

Volatile Organic Compounds Inside Homes Impacted by Smoke from the Marshall Fire

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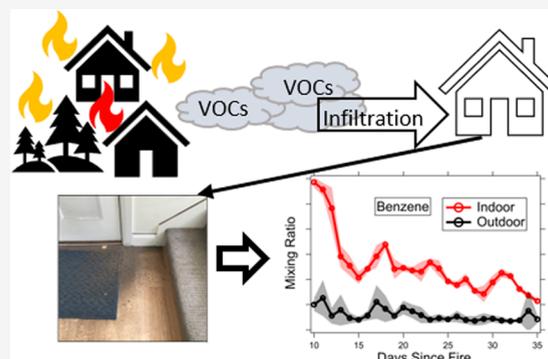


Supporting Information

ABSTRACT: Wildfires at the wildland–urban interface (WUI) have been increasing in frequency over recent decades due to increased human development and shifting climatic patterns. The work presented here focuses on the impacts of a WUI fire on indoor air using field measurements of volatile organic compounds (VOCs) by Proton-Transfer-Reaction Time-of-Flight Mass Spectrometry (PTR-TOF-MS). We found a slow decrease in VOC mixing ratios over the course of roughly 5 weeks starting 10 days after the fire, and those levels decreased to ~20% of the initial indoor value on average. The VOC composition could be described by a combination of biomass burning emissions and indoor air composition. Comparisons were made between polycyclic aromatic hydrocarbon (PAH) distributions in the gas phase and ash, with differences observed in their distribution between each other and when compared to fresh fuel inventory measurements.

Mitigation tests were conducted running air cleaners with activated carbon and opening windows to promote indoor–outdoor air exchange, with both methods showing a decrease greater than 50% for average VOC levels indoors while active. We compare our results with simulated smoke impact experiments that show the slow decline in VOCs must be understood in the context of indoor reservoirs, beyond just on surfaces, leading to the slow release of VOCs to indoor air.

KEYWORDS: wildfires, wildland–urban interface, volatile organic compounds, indoor air, smoke, PTR mass spectrometry, mitigation, gas phase surface interaction



INTRODUCTION

The intensity and frequency of wildfires in the U.S. have been increasing steadily in recent decades.^{1,2} This shift in fire behavior requires a better understanding of the impacts of wildfires on climate, air quality, and human health.^{3–5} Wildfires are large sources of fine particles that can be damaging to human health and also emit volatile organic compounds (VOCs), which can be toxic and undergo reactions that form ozone and secondary organic aerosols downwind.^{3,6} Fires at the wildland–urban interface (WUI) have become more prevalent and destructive in recent decades.^{7–9} The WUI is defined as the area where human settlements meet the natural environment and has been increasing in area across the U.S. for the past several decades.^{7,9,10} The proximity of these wildfires to structures and people raises unique concerns regarding the levels of smoke exposure as well as the available fuel for the fires. While the emissions from biomass fires have been examined in detail in both lab and field settings, the emissions and impacts from WUI fires are less well studied.^{11,12}

The Marshall Fire was a WUI fire that occurred on December 30th, 2021 in and around the towns of Louisville, Superior, and unincorporated areas around Boulder County, Colorado. The combination of extremely dry grasslands and intense winds on the day of the blaze resulted in a fast-moving fire spread. Multiple neighborhoods in Louisville and Superior were burned, with a total structural loss of more than 1000 buildings and with many more homes and buildings experiencing intense smoke impacts from the fire.¹³ Figure 1 outlines the area affected by the fire and illustrates some of the smoke impacts that were seen inside many homes. In addition to these visible impacts, the smoke-impacted homes had a strong burn smell indoors.¹⁴ Many residents had questions

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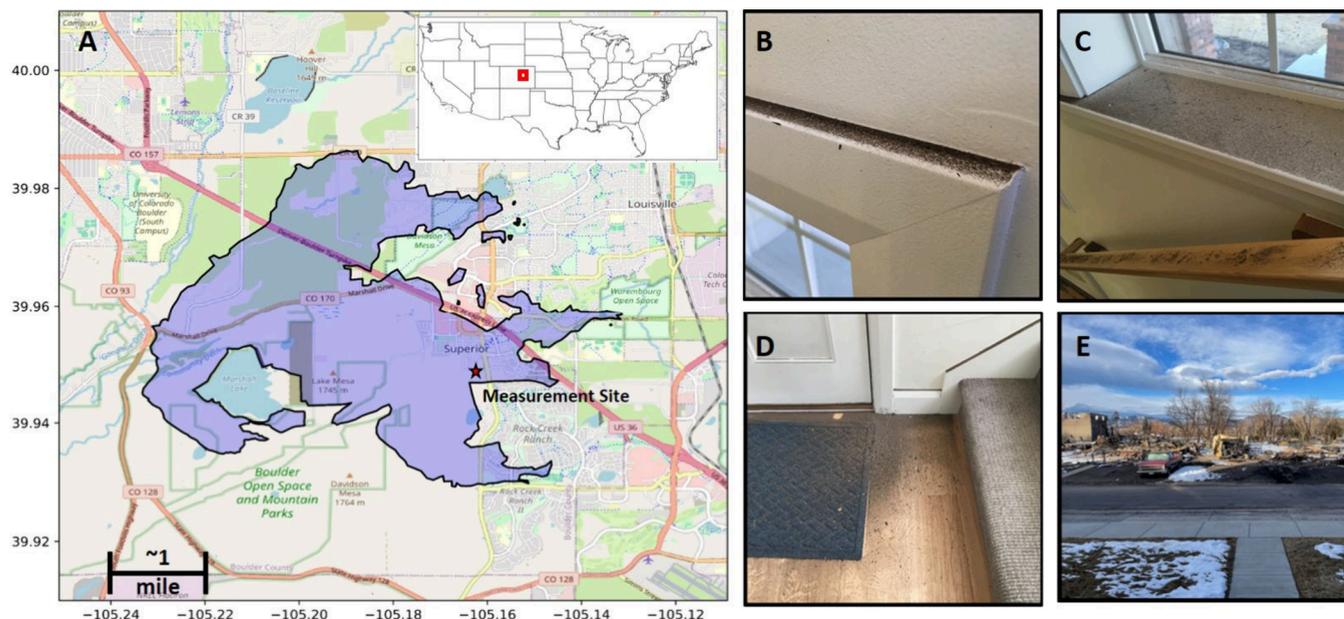


Figure 1. Outline of the area impacted by the Marshall Fire (A) with an inset of a U.S. map showing the area in the red square.¹⁵ The marker shows the site home located in Superior. Photos show ash and soot deposits in the site home (B–D) and the view from the site to the west showing the fire impacts across the street (E).

about the smoke impacts on their homes, potential health concerns, and how to clean their homes following the fire. However, the existing literature on these topics is very limited.

