AUGUST 2023

PILOT STUDY

The Effect of Wildfires and the Wildland Urban Interface (WUI) on Indoor Air Quality and Health in Residential Homes

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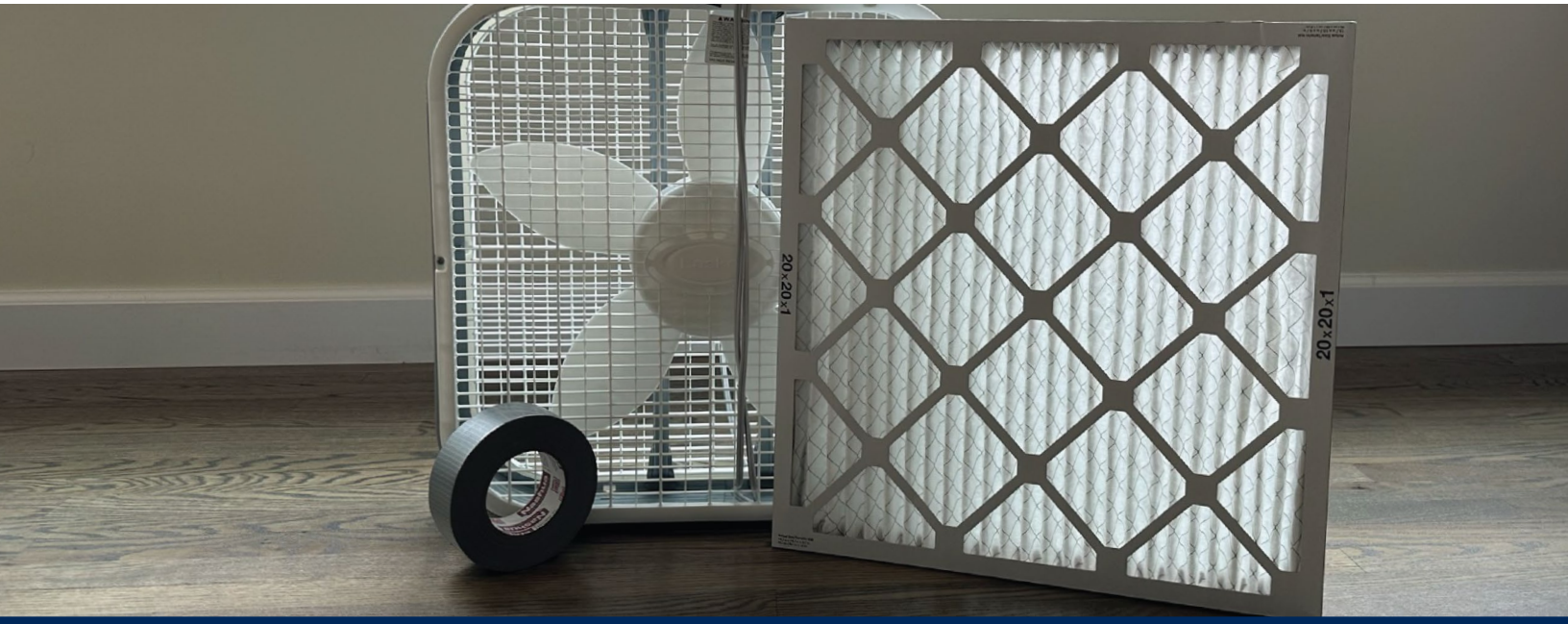
Introduction

