (Figure 4). The first four
366 compounds in the top and bottom panels in Figure 4 represent SVOCs with volatilities above and
367 below C₂₃ alkane-equivalent volatility respectively. This distinction is highlighted to explain
368 dynamic SVOC behavior that has been reported in prior residential indoor air studies. Using the
369 same instrument and methods in an observational study, Lunderberg et al.⁴⁷ reported that certain
370 indoor SVOCs exhibited shifting gas-particle phase partitioning in response to changes in PM_{2.5}
371 concentration. SVOCs with volatilities lower than the C₂₃ alkane were observed to partition onto
372 airborne particles when particle mass concentration increased. This effect was less prominent for
373 higher volatility SVOCs. We observed similar effects in our experimental incense study with the
374 strongest correlations for SVOCs with lower volatilities (Figure 4). For SV-TAG samples of
375 indoor SVOCs with volatilities above C₂₃, the background concentrations were mostly gaseous as
376 evidenced by the high intercepts of the regression lines for gas-plus-particle measurements shown
377 in Figure 4. With increased PM_{2.5} mass during incense burning events, concentrations of these
378 higher volatility SVOCs generally remained above background levels. Similar behavior was
379 reported by Lunderberg et al.⁴⁷ and Kristensen et al.⁴⁶ as these higher volatility indoor SVOCs
380 were not expected to strongly partition to airborne PM_{2.5}. In contrast, for indoor SVOCs below C₂₃
381 volatility, as displayed in the bottom panel of Figure 4, strong associations between total (gas-plus-
382 particle) SVOC abundance and incense particle mass concentrations were observed, with

383 regression intercepts close to zero across displayed compounds. These relationships strengthen
384 moving from left to right for these lower volatility SVOCs, as partitioning to airborne particles
385 appears to drive the enhancement of their airborne particle-phase concentrations.

386 Some laboratory incense chamber studies have shown the presence of certain plasticizers and
387 related indoor SVOCs in particulate incense emissions.^{31,38} DEP is the only phthalate plasticizer
388 that has been reported to be used as a binder ingredient for incense production in India.^{17,68} In the
389 present work, although DEP was enhanced in incense filter samples, there was no real-time
390 association with airborne particles during incense burning experiments (Figure 4) when compared
391 to similar higher volatility indoor SVOCs. For other plasticizers and SVOCs discussed, the gas-
392 particle phase partitioning behavior presented in this work, and supported by SVOC measurements
393 in prior indoor studies, provides substantial evidence that these SVOCs largely originate from
394 other residential indoor sources, rather than directly from incense emissions. Furthermore, if it
395 were the case that the discussed indoor SVOCs were emitted primarily from incense emissions,
396 one would expect to observe different time-resolved behavior of their abundance in indoor air than
397 was exhibited in the SV-TAG data. Specifically, associations should be very strongly correlated
398 with incense-generated PM_{2.5} as the increases and eventual decay of airborne PM_{2.5} would be equal
399 to the presence and relative abundance of emitted indoor SVOCs.

400 Overall, the findings in this work are consistent with prior studies in residences^{46,47} and
401 chambers,⁶⁹ augmented by modeling studies,⁷⁰ which specifically show enhanced DEHP emissions
402 from surfaces being influenced by the presence of airborne particles. That lower volatility SVOCs
403 sorb to incense-generated particles is important for recognizing how SVOCs can indirectly
404 contribute to indoor organic PM_{2.5} mass and how strong indoor particle sources can alter the mode
405 and intensity of SVOC inhalation exposures for occupants.⁴⁴ Inhaled PM_{2.5} with increased toxicity
406 from sorbed SVOCs would deposit in the respiratory tract differently than would a gas-phase
407 SVOC.⁷¹ These observations are not only relevant for indoor SVOCs such as DEHP and BBzP,
408 which have been shown to contribute to adverse health outcomes in their roles as endocrine-
409 disrupting chemicals,⁷² but also for other unexplored low-volatility indoor SVOCs with unknown
410 health effects.



411
 412 **Figure 4.** Associations of time-resolved indoor SVOCs abundance with $PM_{2.5}$ mass concentrations
 413 during incense burning experiments. Reported SVOC measurements are total (gas-plus-particle)
 414 internal standard normalized signal (equivalent to mass concentrations). SVOCs are arranged in
 415 order of increasing retention index (see Table S8). “TXIB,” “DEP,” “BBzP,” “TEG-EH,”
 416 “DEHP,” and “DEHT” refer to 2,2,4-trimethyl-1,3-pentanediol diisobutyrate, diethyl phthalate,
 417 butyl benzyl phthalate, triethylene glycol di(2-ethylhexoate), bis(2-ethylhexyl) phthalate, and
 418 bis(2-ethylhexyl) terephthalate, respectively.

419 3.5. Emission Factors of Incense-Generated $PM_{2.5}$ in Indoor Air

420 Consistent with prior incense studies,^{28,29} total organic carbon (OC) mass comprised the majority
 421 of $PM_{2.5}$ in incense filter samples with concentrations of 17.4–37.2 $\mu\text{g m}^{-3}$. An assumed OA/OC
 422 ratio of 1.6, as derived from field and laboratory primary BBOA AMS measurements,^{73,74} was
 423 applied to estimate total $PM_{2.5}$ OA in incense samples based on OC measurements (Table S9). The
 424 speciated mass concentrations of indoor background and incense-attributed compounds quantified
 425 in incense samples (Figure 2a) can explain, on average, 20% of the total $PM_{2.5}$ OA mass in each
 426 sample. This extent of successful speciation is credited to online derivatization that facilitated
 427 enhanced recovery of more polar and oxygenated incense particle-phase organics compared to
 428 non-derivatized analysis of incense emissions.³⁸

429 To evaluate and more easily compare incense burning contributions in H3 with prior studies, $PM_{2.5}$
 430 emission factors (mass of $PM_{2.5}$ emitted per mass of incense burned) were estimated using the
 431 integral mass balance approach for episodic emissions.⁷⁵ Equation (1) determines the mass, M , of
 432 $PM_{2.5}$ emitted from an incense burn event in a well-mixed indoor environment with volume, V ,
 433 where C_i is the time-averaged OA concentration in incense filter samples, C_b is the background
 434 OA concentration in H3, Δt is the sampling duration, and L is the total removal rate of incense-

435 generated PM_{2.5} during and following emissions. *L* was estimated by fitting time-resolved incense
436 PM_{2.5} data from the Particles Plus to a first-order decay⁷⁶ (see SI). For this calculation, a few
437 assumptions were made: 1) incense-generated PM_{2.5} is well-mixed throughout the interior volume
438 of H3 during the burning and decay period; 2) the background OA concentration during incense
439 burns is the same as that measured in the time-averaged indoor background sample collected prior
440 to incense experiments; and 3) the loss rate estimated during the post-burning decay period applies
441 throughout the incense emission event. Applying these assumptions, the PM_{2.5} emission factor,
442 *EF*, is then estimated using equation (2), where *m* is the mass of two incense sticks burned per
443 experiment.