Smoke impacts on indoor environments have been studied for other sources, such as cigarette smoke, but are not well studied for wildfire smoke.^{16–19} Long-term effects were compared in wildfire-smoke-impacted and non-smoke-impacted homes after many months showing little difference, but the short-term effects are essentially unknown, though critical for those returning in the days following a fire.^{12,20–22} Indoor environments have high surface-to-volume ratios, which promotes the partitioning of compounds from the air to surfaces thereby affecting the persistence of these compounds in indoor environments.¹⁶ This partitioning to surfaces has been shown to occur on a time scale of hours.²³ A recent simulated home study looked at the fate of wildfire smoke compounds in indoor spaces.²⁴ This study noted retention of compounds in the indoor air on the time scale of hours to days depending on the chemical composition of the compounds and mitigation methods used.²⁴ In WUI fires, fuels do not just include vegetation, but also include materials such as roofing, siding, furniture, carpeting, insulation, electronics, wiring, tires, and plastics, which could change the compounds found in smoke-affected indoor environments.^{8,11} It is not well understood what VOCs are released from the combustion of such materials and how these species persist in indoor environments after WUI fires.

In response to the questions from residents after the Marshall Fire and the absence of good information in the literature, we started the HOME Smoke and Odor Study (HOME SOS) within days after the fire. The goals of HOME SOS were to measure gas and particle-phase pollutants in multiple homes impacted by the Marshall Fire, their behavior over time and the effectiveness of different remediation efforts. We deployed research-grade instrumentation in one heavily impacted home in Superior (see Figure 1 for the location¹⁵), which is the focus of this work, and low-cost sensor packages

to ten more homes in the burn area. Measurements began roughly 10 days after the fire. Indoor and outdoor VOC mixing ratios were measured in real time over the course of roughly 5 weeks. In this paper, we first describe the decrease in the indoor VOC mixing ratios with time after the fire. Next, we compare the composition of measured VOCs with data reported in the literature for indoor air and wildfire smoke, which allows us to separate the smoke impacts from expected indoor VOCs. Ventilation and air cleaning experiments were performed to study if and how residents could protect themselves. Potential tracers for WUI fires such as polycyclic aromatic hydrocarbons (PAHs) were examined with context from ash studies and previous emission measurements. The decrease in indoor VOCs is discussed in the context of other studies that have quantified the removal of VOCs from indoor air.

INSTRUMENTATION/SAMPLING

Instrumentation. Measurements were made using a Vocus 2R Proton Transfer Reaction Time of Flight Mass Spectrometer (PTR-TOF-MS, ToFwerk) described by Krechmer et al.²⁵ Briefly, hydronium ions are generated using a discharge ion source and act as the chemical ionization reagent ions for VOCs. The product ions are formed in a Focusing Ion Molecular Reactor (FIMR), transmitted by a big segmented quadrupole (BSQ), and detected using a time-of-flight (TOF) mass analyzer. In this work, the FIMR had an RF voltage of 400 V, DC voltage of 500 V, and a pressure of 1.5 mbar resulting in an E/N value of ~ 160 Td for the reactor. In addition to transmitting ions from the reactor to the mass analyzer, the BSQ acts as a low mass filter to exclude reagent ions and had an RF voltage of 255 V.²⁵

Sampling Site and Set-up. The site home was a two-story single-family home built in 2020 with a size of 2878 ft². The main room on the first floor was made up of the living room, kitchen, and dining room with two additional rooms on the first floor. There were three rooms on the second floor of the

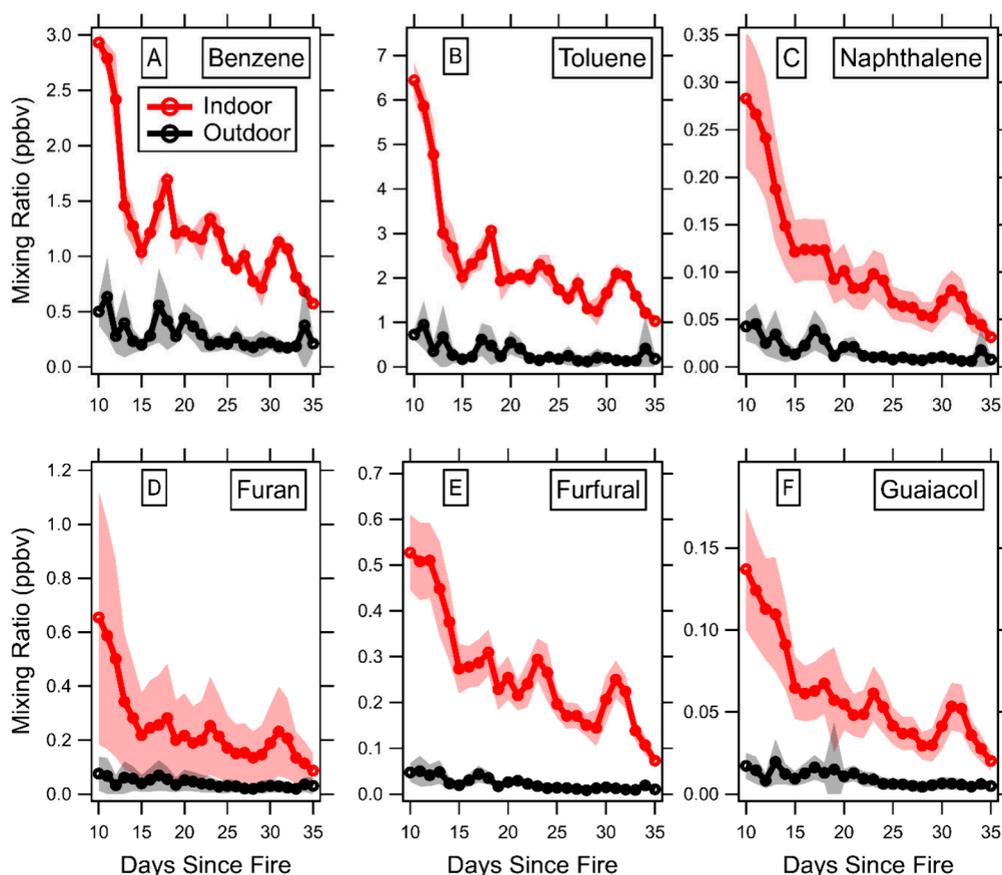


Figure 2. Panels A, B, and C show the daily average mixing ratios of several aromatic VOCs relative to the day of the fire. The symbols are daily averages showing both indoor and outdoor mixing ratios, with the shaded area showing the standard deviation. Panels D, E, and F show the same measurements but for several VOCs known to come from biomass burning.