Across the globe wildfires are increasing in frequency and severity. The average number of individual fires from 2012-2022 has remained at approximately 60,000 – 70,000 events per year but the total acres burned has been steadily increasing from an annual average of 2.9 million acres burned from 1983 - 1999 to an annual average of 7 million acres burned from 2000 – 2020. The three-year average acres burned from 2020 – 2022 have increased to over 8.3 million acres per year.[1] These data only represent fire events in the United States but are indicative of increasing fire events on a global scale. These disastrous events not only destroy property and endanger the lives of community members but they also negatively impact air quality in close proximity to the event and over a large geographical area.[2] The environmental impacts of these events may last for days to months after the fire has been extinguished. In addition to the increasing frequency and intensity of wildfires, the growth of communities in the wildland urban interface (WUI) has increased the number of people who may be directly impacted by wildfires that cross into inhabited areas.[3,4] There are significant data gaps in the toxicological and public/occupational health literature related to emissions from large WUI fires. The determination of the emission profile and potential toxicity from WUI fires is an on-going active area of environmental public health research.[5]

Public health officials typically recommend community members to evacuate to a safe location if in eminent danger from a fire. However, many large fires may impact air quality at a great distance from the actual event. When this type of smoke exposure occurs, public health officials often recommend community members to shelter in place (indoors) and use filtration to decrease indoor particle (smoke) concentrations. The use of heating, ventilation, and air-conditioning (HVAC) systems equipped with high efficiency filters (MERV 13 and higher) and/or portable air cleaning and filtration devices have been shown to decrease airborne particulate levels making these devices part of the recommended strategies to reduce exposure to WUI/wildfire smoke indoors.[6]

WUI/wildfire smoke is a complex mixture of airborne particulate matter (PM) and organic and inorganic gases including volatile organic compounds (VOCs). Air filtration devices, including filters in HVAC systems and portable air cleaners, operate by pulling contaminate laden air through a filter, thereby capturing airborne materials and decreasing the airborne particulate levels. This process is effective for the removal of large PM and sometimes respirable PM less than 2.5 microns in diameter ($PM_{2.5}$), depending on the filtration effectiveness.[7,8] Any device, whether commercially available or constructed by end-users, that operates in a similar fashion can be used to mitigate WUI/wildfire related indoor $PM_{2.5}$



exposure potential. While these DIY and commercially available devices are suitable for PM reduction, their efficacy for the removal of airborne VOCs remains unclear. In April 2022 Chemical Insights Research Institute (CIRI) of UL Research Institutes published a guidance document describing the construction and fire safety evaluation of Do-It-Yourself air filtration devices constructed from a furnace filter attached to a standard free-standing box fan.[9,10]

CIRI is engaged in a collaborative study with the United States Environmental Protection Agency (U.S. EPA) Office of Research and Development - Center for Environmental Measurement and Modeling – Air Methods and Characterization Division to evaluate exposures and health impacts associated with WUI/wildfire smoke events. This study is being conducted in Tulare County, California, which is a rural, agriculturally intensive county in southeastern California frequently impacted by WUI/wildfire events.[11] U.S. EPA is investigating the efficacy of DIY air cleaners in reducing exposure potential to indoor air hazards and assessing the use of real-time chemical and passive dust monitors to evaluate chemical hazards in the indoor environment. U.S. EPA scientists also seek to evaluate the health impacts of smoke exposure to residents utilizing sensitive blood and nasal-fluid biomonitoring approaches to detect changes in inflammation and stress associated with exposure to air pollution. CIRI's role is to characterize the VOC content of the smoke. We are collecting short-term (1-hour) active air samples and long-term (6-day) passive air samples for VOCs and aldehydes. We are also collecting settled household dust for future chemical and toxicological evaluation. Recruitment for this project has been accomplished with the assistance of the Central California Environmental Justice Network (CCEJN) that also plays an active role as community liaisons to assist with communication between study staff and participants.

OVERVIEW OF THE PILOT STUDY

CIRI conducted a pilot study on 6 homes in July of 2022 to evaluate the baseline ambient indoor and outdoor air quality in Tulare County, California without any WUI/wildfire activity. The indoor and outdoor levels of VOCs and aldehydes were measured in 4-hour and 1-hour active air samples. In addition to air sampling, settled dust was collected with a standard method of a floor vacuum cleaner equipped with an in-line thimble filter.[12,13] This pilot study allowed CIRI personnel to optimize the sampling plan and collect household-level baseline information to guide the sampling strategy development for the next phase of the study. **Figure 1** shows typical indoor and outdoor sampling locations of household air and settled dust samples.