$$444 \quad M = V \cdot L \cdot (C_i - C_b) \cdot \Delta t \quad eq (1)$$

$$445 \quad EF = \frac{M}{m} \quad eq (2)$$

446 Evidence from analysis of episodic point source emissions⁷⁷ shows that the use of the well-mixed
447 assumption should not result in large estimation errors if the gamma (γ ; source inactive and well
448 mixed) period is longer than the alpha (α ; source active and poorly mixed) plus beta (β ; source
449 inactive and poorly mixed) periods. Figure S3 illustrates time-resolved PM_{2.5} concentrations for
450 one of the experimental runs, showing that the duration of alpha plus beta periods is much less
451 than the gamma period. PM_{2.5} EFs from incense experiments ranged from 7 to 31 mg g⁻¹ (Table
452 S10) and were within the range of results from other incense stick burning studies^{9,12,16,29,59}
453 summarized in Table S11. Estimated PM_{2.5} EFs in this work indicated that Douglas fir incense
454 burns (average: 27 mg g⁻¹) produced more PM_{2.5} emissions than lavender (7 mg g⁻¹), which is
455 likely attributable to higher carbonaceous matter from woody biomass materials in Douglas fir
456 incense compared to the higher floral content in lavender incense. The estimated EFs could be
457 affected by both incense composition and burning conditions, which can vary in ways that are
458 neither easily predicted nor effectively controlled in H3 incense experiments. Nonetheless, results
459 suggest that the severity of indoor particle pollution from incense burning may be influenced by
460 incense scent or materials. In particular, incense with lower carbon and higher calcium content has
461 been shown to result in lower particle emission factors.^{16,78} Incense burning is often an episodic or
462 short-term source of PM_{2.5} indoors; however, long-term habitual use by occupants could have
463 cumulative effects on indoor air pollution and human health.

464 **3.6. Implications**

465 Exposure to incense-generated PM_{2.5} has been shown to be harmful to human health.²⁰ In this
466 study, we characterized in detail the chemical profile of fine particulate matter resulting from five
467 incense burning experiments in the H3 residence. Organic PM_{2.5} fractions from lavender and
468 Douglas fir incense burns resulted in 4.6–7.9 times higher concentrations of speciated OA
469 compared to background conditions when averaged over 6-h time periods. Incense-attributed
470 compounds showed clear similarities to BBOA with abundant masses of tracers such as
471 levoglucosan and dehydroabietic acid. Incense type also influenced the chemical composition of
472 OA as well as EFs with Douglas fir incense generating more PM_{2.5} than lavender (27 vs 7 mg g⁻¹).

473 Furthermore, ubiquitous indoor SVOCs, such as plasticizers, observed in H3 indoor background
474 air were influenced by increasing PM_{2.5} concentrations during incense burns due to volatility-
475 dependent gas-particle phase partitioning. Low-volatility indoor SVOCs were shown to strongly
476 correlate ($R^2 > 0.75$) with time-resolved concentrations of PM_{2.5} mass during incense burning
477 events, thus indirectly contributing to organic PM_{2.5} incense mass. These observations also
478 demonstrate how the chemical composition of incense-generated PM_{2.5} can be altered in indoor
479 air and point to potential increases in occupant uptake of low-volatility SVOCs such as DEHP and
480 BBzP, through shifts in their airborne concentrations and gas-particle phase partitioning. We
481 showed that incense burning, when it occurs, is a substantial combustion source of indoor PM_{2.5}
482 pollution with diverse chemical complexity and interactions with components of the indoor
483 environment. As such, more research directed toward chemical speciation would help to better
484 understand the impacts of incense burning emissions on indoor air quality in different indoor
485 environments. Given that this study was conducted in a single residence with only two types of
486 incense tested, readers are advised to exercise caution in extrapolating toward generalized
487 conclusions from this study.

488 **AUTHOR CONTRIBUTIONS**

489 J.O. wrote the manuscript, conducted incense experiments, and analyzed H3 PM_{2.5} filter samples;
490 M.R.A., Y.L., and E.B.F. supported data analysis and manuscript development; D.M.L. collected
491 and analyzed SV-TAG SVOCs data; C.E.I. supported experimental design and manuscript
492 development; B.C.S., W.W.N., and A.H.G. oversaw incense experiments and sample and data
493 analysis. All co-authors reviewed and contributed comments to the manuscript.

494 **SUPPORTING INFORMATION**

495 GC×GC methods and materials, quantification, compositional analysis, and derivatization;
496 Detailed descriptions of field campaign and incense experiments; Speciated mass concentrations
497 of indoor background and incense-attributed chemical families in incense PM_{2.5} samples;
498 Enhancement ratios of indoor background compounds; Incense PM_{2.5} OC, OA, loss rates, and EFs.

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511 **NOTES**

512 The authors declare no competing financial interests.

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1 *Supporting Information for*

2 **Characterizing PM_{2.5} Emissions and Temporal Evolution of Organic**
3 **Composition from Incense Burning in a California Residence**

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5 Cesunica E. Ivey, Brett C. Singer, William W Nazaroff, and Allen H. Goldstein

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7 **Supporting Information:**

8 Includes 17 pages, 6 experimental descriptions, 3 figures, and 11 tables.

9 Experimental:

- 10 • Field Campaign and Study Site, *p. S3*
- 11 • Detailed Incense Experiments and PM_{2.5} Sample Collection, *p. S3–S4*
- 12 • Detailed PM_{2.5} Filter Analysis and Quantification: GC×GC, *p. S5–S6*
- 13 • Compositional Analysis of Incense PM_{2.5} Samples, *p. S9*
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16 Tables:

- 17 • Table S1. Instrument Specifications and Materials, *p. S6*
- 18 • Table S2. Deuterated Internal Standard Compounds Applied to Each Filter Sample, *p. S7*
- 19 • Table S3. Indoor-Specific Authentic External Standards, *p. S7*
- 20 • Table S4. Biomass-Burning Related Authentic External Standards, *p. S8*
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22 Related to Biomass Burning and Possessing Hazard Codes, *p. S11*
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26 Total Indoor Background Mass Concentration from Each Incense Burn Sample, *p. S12*
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- 29 • Table S9. Total GC×GC Speciated Mass, OC, and OA Concentrations ($\mu\text{g m}^{-3}$) for H3 Incense
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- 31 • Table S10. PM_{2.5} Loss Rates, L (h^{-1}), and Emission Factors, EF (mg g^{-1}), for OA in H3 Incense
32 Burning Experiments, *p. S15*
- 33 • Table S11. PM_{2.5} Emission Factors, EF (mg g^{-1}), from Incense Sticks Burning Studies, *p. S15*

34 Figures:

- 35 • Figure S1. Time-resolved PM_{2.5} concentrations by Particles Plus during a Douglas fir incense
36 burn, separated by three experiment periods. The burning period for incense sticks is ~60 min
37 followed by the removal of the incense source from H3 at its conclusion. The sampling period
38 begins before incense combustion and is 6 h on average, *p. S5*
- 39 • Figure S2. Incidence of derivatized compounds in (a) the indoor background sample and (b, c)
40 in samples collected during Douglas fir and lavender incense burns, respectively, *p. S10–S11*
- 41 • Figure S3. Time-resolved PM_{2.5} concentrations by Particles Plus during a Douglas fir incense
42 burn, separated by three phases of mixing (α = source active, mixing incomplete; β = source
43 inactive, mixing incomplete; γ = source inactive, mixing complete), *p. S14*

44 **Field Campaign and Study Site**

45 Incense burning measurements analyzed in this study were conducted in a normally occupied
46 single-family residence (designated H3 as the third installment in a series of indoor observational
47 campaigns¹⁻³) located in a residential area of Oakland, California. The H3 residence was the study
48 site of a much larger effort that entailed a continuous observational indoor monitoring campaign.
49 The decision to investigate incense burning as a source of fine particle-phase organics in this
50 residence was intended to contribute new knowledge about the influence of an important indoor
51 emission source on indoor air chemistry. This specific site also served as a matter of convenience
52 for the incense experiments explored in the current study. Although no individual house can be
53 fully representative of all residential conditions, the H3 residence is a common example of older
54 construction (50-100 yr. old) single-family homes in urban core areas of the west coast of the US.