home. The Vocus was placed in the main room on the first floor. Sampling flow of ~ 1.2 L/min was passed in front of the instrument through a three-way tee union with a flow of roughly 0.1 L/min sampled by the instrument. Two three-way valves were set up to automatically switch between sampling indoor and outdoor air with Teflon tube lengths of 2.3 m. Air was pulled through both lines continuously to minimize sampling memory effects. The sampling was switched at 10 min intervals for the majority of the campaign (Figure S1). The site home was unoccupied for the duration of the experiments but there were periodic visits by scientists as well as the homeowners that were logged. The HVAC system was active for the majority of the study, aside from ventilation events, with the temperature set to 55 °F and a filter installed. The air exchange rate (AER) of the house was measured at 0.13 ± 0.04 air changes per hour (ACH) using the CO_2 removal rate in unoccupied periods enhanced by CO_2 releases through dry ice.²⁶

Mitigation and Ventilation. Tests were conducted to investigate the effects of ventilation and indoor air cleaning techniques on the indoor VOC levels. For the ventilation tests, a group of 5 windows both upstairs and downstairs were opened systematically with starting and ending times noted. The air cleaning tests involved the construction of Corsi-Rosenthal boxes of various sizes and with different filters.²⁷ These boxes use a box fan and pleated air filters and have been shown to be effective at improving indoor air quality in multiple settings.^{27,28} Two boxes were constructed and both placed in the main room on the first floor during testing. Either

20 in \times 20 in particle filters or activated carbon filters (3 M Filtrete Merv 11 Odor Reduction) were used in both boxes to note differences in efficacy for VOC removal. Multiple tests were performed at varying durations to gauge effectiveness over time and time to reach maximum effectiveness. We also conducted multiple temperature ramping experiments in the house to investigate increasing indoor VOC partition from surfaces to the gas phase and potential removal by indoor ventilation as a method to reduce the indoor VOC mixing ratios.

Sampling and Quantification. Vocus 2R data were collected at 1 Hz averaged to 5 s over a mass range of m/z 1–600. Six-point calibrations were performed daily with short instrument background measurements and calibrations performed every 1 and 2 h, respectively. The calibration tank (Apel Riemer) contained 13 VOCs at known mixing ratios of around 1000 ppbv \pm 5%. Flows were set at 0.4 L/min of zero air using a catalyst clean air system (Tofwerk AG) and 0.05 L/min of calibration gas composed of a mix of 12 VOCs. Quantification of VOCs beyond those directly calibrated with a tank was done using the method described by Sekimoto et al.^{29,30} Where appropriate, our data were corrected with a mass transmission curve and weighted by the standard error in the measurement values. The mixing ratios error vary by VOC but in general see an average deviation of 10% for those we explicitly calibrated and uncertainties of around 30% for those approximated using the reaction rate approximation which falls in line with expectation from the method. Long average times

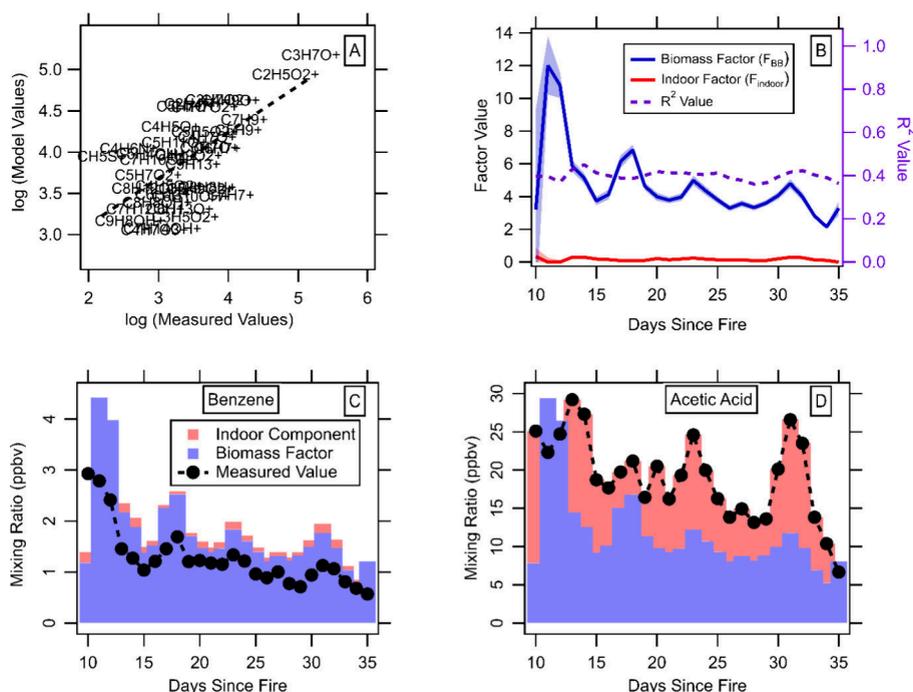


Figure 3. Outline of the two-factor fit using data sets for indoor and fresh structural burn emissions. Panel A gives an example fit of the model output values versus the measured values on day 2 with the resulting fit coefficient in log space. Panel B shows the daily fit parameters (F_{indoor} , F_{BB}) and fit coefficient when comparing model output to measurement values with a value $n = 38$ for all days of the study. Panels C and D outline fit examples with both factors and the sum versus measured values for acetic acid and benzene. The initial day of measurements involved a large degree of variability due to setup, which could explain the variability in the fit over that day.

and high signal on ions do allow us to have high precision and quantify small changes over time.²⁹

RESULTS

Indoor Mixing Ratio Evolution. Figure 2 shows the daily averaged mixing ratios for six different VOCs measured during the study. Measured indoor mixing ratios are in red, while outdoor mixing ratios are in black, with the shaded areas showing the standard deviations for each day. Data are shown for three different aromatic compounds in the top row, and three different compounds that are released from biomass burning in the bottom row.³¹ In addition to these six VOCs, we quantified mixing ratios for 48 additional compounds. Several observations can be made:

- The indoor mixing ratios were much higher than the outdoor mixing ratios, sometimes by an order of magnitude (i.e., furfural). This by itself is not unusual for indoor environments,^{32,33} so further work was required to tie elevations to smoke impacts, which will be discussed later in this work. This is true for the six VOCs shown in Figure 2, but also for almost all of the other compounds that were quantified (Figure S2).
- There was a decline in the mixing ratios across the duration of the study. The decline was relatively pronounced from day 10 to day 15 after the fire. After those first 5 days of the study, the decline continued but at a slower rate. The smaller spikes later on in the graphs, particularly around day 30, are related to the temperature ramping experiments, resulting in increased mixing ratios in the gas phase, while the temperature increases and then decreases as the temperatures are lowered again (Figure S3). The indoor increase around day 17 is likely tied to outdoor increases, seen in the

aromatics in Figure 1, resulting in infiltration and increases in the mixing ratios in the indoor environment.

- The outdoor mixing ratios declined as well during the study, which may be due to the regular seasonal cycle in VOC mixing ratios caused by increased boundary layer heights and decreased atmospheric lifetimes. The outdoor declines could also be related to local traffic declining for a period after the fire. There is some variability, particularly in the C8-aromatics (xylenes and ethylbenzene), which may be due to traffic emissions in the area related to postfire clean up.
- The VOC mixing ratios were relatively high at the beginning of the study (10 days after the fire). For perspective, benzene mixing ratios of 3 ppbv and toluene mixing ratios of 6 ppbv were regularly observed in urban air in Los Angeles in the 1990s, but have declined significantly since.³¹ The gas mixing ratios at the end of our study are more regularly observed in indoor air.³² A full risk assessment of exposure to these VOC levels is beyond the scope of this study. We attribute the decline in VOC mixing ratios to the gradual evaporation from reservoirs over the course of the study and the lack of significant indoor sources throughout the time period; this will be discussed in more detail below.

We can place these results in the context of what residents in the area reported on indoor air quality in a study by Reid et al. (10.1021/acsestair.4c00258). After returning to smoke-impacted homes, residents complained about indoor air quality, with 60% of those who reported a change likening the smell inside their home to a campfire and 28% of respondents attributing the smell to a chemical fire.¹⁴ These reported smells are consistent with the data we collected, with enhanced VOC mixing ratios indoors, which can have strong smells after the

fire and a gradual decline on a time scale of ~ 5 weeks. We conclude that the enhanced indoor mixing ratios of VOCs observed in Figure 2 were likely caused by smoke impacts from the Marshall Fire. More evidence will be presented in the next section.

Source Apportionment of VOCs. To provide further evidence, we investigate the composition of the VOCs in this section and compare it with data sets from the literature that represent the major expected sources in the air we were measuring, i.e., an indoor VOC profile and a biomass/structural burning profile. For normal indoor air, we use a study by Lunderburg et al.³⁴ who compiled data from indoor air VOC measurements in multiple homes in California. For WUI fires, we used a study by Brillì et al.³⁵ who measured mixing ratios of VOCs from a biomass fire that consumed one structure. These studies were also chosen to maximize overlap between the specific VOCs measured in both reference sets and our measurements (Figure S4). We investigated if the composition of air in our measurements could be described by a combination of these two sources (residential indoor air and biomass burning emissions). Specifically, we use a regression that fits our daily average VOC data values using a linear combination of the composition data from indoor air and the biomass/structure fire from these two studies. Equation 1 summarizes the method, with F_{indoor} representing the indoor factor that weights the indoor contribution of the reference indoor VOC set and F_{BB} being the same for the biomass burning data.

$$\begin{pmatrix} \text{VOC}_1 \\ \text{VOC}_2 \\ \vdots \\ \text{VOC}_n \end{pmatrix} = F_{\text{indoor}} \times \begin{pmatrix} \text{VOC}_1 \\ \text{VOC}_2 \\ \vdots \\ \text{VOC}_n \end{pmatrix} + F_{\text{BB}} \times \begin{pmatrix} \text{VOC}_1 \\ \text{VOC}_2 \\ \vdots \\ \text{VOC}_n \end{pmatrix} \quad (1)$$

The results of this analysis are presented in Figure 3. Figure 3A shows an example fit on day 2 of the study between the modeled values and measured values. The fit coefficients F_{indoor} and F_{BB} for each day are shown in Figure 3B. What we find is that the VOC composition at our site was consistently described by this approach with an R^2 average of 0.4 (Figure 3B) and showed a general trend of placing more weight on the biomass factor initially which decreased over time and a smaller, more constant weight on the indoor factor, which we would not expect to change over the study period. The lower R^2 could be due to the fact that we are only able to compare to fresh emissions while our measurements are >10 days after the fire and that the home may have retained VOCs with different efficiencies. The comparison data sets are also limited as they do not exactly reflect the indoor environment we measured or the emissions of this fire. The variability shown in the first day of data likely stems from instrument start-up and a larger number of people in the home, which may have contributed to increased variability of VOC species. While these factors cannot be compared quantitatively due to the differences in the mixing ratios from the two data sets; from the fit, we can determine the relative contributions of biomass/structure burning and indoor air for each measured compound. We see good agreement, particularly for higher signal species such as acetic acid (Figure 3D) with the fit showing a dominant biomass factor in the first few days followed by a more even split of the two. For benzene (Figure 3C), the model overestimates the data but captures the variability and

attributes the dominant portion of the signal to the biomass burning factor. This provides further evidence that the enhanced VOC mixing ratios at the beginning of our study are attributable to the smoke impacts from the Marshall Fire, and that these impacts decreased with time for several weeks.

Comparisons to Particle/Ash Results – PAHs. Polycyclic aromatic hydrocarbons (PAHs) are a class of compounds that are emitted from wildfires³⁶ and are of concern due to their adverse health impacts.³⁷ Holder et al. summarized data from multiple sources to look at the composition of PAH species not only in traditional biomass burning but also from burning materials that are part of the WUI environment.¹¹ Figure 4A,B shows the composition of

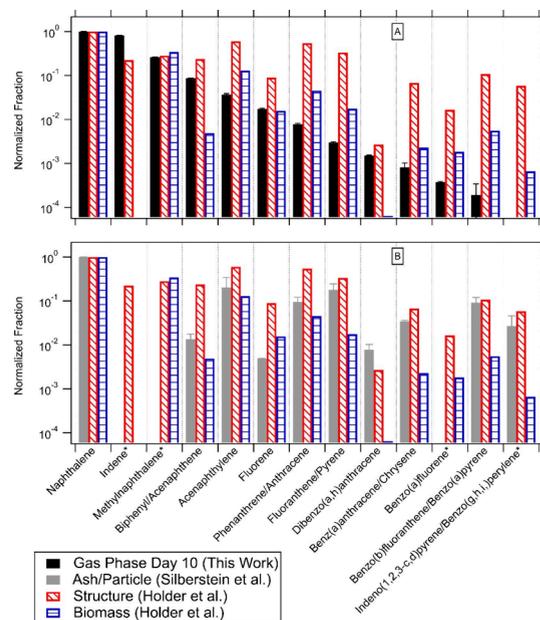


Figure 4. Comparison of indoor gas phase and ash (Silberstein et al.) PAH compositions for the site house from the Marshall Fire versus emission values from Holder et al. Values normalized to naphthalene, which is the highest value in all sets. Panel A shows the gas phase versus both reference data sets showing agreement at the higher volatility that diverges at lower volatility species moving right across the x -axis. The particle/ash values (Panel B) show a difference in agreeing much more with the emission distribution for structural material. Species not quantified in one of either the gas or ash phase analysis are marked with an asterisk and not included in normalized value.