55 The H3 observational campaign spanned 10 weeks from early October to early December 2021.
56 H3 is a wood-framed detached home initially constructed in the 1910s as a 1200 square foot (sf)
57 dwelling consisting of two bedrooms, one bathroom, a kitchen, dining room, and living room.
58 These rooms are situated over an enclosed, dry, and well-ventilated standing height basement that
59 functions as both a garage and a storage area. A 600-sf two-story addition was constructed at the
60 back of the house in 1960 and adds a bedroom, bathroom, and office upstairs with an open bonus
61 room downstairs at ground level. The kitchen is outfitted with hardwood flooring, located at the
62 back of the original structure, with open doorways to the dining room and one bedroom in the main
63 original structure as well as to the upstairs hallway in the addition. At the time of the study, the
64 house had a central forced air, natural gas furnace with supply registers located in each room of
65 the original structure and on each floor of the addition with a single return register in the dining
66 room. This system was equipped with a MERV 13 air filter and controlled with a programmable
67 thermostat. The occupants of H3 comprised one adult male, one adult female, and one cat. They
68 lived in H3 residence as usual during the monitoring campaign. During the incense experiments,
69 H3 occupants were away from the house for several days. By normal practice of the residents, the
70 home was generally well-ventilated throughout the campaign by opening of multiple windows
71 during each day. However, during the incense burning experiments, all exterior doors and windows
72 were kept closed.

73 **Detailed Incense Experiments and PM_{2.5} Sample Collection**

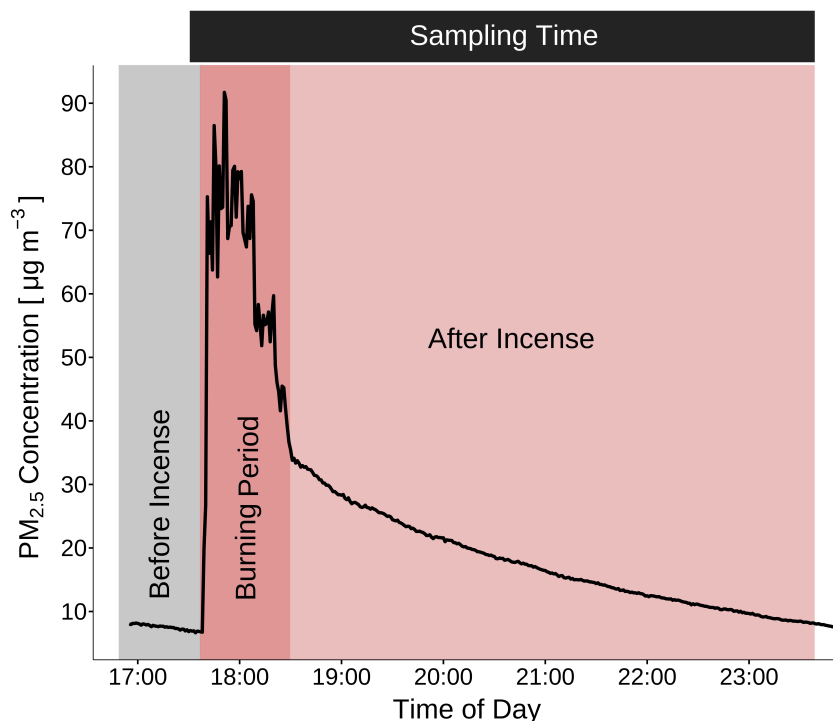
74 Incense smoke was sampled in H3 kitchen through a custom designed aerosol sampler (DEFCON,
75 UCB Goldstein Lab) with prior applications in biomass burning campaigns.^{4,5} DEFCON's inlet
76 housed a 2.5 μm sharp cut cyclone (BGI by Mesa Laboratories, SCC2.654) with an airstream flow
77 at 10 L min⁻¹ and downstream collection of airborne particle-phase (PM_{2.5}) aerosol on 47 mm
78 quartz fiber filters (Pallflex, Tissuequartz). Flow rates were measured and monitored with a data
79 logger (DATAQ Instruments, DI-2108) to verify constant flow at the target rate. Prior to sample
80 collection, quartz fiber filters were thermally prepared by baking at 550 °C for 12 h before being
81 individually stored in pre-baked aluminum foil, sealed in mylar bags, and packed in secondary
82 plastic Ziploc bags.

83 At H3, two different types of incense sticks were used in burning experiments. Lavender and
84 Douglas fir incense were purchased from a local supermarket, having been produced in India and
85 California, respectively. The selection of the incense scents burned in the study residence depended
86 on the preferences of H3 occupants. While the choice of incense scents by end users may be very
87 subjective, lavender and wood-based scents like Douglas fir are among the most popular and
88 relatively well-represented incense scents on the market.

89 Before incense experiments, a background sample of the indoor air at H3 was collected in the
90 kitchen over a 22-h period. H3 occupants reported that they had never burned incense during their
91 20-yr occupancy of the house. As a result, the background sample is assumed to be representative
92 of the H3 indoor environment, unperturbed by incense-related combustion products. Occupants
93 departed from the H3 residence the night prior to indoor background sampling. The gas-fired
94 furnace was off and all windows and doors to the outdoors were closed throughout the vacant
95 period (except for brief door opening for the ingress and egress of researchers).

96 Five incense experiments were carried out in all, once for lavender incense and four times for
97 Douglas fir incense, with burns occurring twice a day around noon and 5:30 pm. Incense
98 experiments were completed using two incense sticks for each “burn”. Both sticks were ignited
99 simultaneously in the kitchen and allowed to burn to completion over a ~60-min duration
100 designated as the burning period (see Figure S1). Following the burning period, the incense source
101 (uncoated stick remnants and tray holder) was removed from the kitchen and the H3 residence.
102 Indoor filter sampling started on average 8 min prior to incense ignition. Samples were collected
103 over 6-h periods on average, with one sample (DougFir-2) running through the night. Incense
104 emissions during the burning period of the fourth experiment for Douglas fir incense (DougFir-4)
105 were disturbed as one of the two sticks did not burn to completion once lit and needed to be
106 reignited several times. We observed lower PM_{2.5} organics attributed to incense for this DougFir-
107 4 experiment compared to others, which was likely a result of this incomplete combustion behavior
108 after the initial ignition.

109 All H3 indoor samples were collected under closed home conditions, except for brief entry by a
110 researcher to set up and remove sampling equipment. Three outdoor air samples, coinciding with
111 indoor sampling periods, were collected using a second DEFCON sampler placed on the wooden
112 deck in the small back yard with vegetation outside the H3 residence. Field blanks were collected
113 before each indoor and outdoor sample to estimate contributions from sampling components and
114 the kitchen indoor air. After sample collection, all filters were returned to their initial storage form
115 and frozen (-20 °C) prior to instrument analysis.



116
 117 Figure S1. Time-resolved PM_{2.5} concentrations by Particles Plus during a Douglas fir incense burn,
 118 separated by three experiment periods. The burning period for incense sticks is ~60 min followed
 119 by the removal of the incense source from H3 at its conclusion. The sampling period begins before
 120 incense combustion and is 6 h on average.

121 Detailed PM_{2.5} Filter Analysis and Quantification: GC×GC

122 PM_{2.5} filters collected in H3 were analyzed by offline thermal desorption two-dimensional gas
 123 chromatography with online derivatization coupled with electron ionization high resolution time-
 124 of-flight mass spectrometry (TD-GC×GC-EI-HR-ToF-MS). A complete methodological
 125 description of this instrument has been published⁶ and instrument specifications are summarized
 126 in Table S1. Filter punches (0.07-0.82 cm²) from all H3 filters were impregnated with isotopically
 127 labeled internal standards (Table S2) prior to analysis to correct for matrix effects and instrument
 128 performance. During thermal desorption of filter punches at 320 °C, a derivatization agent, N-
 129 methyl-N-(trimethylsilyl)trifluoroacetamide (MSTFA), was introduced to the helium gas flow.
 130 Online derivatization replaces the active hydrogen in -OH, -SH, and -NH₂ groups with a
 131 trimethylsilyl group, -Si(CH₃)₃, which enables easier elution and enhanced recovery of polar
 132 organic compounds. Thermally desorbed compounds were trapped on a 30 °C cooled inlet system
 133 with a quartz wool glass liner before injection into the GC system. Compounds were separated by
 134 volatility in the first column and then by polarity in the second column, with transfer between the
 135 two columns being cryogenically modulated (2.3 s). Separated compounds were then ionized by
 136 70 eV electron impact before detection by HR-ToF-MS with a resolving power of 4000. The
 137 volatility range of this analysis spans between ~C₁₃ and ~C₃₆ *n*-alkane volatility equivalents,
 138 accounting largely for semivolatile organic compounds (SVOCs), and some intermediate volatility
 139 organic compounds (IVOCs) and low volatility organic compounds (LVOCs).

140 For compound quantification, external standard mixtures of 110 compounds were prepared on
 141 quartz fiber filters and analyzed identically to sample filters. Both standard compounds and sample
 142 analytes were normalized (i.e., divided) by the average of the three nearest internal standards. Each
 143 internal standard compound is initially self-normalized by its respective mean across all GC×GC
 144 chromatograms during the analysis period. This normalization process ensures that any variations
 145 in instrument response of the internal standards are accounted for and prevents artificial inflation
 146 or deflation of quantified compounds.⁷ The authentic standards used in this work were selected for
 147 corresponding and relating to analytes observed in incense smoke and indoor environments. As
 148 such, 82 standard compounds were biomass-burning (BB) related (e.g., alkanes, acids, sugars, etc.)
 149 while the remaining 28 were indoor-specific (e.g., phthalates, esters, pesticides, etc.). The full list
 150 of external standard components is given in Tables S3 and S4. Six-point calibration curves ($R^2 >$
 151 0.90) for all external standards were generated and used to quantify compounds in H3 samples.
 152 Sample analytes matching an external standard were directly quantified while sample compounds
 153 not present in the standard mix were quantified by a proxy standard assignment.^{4,8} Sample
 154 compounds in the same chemical family as an existing standard were quantified using the closest
 155 external standard compound in that family. For unidentifiable and unknown compounds, the
 156 nearest external standard in 2D space was used for quantification. Mass loadings of quantified
 157 compounds were first blank subtracted when applicable before converting observed signals to
 158 mass concentrations using sampling duration and flow rate data. The quantification method
 159 described has approximate uncertainties of $\pm 10\%$ for standard matched compounds, $\pm 30\%$ for
 160 classified compounds using the nearest standard in the same family, and a systematic uncertainty
 161 of 200% for unknown compounds.⁴

162 **Table S1. Instrument Specifications and Materials.**

	TD-GC×GC-EI-HR-ToF-MS
Carrier gas	Helium: 2 ml min ⁻¹
Thermal desorption unit	Gerstel: TDS-3 and TDSA2
Thermal desorption temperature	320 °C
Cooled inlet system material	Gerstel: CIS4 (quartz wool)
Cooled inlet system temperature	Trap: 30 °C Release: 320 °C
Oven	Agilent: 7890A
Column 1 material	Restek, Rxi-5Sil MS: 60 m × 0.25 mm × 0.25 μm
Column 1 temperature	3.5 °C min ⁻¹ from 40 to 320 °C Hold: 5 min at 320 °C
Column 2 material	Restek, Rtx-200 MS: 1 m × 0.25 mm × 0.25 μm
Column 2 temperature	15 °C higher than column 1
Thermal dual-stage modulator	ZOEX
Guard column	Restek, Siltek: 1.5m × 0.25mm × 250 μm
Modulation period	2.3 s
Ionization	70 eV
Ionization chamber temperature	270 °C
Mass spectrometer	Tofwerk: HR-ToF-MS (m/Δm = 4000)

163 **Table S2. Deuterated Internal Standard Compounds Applied to Each Filter Sample.**

Internal Standard Compounds	
2 ¹³ C-pentaerythritol	d46-C22 alkane
C12 diacid	d50-C24 alkane
C6 diacid	d51-C26 acid
d10-phenanthrene	d5-3-hydroxyglutaric acid
d10-pyrene	d54-C26 alkane
d12-chrysene	d5-4-hydroxybenzaldehyde
d12-perylene	d58-C28 alkane
d21-decanol	d5-benzoic acid
d25-dodecanol	d5-C10 acid
d31-pentadecanol	d5-cholestane
d34-C16 alkane	d62-C30 alkane
d35-C18 acid	d66-C32 alkane
d37-octadecanol	d6-syringic Acid
d38-C18 alkane	d70-C34 alkane
d41-eicosanol	d74-C36 alkane
d42-C20 alkane	d7-cholesterol
d43-C22 acid	d8-anthraquinone
d4-4-methoxy-benzaldehyde	d8-methylcatechol