PAHs from biomass and structural fires, normalized to the highest emitted species, which is naphthalene. The x -axis shows different PAHs, with the molecular weight generally increasing and volatility decreasing as you move right on the axis. We can compare the composition of VOCs from our work to both of these factors (Figure 4A) and additionally look at work from Silberstein et al., who investigated the composition of PAHs present in ash collected in multiple homes affected by the Marshall Fire, including averages from the site home studied here (Figure 4B).²⁶

Comparing our measurements with the Holder data shows better agreement with a biomass profile versus a structural emission profile. The gas phase profile shows a strong dependency on volatility that agrees with the understanding of surface–gas phase interactions.^{23,38} We expect that lower volatility species are removed more readily from the gas phase

through surface interactions. The profile for biomass burning contains a lower relative percentage of these higher molecular weight (MW) species and so aligns better with our measurements. This is different from the ash measurements which show greater agreement with the fresh structural emissions profile, retaining high relative fractions of low-volatility species (Silberstein et al. 2023). We note decreases over time for gas-phase PAH compounds (Figure S5) showing that there is still evolution in the days after measurements started. The differences emphasize that the evolution is distinct in the gas and solid phases and that indoor interactions can seemingly shift the gas phase profile significantly over the first several days after a smoke event. This also highlights potential differences in exposure with the two phases, likely presenting different risk profiles and resuspension of ash particles changing the indoor air profile.

Air Cleaning/Mitigation. A commonly asked question after the Marshall Fire was how residents could mitigate the smoke impacts on their homes and improve indoor air quality. To answer this question we conducted experiments with home-built air cleaners constructed out of a box fan and four pleated air filters coated with activated carbon. These air cleaners had the same design as Corsi-Rosenthal boxes,²⁷ but with the important difference that we used activated carbon to remove VOCs rather than only fine particles, which are removed with standard filters. The results from these experiments are summarized in Figure 5. Figure 5A illustrates that within an hour after turning on the air cleaners, the mixing ratios of three aromatic VOCs had dropped significantly and stayed at much diminished mixing ratios while the air cleaners were running. After the air cleaners were turned off, however, the mixing ratios rebounded to levels close to what they were before the use of the air cleaner. This indicates that these three VOCs were continuously released from reservoirs in the home and that air cleaners only provided temporary relief.³⁹ Given that we saw relatively constant effects over our later tests, we concluded that these filters were effective for the full study, but are limited to giving a lifetime for them and note that the lifetime may vary considerably based on filters used.

The air cleaners were found to be effective for almost all measured VOCs, and the effectiveness did not noticeably decrease during the study. To illustrate, Figure 5B shows the percent decrease in mixing ratio while running the air cleaner for many different individual VOCs as a function of fan cycle, i.e., the number of the conducted experiment. The percent decrease is calculated from the average mixing ratios during the 10 min prior to turning on the air cleaner (initial, purple period in Figure 5A) and the last 10 min before turning it off (end, blue period in Figure 5A). We used two different types of air cleaner designs during the study, with new filters of the same type used between the designs: the first design (triangle) consisted of a box fan and two air filters, and the tests in the orange highlight region correspond to this design, while the second design (square) contained four filters and was used for the remaining tests (Figure S6). The triangle cleaners were found to be more effective (VOC decreases between 60 and 80%) in comparison with the square cleaners (decreases between 30 and 70%). This may also reflect some variability in the absorbing capacity of the activated carbon filters rather than a design advantage of the triangle over the square cleaners. Figure 5B also illustrates that the air cleaners were effective for almost all measured VOCs; however, it should be noted that these results may not be reproducible for all filters

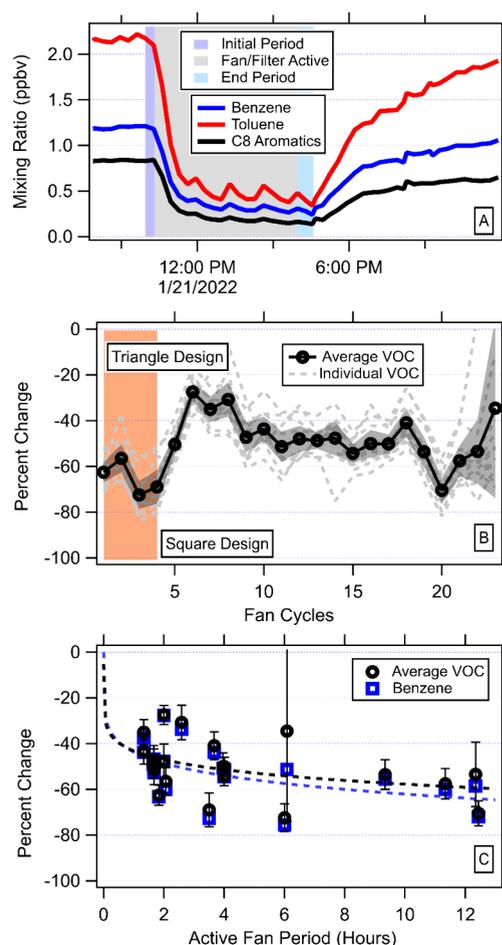


Figure 5. Panel A shows an example of a test conducted with activated carbon filters on several indoor aromatic values. Ten minutes of average data were taken initially before the fans were active and then 10 min at the end to calculate an efficacy. Panel B shows these percent decreases in indoor VOC on average for each of the cycle tests performed and then for individual VOCs comparing an original triangular box design versus a square design used later in the study. Panel C shows how the percent decrease changed based on the active fan period for several compounds, with minimal improvement in removal beyond the first several hours.

of this type and may change based on maker and design. The particle filters (i.e., noncarbon activated filters) we tested in the study did not show an impact on the observed VOC levels (Figure S7), not even for compounds that partition to surfaces easily.

The air cleaners were not always run for the same amount of time, which explains some of the variability in percent decrease seen in Figure 5B. In Figure 5C, the percent decrease is shown as a function of the time the air cleaners were run. This analysis shows that the percent decrease in VOC mixing ratio is not as high when the air cleaner is run for only 2 h, but reaches an equilibrium after ~ 4 h. A clean air delivery rate (CADR) value was estimated based on the decay time and estimated volume of the house, with a value of 220 ft³/min for each cleaner assuming complete mixing in the home. This value is reduced to roughly 110 ft³/min if we assume that the mitigation only occurred on the first floor of the home, which is mostly open.

Ventilation experiments (i.e., opening windows) were also conducted, and the results are summarized in the Supporting Information (Figure S8). We see decreases in the range of 55–

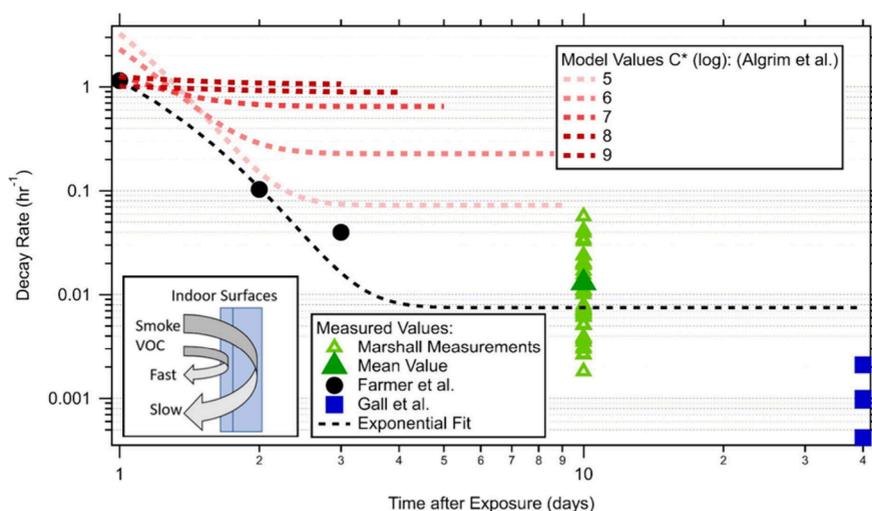


Figure 6. Comparison of measured indoor decay rates (hr^{-1}) of VOCs for simulated smoke exposure to measured values from this study. Also included are modeled decay rates over several vapor saturation mixing ratios (C^*) for comparison.

85% for VOC mixing ratios without a clear pattern across the window opening tests or time of window opening. Ventilation as a mitigation method is effective, but dependent on outdoor temperature and pollutant mixing ratios. If there are active outdoor sources of VOC and/or particle emissions, opening windows can actually bring in pollutants.

DISCUSSION

The evolution of indoor VOCs in this study can be compared with other studies that investigated indoor environments after exposure to simulated fire smoke. As stated in the [Introduction](#), the indoor impacts of wildfire smoke exposure are a relatively understudied area, especially shortly after the fire. However, we can look to several studies conducted in controlled settings to compare our work to, namely, Farmer et al.^{24,40} and Gall et al.³⁹ One important observation from our study was the long-term retention of VOCs in the indoor environment, even for relatively volatile compounds. We investigated how these decay rates for VOCs compared with what was found in the controlled studies. We were able to calculate exponential fits for all VOCs we measured ([Figure S9](#)), excluding mitigation periods. [Figure 6](#) shows the decay rate comparisons relative to time after exposure for our measurements, as well as the comparison studies. Farmer et al. looked at a simulated smoke release in a model home and were able to capture both the initial impact and the decay of VOCs immediately following the event. The work from Gall et al. investigated the decay of wildfire PAHs on common indoor surfaces over longer time scales. They noted elevated surface levels for the first ~ 40 days after the exposure above background and fitted decay curves to mixing ratios. [Figure 6](#) shows that in our study the decay rates are in between the values obtained in the Farmer et al. study and the Gall et al. study, consistent with the fact that our study was started 10 days after the exposure, i.e., in between the times after exposure in those two studies. The overall picture that emerges from the comparison is that VOCs in a smoke-impacted home initially decrease fast, but that the rate of decrease slows, though not to zero, for many weeks after the exposure. This can perhaps be explained by the partitioning of VOCs from different types of reservoirs (inset in [Figure 6](#)): the fast decrease in the first few days may be due to repartitioning of

VOCs back to the gas-phase from surfaces (whether the compounds were adsorbed or absorbed into surfaces). The slower decrease on longer time scales may be due to repartitioning of VOCs from other reservoirs such as drywall and wood.

Algrim et al. studied the repartitioning of VOCs from painted surfaces after exposure. We compare their model with the data in [Figure 6](#). The model simulates a painted room with surface interaction between VOCs and surfaces and allows for variable indoor conditions and VOC properties.²³ We assumed a large VOC influx that lasted for 6 h, similar to the Marshall fire event. This model assumes that painted surfaces act as a temporary sink to the VOCs that will later be lost through repartitioning and air exchange. The decay rate in the model depends on the vapor saturation mixing ratio (C^*), indicating a shift in behavior from the first days after exposure to the later days, with less volatile compounds being removed more efficiently followed by a slower removal. Comparing the model data with the work from Farmer et al. shows an initial good agreement with the model and our measured values. However, the measured values decrease faster compared with the modeled value (Algrim et al.). This supports a more complex type of reservoir with potential for a greater and longer lasting partition in real-world settings. This can help constrain the evolution of smoke impacts and better define expected evolution behavior with the understanding that the rates will depend on initial smoke impacts, surface uptake, and mitigation steps.

This study has shown that residences impacted by WUI fire smoke can retain VOCs for several weeks and longer than expected. The exact mechanisms for this retention are not fully understood. We investigated the relationship of the observed decreases with vapor pressure and did not see obvious correlations with vapor pressure, leading us to conclude that it was not an obvious driver for the trends we noted. This indicates that the reservoirs of VOCs in the home might be tied to physical reservoirs as opposed to surface VOC reservoirs. Laboratory experiments with different building materials such as drywall and wood are needed to study these processes in detail. These results only cover a single home and may differ for homes that contain different materials and have different air exchange rates. The location of the

sample house in a higher elevation, relatively low humidity geography could also affect the removal time frame compared to homes in other locations. The study also showed that air cleaning using carbon-activated filters and ventilation can temporarily reduce the VOC exposure to residents, however they need to be used continuously to keep mixing ratios of VOCs low. This study did not attempt to quantify potential health impacts. Data is limited on the health impacts from different VOCs and especially mixtures of VOCs. A survey-based study of health impacts was performed in parallel with our study and the results are published elsewhere.¹⁴

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsestair.4c00259>.