164 **Table S3. Indoor-Specific Authentic External Standards.**

External Standard Compounds (Indoor)					
Compound Name	RT2	RI ^a	Compound Name	RT2	RI ^a
1-Nonanol	0.46	1262	Diethyl phthalate	1.32	1587
2,4-Dihydroxybenzophenone	1.00	2146	Dimethyl phthalate	1.46	1449
2,5-Di-tert-butyl-1,4-benzoquinone	1.05	1474	Ethylparaben	0.95	1565
2-Phenoxyethanol	0.67	1357	Galaxolide	0.74	1849
4-Nonylphenol	0.58	1921	Homosalate	0.85	2019
Anethole	0.79	1277	Isopropyl myristate	0.67	1822
Benzophenone	1.09	1635	Methyl salicylate	0.91	1394
Benzyl butyl phthalate	1.15	2345	Methylparaben	0.98	1494
Bis(2-ethylhexyl) phthalate	0.96	2531	Propylparaben	0.93	1662
Butylparaben	0.90	1766	Tonalid	1.03	1858
Carvacrol	0.59	1320	Trimethyl pentanediol diisobutyrate	1.04	1589
D6 siloxane	0.49	1290	Tripropylene glycol monomethyl ether	0.58	1426
DEET (Diethyltoluamide)	1.62	1576	Tris(2-chloroethyl) phosphate	1.79	1757
Dibutyl phthalate	1.13	1954	α-Terpineol	0.52	1312

^aRI is based on linear *n*-alkanes

165 **Table S4. Biomass-Burning Related Authentic External Standards.**

External Standard Compounds (BB)					
Compound Name	RT ²	RI ^a	Compound Name	RT ²	RI ^a
1,2-Benzanthracene	1.17	2474	C28 alkane	0.53	2800
2,4-Dinitrophenol	2.24	1753	C28 carboxylic acid	0.67	3231
3,5-Dimethoxyphenol	0.80	1503	C29 alkane	0.54	2900
4-Hydroxybenzoic acid	0.83	1625	C30 alkane	0.54	3000
4-Methylcatechol	0.59	1383	C31 alkane	0.55	3100
4-Nitrocatechol	1.46	1742	C32 alkane	0.56	3200
5-(Hydroxymethyl) furfural	1.25	1301	C33 alkane	0.57	3300
5-Nitrovanillin	1.92	1834	C34 alkane	0.59	3400
Abietic acid	0.75	2425	C35 alkane	0.62	3500
Acenaphthylene	0.95	1459	C36 alkane	0.65	3600
Anthracene	1.03	1805	C9 carboxylic acid	0.64	1354
Benzo(a)pyrene	1.34	2886	Cholesterol	0.79	3153
Benzo(b)fluoranthene	1.33	2794	Chrysene	1.19	2484
Benzo(g,h,i)perylene	1.48	3279	D-(+)-mannose	0.56	1795
Benzo(k)fluoranthene	1.33	2802	Dibenz(a,h)anthracene	1.39	3217
C10 carboxylic acid	0.64	1457	D-pinitol	0.55	1825
C11 carboxylic acid	0.63	1554	Ergosterol	0.77	3236
C12 carboxylic acid	0.64	1651	Fluoranthene	1.13	2078
C13 carboxylic acid	0.63	1748	Fluorene	0.88	1593
C14 carboxylic acid	0.63	1847	Hexadecane, 2,6,10,14-tetramethyl-	0.49	1807
C15 carboxylic acid	0.63	1944	Hydroquinone	0.67	1397
C16 alkane	0.45	1600	Indeno(1,2,3-cd)pyrene	1.46	3207
C16 carboxylic acid	0.63	2043	Isopimaric acid	0.78	2343
C17 alkane	0.46	1700	Levoglucozan	0.78	1698
C17 carboxylic acid	0.62	2141	Maltol	1.02	1270
C18 alkane	0.46	1800	p-Anisic acid (4-methoxybenzoic acid)	0.88	1521
C18 carboxylic acid	0.62	2240	Pentadecane, 2,6,10,14-tetramethyl-	0.48	1704
C19 alkane	0.47	1900	Phenanthrene	1.03	1795
C20 alkane	0.47	2000	Pyrene	1.16	2137
C20 carboxylic acid	0.62	2439	Pyrocatechol (Catechol)	0.62	1303
C21 alkane	0.47	2100	Resorcinol	0.66	1376
C22 alkane	0.48	2200	Retene	0.97	2227
C22 carboxylic acid	0.64	2637	Sinapinaldehyde	1.43	2000
C23 alkane	0.49	2300	Stigmasterol	0.80	3283
C23 carboxylic acid	0.64	2735	Syringaldehyde	1.25	1698
C24 alkane	0.50	2400	Syringic acid	0.81	1892
C24 carboxylic acid	0.64	2833	Syringol (2,6-Dimethoxyphenol)	0.75	1395
C25 alkane	0.50	2500	Vanillic acid	0.80	1760
C26 alkane	0.51	2600	Vanillin	1.25	1536
C26 carboxylic acid	0.65	3031	α -Amyrin	0.92	3417
C27 alkane	0.52	2700	β -Sitosterol	0.77	3345

^aRI is based on linear *n*-alkanes

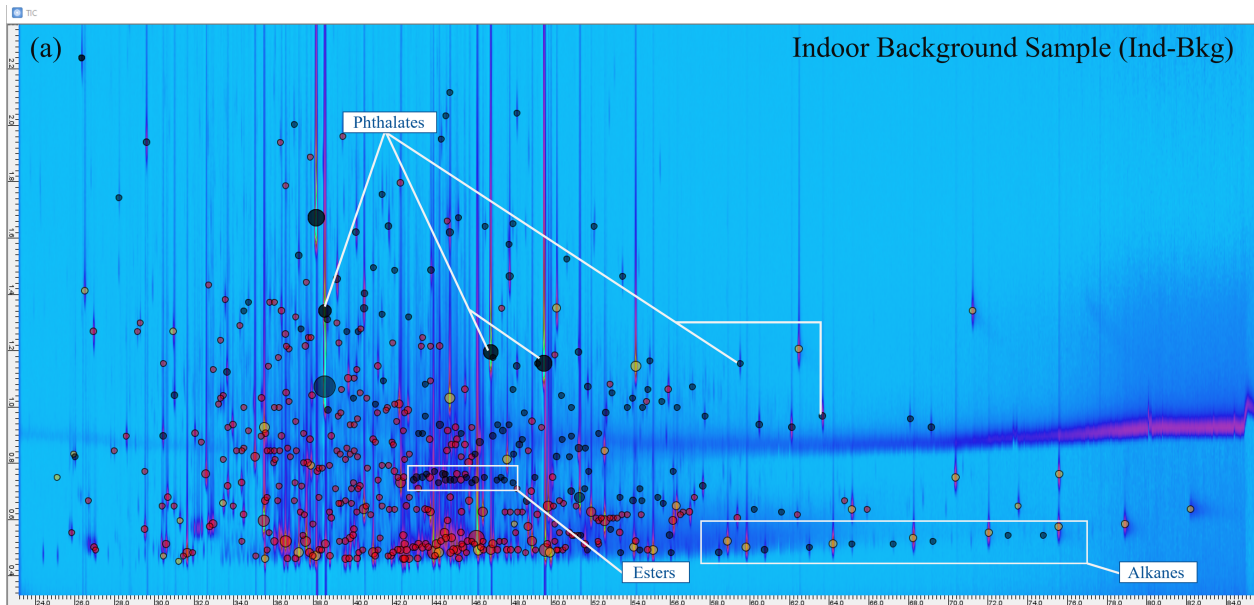
166 **Compositional Analysis of Incense PM_{2.5} Samples**

167 GC×GC chromatograms were analyzed with GC informatics software (GC Image, LLC). Initial
168 identification and classification of sample compounds into chemical families was accomplished
169 through direct matches with authentic standards, as determined by matching mass spectra and
170 retention times. Using the National Institute of Standards and Technology (NIST) Mass Spectral
171 Search software, the remainder of unmatched compounds were searched against the NIST-20 mass
172 spectral database and Goldstein Library of Biogenic and Environmental Spectra (UCB-GLOBES).
173 UCB-GLOBES was created at UC Berkeley with MS library entries from previous studies using
174 GC×GC.^{4,8} Compound matching (match factor > 700) relies on the first-dimension volatility linear
175 retention index (RI) that tracks the elution order from the first GC column. For compounds
176 analyzed using the same instrument, the RI is expected to be analogous and factored into the
177 analysis. Subsequent classification of compounds not readily identified by matching with external
178 standards and MS libraries was achieved with RI and second dimension retention times (RT₂)
179 comparisons as well as examination of EI mass spectra for specific molecular ions that are
180 representative of certain functional groups (e.g., $m/z = 204$ and $m/z = 217$ for derivatized sugars).
181 Compounds that could not be identified or classified using these methods are reported as unknown.

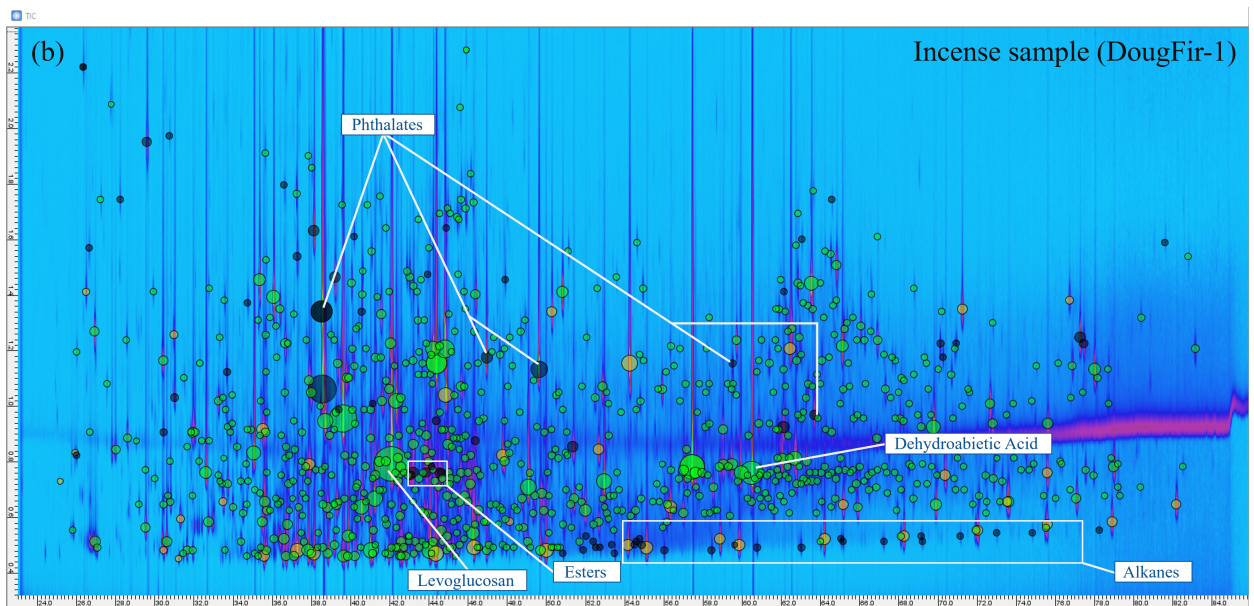
182 **GC×GC Derivatization Classification**

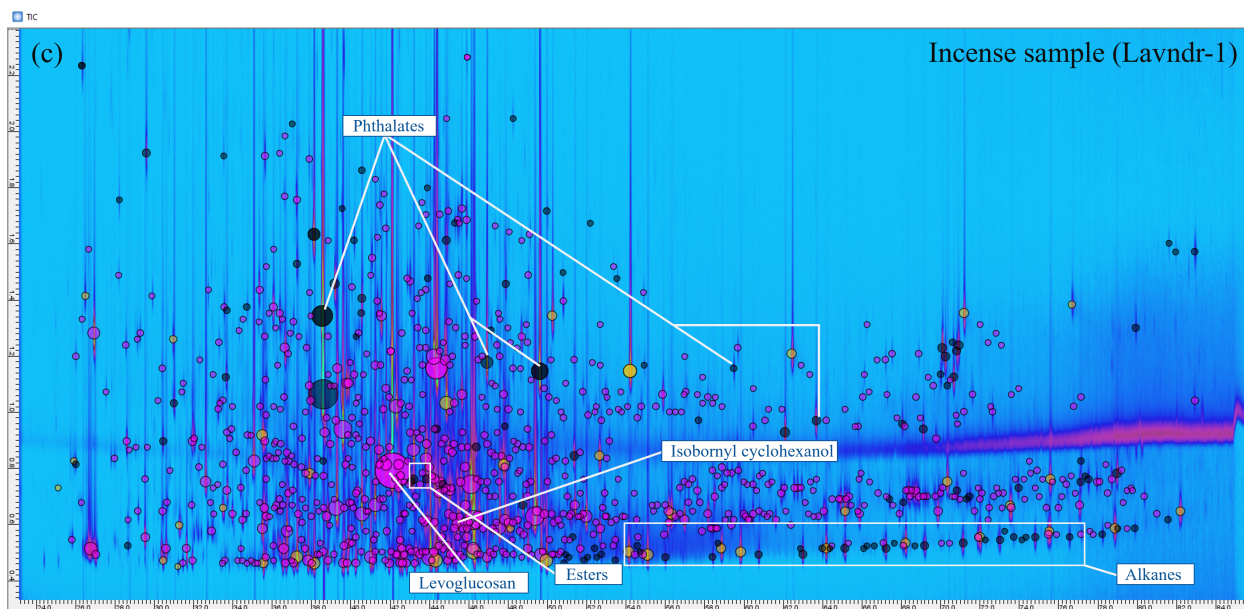
183 External standard compounds such as alkanes, phthalates, PAHs, and esters without active
184 hydrogens (e.g., -OH) were used to determine if a compound was derivatized in a sample. The
185 criteria for this process used the intensity of the $m/z = 73$ ion, which is indicative of a derivatized
186 compound as a result of $[\text{Si}(\text{CH}_3)_3]^+$, relative to (i.e., divided by and as a percentage of) the total
187 intensity value of the EI multi-spectrum for each compound. For the standard compounds used,
188 the threshold was a less than 5% contribution of the $m/z = 73$ ion intensity relative to the total
189 intensity of the multi-spectrum. As a result, compounds within a sample that exhibited $m/z = 73$
190 ion intensities less than 5% were categorized as underivatized. Figure S2 shows the distribution of
191 derivatized and underivatized compounds in the indoor background sample and burn samples of
192 Douglas fir and lavender incense. On average, derivatized compounds accounted for 86% of all
193 compounds detected and separated across all H3 samples. Black points highlighted in Figure S2
194 are underivatized compounds. Samples collected during incense burns had less than 12% of
195 incense-attributed compounds underivatized while the indoor background sample had 30%
196 underivatized compounds. Analysis with GC×GC coupled with online derivatization captures and
197 retains polar and oxygenated compounds in incense smoke.