Additional information on data collection, graphics on ventilation and mitigation work, background data analysis graphs, and photos of Corsi-Rosenthal boxes (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

- (1) Iglesias, V.; Balch, J. K.; Travis, W. R. U.S. Fires Became Larger, More Frequent, and More Widespread in the 2000s. *Sci. Adv.* **2022**, *8* (11), No. eabc0020.
- (2) Balch, J. K.; Bradley, B. A.; Abatzoglou, J. T.; Nagy, R. C.; Fusco, E. J.; Mahood, A. L. Human-Started Wildfires Expand the Fire Niche across the United States. *Proc. Natl. Acad. Sci. U. S. A.* **2017**, *114* (11), 2946–2951.
- (3) Chen, H.; Samet, J. M.; Bromberg, P. A.; Tong, H. Cardiovascular Health Impacts of Wildfire Smoke Exposure. *Part. Fibre Toxicol.* **2021**, *18* (1), 2.
- (4) Pope, C. A.; Dockery, D. W. Health Effects of Fine Particulate Air Pollution: Lines That Connect. *J. Air Waste Manag. Assoc.* **2006**, *56* (6), 709–742.
- (5) Naeher, L. P.; Brauer, M.; Lipsett, M.; Zelikoff, J. T.; Simpson, C. D.; Koenig, J. Q.; Smith, K. R. Woodsmoke Health Effects: A Review. *Inhal. Toxicol.* **2007**, *19* (1), 67–106.
- (6) Liu, J. C.; Mickley, L. J.; Sulprizio, M. P.; Dominici, F.; Yue, X.; Ebisu, K.; Anderson, G. B.; Khan, R. F. A.; Bravo, M. A.; Bell, M. L. Particulate Air Pollution from Wildfires in the Western US under Climate Change. *Clim. Change* **2016**, *138* (3), 655–666.
- (7) Burke, M.; Driscoll, A.; Heft-Neal, S.; Xue, J.; Burney, J.; Wara, M. The Changing Risk and Burden of Wildfire in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **2021**, *118* (2), No. e2011048118.
- (8) National Academies of Sciences, Engineering, and Medicine. *The Chemistry of Fires at the Wildland-Urban Interface*; The National Academies Press: Washington, DC, 2022.
- (9) Radeloff, V. C.; Halmers, D. P.; Kramer, H. A.; Mockrin, M. H.; Alexandre, P. M.; Bar-Massada, A.; Butsic, V.; Hawbaker, T. J.; Martinuzzi, S.; Syphard, A. D.; Stewart, S. I. Rapid Growth of the US Wildland-Urban Interface Raises Wildfire Risk. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115* (13), 3314–3319.
- (10) Higuera, P. E.; Cook, M. C.; Balch, J. K.; Stavros, E. N.; Mahood, A. L.; St. Denis, L. A. Shifting Social-Ecological Fire Regimes Explain Increasing Structure Loss from Western Wildfires. *PNAS Nexus* **2023**, *2* (3), No. pgad005.
- (11) Holder, A. L.; Ahmed, A.; Vukovich, J. M.; Rao, V. Hazardous Air Pollutant Emissions Estimates from Wildfires in the Wildland Urban Interface. *PNAS Nexus* **2023**, *2* (6), No. pgad186.
- (12) Kohl, L.; Meng, M.; de Vera, J.; Bergquist, B.; Cooke, C. A.; Hustins, S.; Jackson, B.; Chow, C.-W.; Chan, A. W. H. Limited Retention of Wildfire-Derived PAHs and Trace Elements in Indoor Environments. *Geophys. Res. Lett.* **2019**, *46* (1), 383–391.
- (13) Dougherty, M.; Johnson, C. Marshall Fire Investigative Summary and Review. 2023. <https://assets.bouldercounty.gov/wp-content/uploads/2023/06/marshall-fire-investigative-summary.pdf> (accessed 2024–03–22).
- (14) Reid, C. E.; Finlay, J.; Hannigan, M. P.; Rieves, E. S.; Walters, H.; Welton-Mitchell, C.; Wiedinmyer, C.; De Gouw, J. A.; Dickinson, K. Physical Health Symptoms and Perceptions of Air Quality among Residents of Smoke-Damaged Homes from a Wildland Urban Interface (WUI) Fire. *ACS ES&T Air* **2025**, na DOI: [10.1021/acsestair.4c00258](https://doi.org/10.1021/acsestair.4c00258).
- (15) OpenStreetMap contributors. Planet Dump Retrieved from <https://planet.osm.org>, 2024 (accessed 2024–05–15).
- (16) Farmer, D. K. Analytical Challenges and Opportunities For Indoor Air Chemistry Field Studies. *Anal. Chem.* **2019**, *91* (6), 3761–3767.
- (17) Price, D. J.; Day, D. A.; Pagonis, D.; Stark, H.; Algrim, L. B.; Handschy, A. V.; Liu, S.; Krechmer, J. E.; Miller, S. L.; Hunter, J. F.;