198



199





200
 201 **Figure S2.** Incidence of derivatized compounds in (a) the indoor background sample and (b, c) in
 202 samples collected during Douglas fir and lavender incense burns, respectively. Red, green, and
 203 purple points in (a, b, c) represent derivatized sample compounds, black points represent
 204 underivatized sample compounds, and yellow points represent internal standard compounds.

205 **Table S5. Speciated OA Mass Concentrations ($\mu\text{g m}^{-3}$) for Positively Identified Compounds**
 206 **Related to Biomass Burning and Possessing Hazard Codes.⁹**

	Lavindr-1	DougFir-1	DougFir-2	DougFir-3	DougFir-4
Levoglucosan	1.31	0.91	1.05	1.20	0.43
Dehydroabietic acid	< 0.01	0.73	0.25	0.49	0.22
Tetracosanoic acid	0.08	0.13	0.08	0.10	0.06
Hexacosanoic acid	0.04	0.13	0.12	0.12	0.04
Pyrogallol	0.02	0.01	< 0.01	0.01	< 0.01
Galactosan	< 0.01	0.01	0.01	0.01	< 0.01
Vanillic acid	0.01	< 0.01	< 0.01	< 0.01	< 0.01
D-pinitol	0.02	< 0.01	< 0.01	–	–
4-Hydroxybenzoic acid	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Catechol	0.02	–	–	0.01	–
Eicosanoic acid	0.06	0.05	0.04	0.04	0.03
Hexanedioic acid	0.05	0.07	0.01	0.02	0.02

207 **Table S6. Speciated GC×GC OA Mass Concentrations ($\mu\text{g m}^{-3}$) of Each Chemical Family for**
 208 **Total Incense-Attributed Mass Concentration from Each Incense Burn Sample.**

	Lavndr-1	DougFir-1	DougFir-2	DougFir-3	DougFir-4
Acids	0.30	0.40	0.31	0.32	0.16
Alcohols	0.03	0.03	0.02	0.02	0.01
Alkanes	0.05	0.01	0.01	0.06	0.08
Aromatics	0.09	0.11	0.09	0.07	0.04
Cyclics/Oxy	0.56	0.56	0.40	0.31	0.14
Methoxyphenols	0.05	0.37	0.15	0.24	0.13
Other Oxy	0.11	0.30	0.11	0.23	0.08
Other Terpenoids	0.19	–	–	–	–
Resins/Diterpenoids	< 0.01	2.18	0.91	1.72	0.79
Sterols/Triterpenoids	0.07	0.26	0.15	0.20	0.08
Sugars	2.80	2.22	1.69	2.43	0.89
Not Identifiable	0.38	0.20	0.11	0.19	0.13
Unclassified	1.07	1.27	0.83	1.06	0.73

209 **Table S7. Speciated GC×GC OA Mass Concentrations ($\mu\text{g m}^{-3}$) of Each Chemical Family for**
 210 **Total Indoor Background Mass Concentration from Each Incense Burn Sample.**

	Ind-Bkg	Lavndr-1	DougFir-1	DougFir-2	DougFir-3	DougFir-4
Acids	0.04	0.28	0.26	0.16	0.23	0.18
Alcohols	0.16	0.58	0.55	0.18	0.35	0.57
Alkanes	0.01	0.13	0.03	0.03	0.17	0.24
Aromatics	0.02	0.08	0.10	0.04	0.07	0.09
Cyclics/Oxy	0.01	0.01	0.01	0.01	0.01	0.01
Esters	0.07	0.15	0.16	0.08	0.15	0.21
Flame Retardants	0.03	0.10	0.02	0.06	0.04	0.08
Other Non-Cyclic Aliphatics/Oxy	0.01	0.01	0.01	0.01	< 0.01	0.01
Other Oxy	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Pesticides	0.15	0.10	0.06	0.07	0.08	0.09
Plasticizers, Non-Phthalates	0.12	0.55	0.33	0.17	0.68	0.68
Plasticizers, Phthalates	0.14	0.28	0.21	0.14	0.18	0.25
Siloxanes	0.04	0.07	0.13	0.03	0.06	0.07
Surfactants	0.36	0.33	0.37	0.28	0.25	0.34
Not Identifiable	0.12	0.47	0.51	0.17	0.23	0.51
Unclassified	0.07	0.20	0.14	0.08	0.13	0.17

211 **Table S8. Mean and Median Enhancement Ratios of Indoor Background Compounds**
 212 **Detected in Incense Samples.^a**