- de Gouw, J. A.; Ziemann, P. J.; Jimenez, J. L. Budgets of Organic Carbon Composition and Oxidation in Indoor Air. *Environ. Sci. Technol.* **2019**, *53* (22), 13053–13063.
- (18) You, B.; Zhou, W.; Li, J.; Li, Z.; Sun, Y. A Review of Indoor Gaseous Organic Compounds and Human Chemical Exposure: Insights from Real-Time Measurements. *Environ. Int.* **2022**, *170*, No. 107611.
- (19) Jacob, P.; Benowitz, N. L.; Destaillets, H.; Gundel, L.; Hang, B.; Martins-Green, M.; Matt, G. E.; Quintana, P. J. E.; Samet, J. M.; Schick, S. F.; Talbot, P.; Aquilina, N. J.; Hovell, M. F.; Mao, J.-H.; Whitehead, T. P. Thirdhand Smoke: New Evidence, Challenges, and Future Directions. *Chem. Res. Toxicol.* **2017**, *30* (1), 270–294.
- (20) O'Dell, K.; Ford, B.; Burkhardt, J.; Magzamen, S.; Anenberg, S. C.; Bayham, J.; Fischer, E. V.; Pierce, J. R. Outside in: The Relationship between Indoor and Outdoor Particulate Air Quality during Wildfire Smoke Events in Western US Cities. *Environ. Res. Health* **2023**, *1* (1), No. 015003.
- (21) Barn, P.; Larson, T.; Noullett, M.; Kennedy, S.; Copes, R.; Brauer, M. Infiltration of Forest Fire and Residential Wood Smoke: An Evaluation of Air Cleaner Effectiveness. *J. Expo. Sci. Environ. Epidemiol.* **2008**, *18* (5), 503–511.
- (22) Henderson, D. E.; Milford, J. B.; Miller, S. L. Prescribed Burns and Wildfires in Colorado: Impacts of Mitigation Measures on Indoor Air Particulate Matter. *J. Air Waste Manag. Assoc.* **2005**, *55* (10), 1516–1526.
- (23) Algrim, L. B.; Pagonis, D.; de Gouw, J. A.; Jimenez, J. L.; Ziemann, P. J. Measurements and Modeling of Absorptive Partitioning of Volatile Organic Compounds to Painted Surfaces. *Indoor Air* **2020**, *30* (4), 745–756.
- (24) Li, J.; Link, M. F.; Pandit, S.; Webb, M. H.; Mayer, K. J.; Garofalo, L. A.; Rediger, K. L.; Poppendieck, D. G.; Zimmerman, S. M.; Vance, M. E.; Grassian, V. H.; Morrison, G. C.; Turpin, B. J.; Farmer, D. K. The Persistence of Smoke VOCs Indoors: Partitioning, Surface Cleaning, and Air Cleaning in a Smoke-Contaminated House. *Sci. Adv.* **2023**, *9* (41), No. eadh8263.
- (25) Krechmer, J.; Lopez-Hilfiker, F.; Koss, A.; Hutterli, M.; Stoermer, C.; Deming, B.; Kimmel, J.; Warneke, C.; Holzinger, R.; Jayne, J.; Worsnop, D.; Fuhrer, K.; Gonin, M.; de Gouw, J. Evaluation of a New Reagent-Ion Source and Focusing Ion–Molecule Reactor for Use in Proton-Transfer-Reaction Mass Spectrometry. *Anal. Chem.* **2018**, *90* (20), 12011–12018.
- (26) Silberstein, J. M.; Mael, L. E.; Frischmon, C. R.; Rieves, E. S.; Coffey, E. R.; Das, T.; Dresser, W.; Hatch, A. C.; Nath, J.; Pliszka, H. O.; Reid, C. E.; Vance, M. E.; Wiedinmyer, C.; de Gouw, J. A.; Hannigan, M. P. Residual Impacts of a Wildland Urban Interface Fire on Urban Particulate Matter and Dust: A Study from the Marshall Fire. *Air Qual. Atmosphere Health* **2023**, *16* (9), 1839–1850.
- (27) Manz, K. E.; Dodson, R. E.; Liu, Y.; Scheidl, L.; Burks, S.; Dunn, F.; Gairola, R.; Lee, N. F.; Walker, E. D.; Pennell, K. D.; Braun, J. M. Effects of Corsi-Rosenthal Boxes on Indoor Air Contaminants: Non-Targeted Analysis Using High Resolution Mass Spectrometry. *J. Expo. Sci. Environ. Epidemiol.* **2023**, *33* (4), 537–547.
- (28) Shi, S.; Zhao, B.; Zhang, J. Effect of Residential Air Cleaning Interventions on Risk of Cancer Associated with Indoor Semi-Volatile Organic Compounds: A Comprehensive Simulation Study. *Lancet Planet Health* **2018**, *2* (12), e532–e539.
- (29) Sekimoto, K.; Li, S.-M.; Yuan, B.; Koss, A.; Coggon, M.; Warneke, C.; de Gouw, J. Calculation of the Sensitivity of Proton-Transfer-Reaction Mass Spectrometry (PTR-MS) for Organic Trace Gases Using Molecular Properties. *Int. J. Mass Spectrom.* **2017**, *421*, 71–94.
- (30) Jensen, A. R.; Koss, A. R.; Hales, R. B.; de Gouw, J. A. Measurements of Volatile Organic Compounds in Ambient Air by Gas-Chromatography and Real-Time Vocus PTR-TOF-MS: Calibrations, Instrument Background Corrections, and Introducing a PTR Data Toolkit. *Atmospheric Meas. Technol.* **2023**, *16* (21), 5261–5285.
- (31) Romanias, M. N.; Coggon, M. M.; Al Ali, F.; Burkholder, J. B.; Dagaut, P.; Decker, Z.; Warneke, C.; Stockwell, C. E.; Roberts, J. M.; Tomas, A.; Houzel, N.; Coeur, C.; Brown, S. S. Emissions and Atmospheric Chemistry of Furanoids from Biomass Burning: Insights from Laboratory to Atmospheric Observations. *ACS Earth Space Chem.* **2024**, *8* (5), 857–899.
- (32) Arata, C.; Misztal, P. K.; Tian, Y.; Lunderberg, D. M.; Kristensen, K.; Novoselac, A.; Vance, M. E.; Farmer, D. K.; Nazaroff, W. W.; Goldstein, A. H. Volatile Organic Compound Emissions during HOMEChem. *Indoor Air* **2021**, *31* (6), 2099–2117.
- (33) Su, F.-C.; Mukherjee, B.; Batterman, S. Determinants of Personal, Indoor and Outdoor VOC Concentrations: An Analysis of the RIOPA Data. *Environ. Res.* **2013**, *126*, 192.
- (34) Lunderberg, D. M.; Misztal, P. K.; Liu, Y.; Arata, C.; Tian, Y.; Kristensen, K.; Weber, R. J.; Nazaroff, W. W.; Goldstein, A. H. High-Resolution Exposure Assessment for Volatile Organic Compounds in Two California Residences. *Environ. Sci. Technol.* **2021**, *55* (10), 6740–6751.
- (35) Brilli, F.; Gioli, B.; Ciccioli, P.; Zona, D.; Loreto, F.; Janssens, I. A.; Ceulemans, R. Proton Transfer Reaction Time-of-Flight Mass Spectrometric (PTR-TOF-MS) Determination of Volatile Organic Compounds (VOCs) Emitted from a Biomass Fire Developed under Stable Nocturnal Conditions. *Atmos. Environ.* **2014**, *97*, 54–67.
- (36) Ghetu, C. C.; Rohlman, D.; Smith, B. W.; Scott, R. P.; Adams, K. A.; Hoffman, P. D.; Anderson, K. A. Wildfire Impact on Indoor and Outdoor PAH Air Quality. *Environ. Sci. Technol.* **2022**, *56*, 10042.
- (37) Venkatraman, G.; Giribabu, N.; Mohan, P. S.; Muttiah, B.; Govindarajan, V. K.; Alagiri, M.; Abdul Rahman, P. S.; Karsani, S. A. Environmental Impact and Human Health Effects of Polycyclic Aromatic Hydrocarbons and Remedial Strategies: A Detailed Review. *Chemosphere* **2024**, *351*, No. 141227.
- (38) Abbatt, J. P. D.; Wang, C. The Atmospheric Chemistry of Indoor Environments. *Environ. Sci. Process. Impacts* **2020**, *22* (1), 25–48.
- (39) Sheu, R.; Fortenberry, C. F.; Walker, M. J.; Eftekhari, A.; Stönnner, C.; Bakker, A.; Peccia, J.; Williams, J.; Morrison, G. C.; Williams, B. J.; Gentner, D. R. Evaluating Indoor Air Chemical Diversity, Indoor-to-Outdoor Emissions, and Surface Reservoirs Using High-Resolution Mass Spectrometry. *Environ. Sci. Technol.* **2021**, *55* (15), 10255–10267.
- (40) Laguerre, A.; Gall, E. T. Polycyclic Aromatic Hydrocarbons (PAHs) in Wildfire Smoke Accumulate on Indoor Materials and Create Postsmoke Event Exposure Pathways. *Environ. Sci. Technol.* **2024**, *58* (1), 639–648.