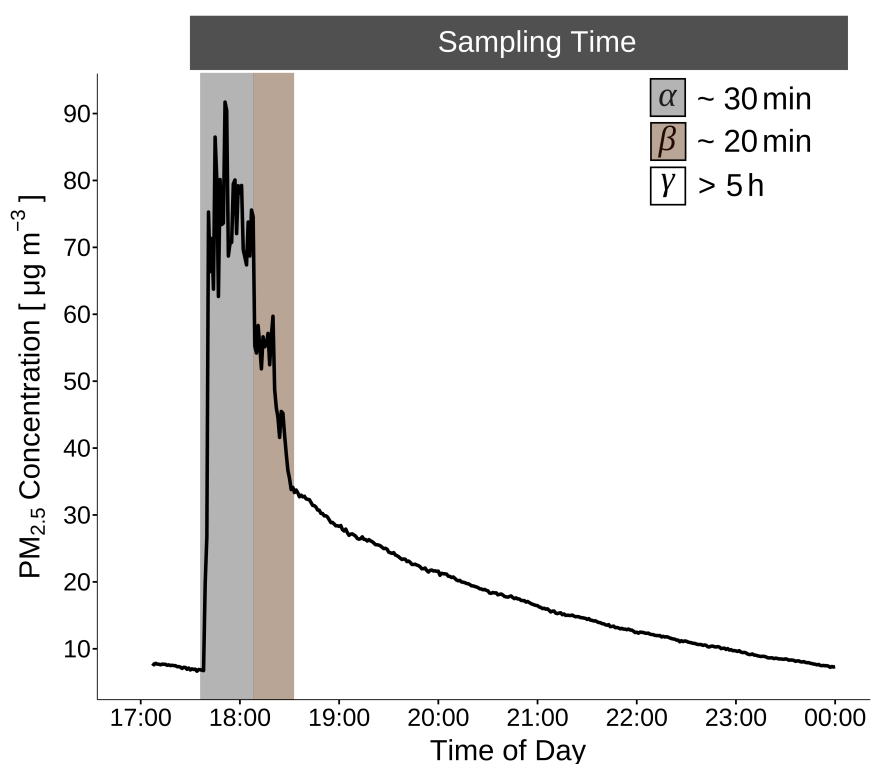
Compound Identification	Chemical Family	RT ²	RI ^b	Median	Mean
Azelaic acid, 2TMS ^c	Acids	0.86	1793	24.2	26.2
C10 carboxylic acid	Acids	0.64	1456	7.7	7.6
C12 carboxylic acid	Acids	0.63	1650	8.0	8.1
C13 carboxylic acid	Acids	0.63	1748	8.3	8.8
C20 carboxylic acid	Acids	0.62	2438	14.5	16.0
Hexanedioic acid, 2TMS	Acids	0.90	1503	8.6	11.9
1-Dodecanol, TMS	Alcohols	0.48	1567	4.6	4.0
1-Tetradecanol, TMS	Alcohols	0.48	1763	2.8	2.7
1-Tridecanol, TMS	Alcohols	0.48	1665	4.9	4.8
2-Tetradecanol, TMS	Alcohols	0.47	1688	4.9	4.9
C21 alkane	Alkanes	0.48	2100	4.9	4.6
C22 alkane	Alkanes	0.48	2200	4.7	5.8
C26 alkane	Alkanes	0.51	2600	40.3	36.4
C27 alkane	Alkanes	0.51	2700	46.5	42.8
C28 alkane	Alkanes	0.52	2800	51.5	41.5
C30 alkane	Alkanes	0.54	3000	16.2	12.9
C31 alkane	Alkanes	0.54	3100	10.1	8.1
2,6-Dimethoxyhydroquinone, 2O-TMS	Aromatics	0.73	1672	8.2	9.8
Homosalate, TMS	Aromatics	0.85	2019	5.3	5.6
Isophthalic acid, TMS	Aromatics	0.88	1756	7.2	6.7
Versalide	Aromatics	0.74	1850	4.3	5.1
γ -Dodecalactone	Cyclics/Oxy	1.75	1678	3.9	3.8
γ -Palmitolactone	Cyclics/Oxy	1.46	2103	2.6	2.7
Diisopropyl adipate	Esters	1.12	1448	2.8	2.8
Isopropyl myristate	Esters	0.66	1822	4.9	4.5
Methyl palmitate	Esters	0.66	1924	3.0	2.8
Vinyl 2-ethylhexanoate	Esters	0.86	1912	2.8	2.7
Benzyl Benzoate	Pesticides	0.93	1773	3.0	2.9
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (TXIB)	Plasticizer, Non-Phthalates	1.07	1589	2.4	2.5
2,2,4-Trimethyl-1,3-Pentanediol, 1-isobutyrate	Plasticizer, Non-Phthalates	1.03	1371	6.2	6.1
Bis(2-ethylhexyl) terephthalate (DEHT)	Plasticizer, Non-Phthalates	0.95	2744	5.7	6.3
Triacetin	Plasticizer, Non-Phthalates	1.93	1330	8.1	7.0
Tributyl phosphate	Plasticizer, Non-Phthalates	1.26	1641	2.2	2.2
Triethylene glycol di(2-ethylhexoate) (TEG-EH)	Plasticizer, Non-Phthalates	0.92	2461	7.8	7.8
Benzyl butyl phthalate (BBzP)	Plasticizer, Phthalates	1.15	2346	5.0	5.3
Bis(2-ethylhexyl) phthalate (DEHP)	Plasticizer, Phthalates	0.96	2531	5.3	5.5
Diethyl phthalate (DEP)	Plasticizer, Phthalates	1.33	1589	5.3	5.3
D7 siloxane	Siloxanes	0.52	1468	5.1	6.5
D8 siloxane	Siloxanes	0.53	1629	5.0	6.0
L10 siloxane	Siloxanes	0.50	1994	2.7	2.7
1-(1-Butoxy-2-propoxy)-2-propanol, TMS	Surfactants	0.51	1359	3.7	3.4
Diethylene glycol, 2TMS	Surfactants	0.55	1220	2.7	3.5
Diethylene glycol, n-butyl ether, trimethylsilyl ether	Surfactants	0.56	1328	4.8	4.8

^aCompounds included are those consistently enhanced (ER > 2) across all incense samples, classified, and positively identified. ^bRI is based on linear *n*-alkanes. ^c“TMS” refers to a single trimethylsilyl group.

213 **Table S9. Total GC×GC Speciated Mass, OC, and OA Concentrations ($\mu\text{g m}^{-3}$) for H3**
 214 **Incense Burning Experiments.**

	Speciated mass	OC ^a	EC ^b	TC ^c	OA ^d
Lavndr-1	9.1	22.2	2.7	25.0	35.6
DougFir-1	10.8	37.2	1.1	38.3	59.5
DougFir-2	6.3	17.4	0.4	17.8	27.9
DougFir-3	9.5	31.8	1.2	32.9	50.9
DougFir-4	6.7	26.7	0.9	27.6	42.8

215 ^aOC = organic carbon; ^bEC = elemental carbon; ^cTC = total carbon
 216 ^dTotal organic aerosol (OA) mass is calculated using OA/OC = 1.6, as derived from Aiken et al.¹⁰ and
 217 Canagaratna et al.¹¹



218
 219 **Figure S3.** Time-resolved PM_{2.5} concentrations from Particles Plus during a Douglas fir incense
 220 burn, separated by three phases of mixing (α = source active, mixing incomplete; β = source
 221 inactive, mixing incomplete; γ = source inactive, mixing complete).¹²

222 **Determining Incense PM_{2.5} Loss (Decay) Rates**

223 The time series of PM_{2.5} concentrations for the decay period, shown in Figure S3 as gamma (γ),
 224 was used in calculating the total loss rate, L , by ventilation and other loss processes (e.g.,
 225 deposition to indoor surfaces) during each incense burning experiment.¹³ Equation (1) represents
 226 a first-order mass balance, where C is incense PM_{2.5} concentration, E is the PM_{2.5} emission rate
 227 during incense combustion, and V is the well-mixed H3 indoor volume.

228
$$\frac{dC}{dt} = -LC + \frac{E}{V} \quad eq (1)$$

229 During the decay period, the incense source is inactive and so $E = 0$. Therefore, equation (2)
 230 provides the solution to equation (1) for the gamma period, where $C(t)$ is time-resolved incense
 231 PM_{2.5} concentrations during the decay time, t . The total loss rate, L , is determined from the slope
 232 of the regression line of the logarithm of concentration versus time shown in equation (3).

233
$$C(t) = C(0) \cdot e^{-Lt} \quad eq (2)$$

234
$$\ln(C(t)) - \ln(C(0)) = -Lt \quad eq (3)$$

235 **Table S10. PM_{2.5} Loss Rates, L (h⁻¹), and Emission Factors, EF (mg g⁻¹), for OA in H3 Incense**
 236 **Burning Experiments.**

	L (h ⁻¹)	EF (mg g ⁻¹)
Lavndr-1	0.25	7
DougFir-1	0.28	24
DougFir-2	0.27	31
DougFir-3	0.30	29
DougFir-4	0.32	23

237 **Table S11. PM_{2.5} Emission Factors (mg g⁻¹) from Incense Sticks Burning Studies.**

Incense Study	EF (mg g ⁻¹)
Jetter et al. ¹⁴	5.0 – 56
Lung and Hu. ¹⁵	21 – 45
Lee and Wang. ¹⁶	7.7 – 104
Yang et al. ¹⁷	17 – 48
See and Balasubramanian. ¹⁸	0.4 – 45

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