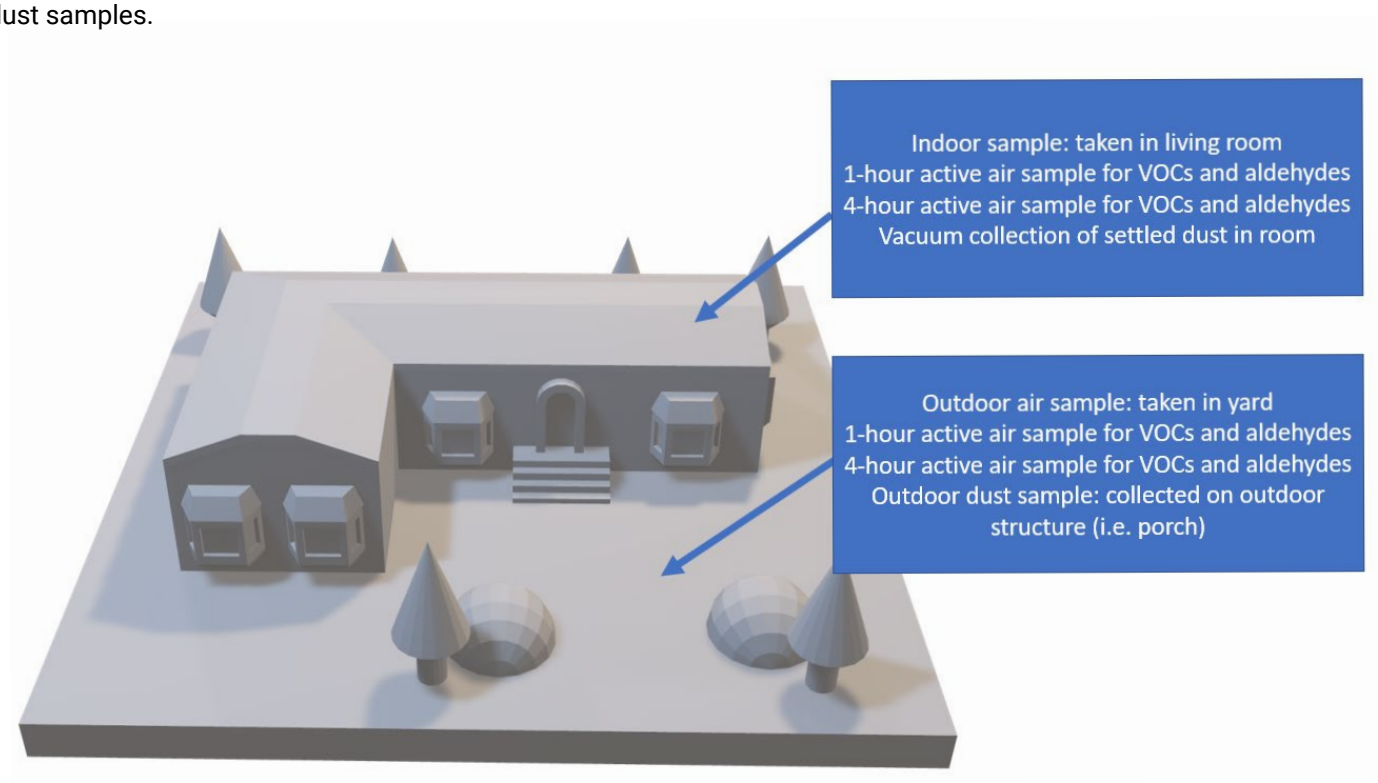


Figure 1: Household-level sampling design

1.0 Objectives

The objectives for pilot study were to:

1. Characterize VOC and aldehyde contributions to indoor and outdoor air quality at each residence
   a. Determine optimal sampling time (1-hour vs. 4-hour) for use in a larger sampling event (50 homes) in phase 2 of the study
   b. Determine contributing factors to observed VOC profile
2. Collect settled household dust for downstream chemical and toxicological assessments.
   a. Evaluate dust-adsorbed VOC and semi-volatile chemical profile with thermal desorption followed by chemical analysis
   b. Toxicity screening of the dust samples for cytotoxicity, oxidative stress, immunological response, and phenotypic changes

2.0 Materials and Methods

VOC AND ALDEHYDE SAMPLING

For each household, CIRI collected air samples for VOCs and aldehydes for two collection durations of 1-hour and 4 hours using calibrated personal air sampling pumps and Tenax TA tubes for VOCs and DNPH cartridges for aldehyde sampling. Air sampling devices were suspended from tripods at a height corresponding to the average breathing zone of an adult using the following calibrated air flow rates.

Chamber Setup	Collection Media	Calibrated Flow Rate (Liters per Minute)	
		1-hour sample	4-hour sample
VOC	Tenax TA	0.2 LPM	0.1 LPM
Aldehyde	DNPH	0.5 LPM	0.5 LPM

VOC samples were collected from outside and inside of the participants' homes and sample start/stop times were recorded for each device and household. **Figure 2** shows the sample collection schedule for the six-home pilot study in detail.

			time	8am-9:30am	10am-11:30am	12pm-1:30pm	2pm-5pm
Jul-22	House	Location	Sample	AM1	AM2	PM1	PM2
7/15/2022	1	outside	short VOC/ALD	60 min			
			long VOC/ALD	4 hr			
			Dust		5 min		
		clean room (study)	short VOC/ALD	60 min			
			long VOC/ALD	4 hr			
			Dust		5 min		
	2	outside	short VOC/ALD		60 min		
			long VOC/ALD		4 hr		
			Dust			5 min	
		clean room (study)	short VOC/ALD*		60 min		
			long VOC/ALD		4 hr		
			Dust			5 min	
	3	outside	short VOC/ALD			60 min	
			long VOC/ALD			4 hr	
			Dust				5 min
		clean room (study)	short VOC/ALD			60 min	
			long VOC/ALD*			4 hr	
			Dust				5 min
7/16/2022	6	outside	short VOC/ALD		60 min		
			long VOC/ALD		4 hr		
			Dust		5 min		
		clean room (study)	short VOC/ALD		60 min		
			long VOC/ALD		4 hr		
			Dust		5 min		
	4	outside	short VOC/ALD	60 min			
			long VOC/ALD	4 hr			
			Dust	5 min			
		clean room (study)	short VOC/ALD*	60 min			
			long VOC/ALD	4 hr			
			Dust	5 min			
	5	outside	short VOC/ALD			60 min	
			long VOC/ALD			4 hr	

* Indicates that duplicate samples were collected

Figure 2: Timeline of 6-home sampling in July 2022

CHEMICAL ANALYSIS

After collection, VOC samples were thermally desorbed and analyzed using GC-MS in an ISO/IEC 17025 accredited laboratory. The analytical methodology of the sorbent collection technique, separation and detection followed methods in U.S. EPA TO-17, ISO 16000–6, and ASTM D6196, applicable to C_6–C_{16} organic chemicals with boiling points ranging from 35 °C to 250 °C.[14–16] VOCs were identified by matching their mass spectral characteristics and retention times using a laboratory specific mass spectral database. This database contains approximately 700 VOCs that have been previously found in indoor air and product emission studies and have been validated by the laboratory for analysis using the laboratory specific systems. Other VOCs not found in this database were identified using mass spectral characteristics of more than 75,000 compounds available from the National Institute of Standards and Technology (NIST), the U.S. EPA, and the National Institutes of Health (NIH). The individual VOCs were quantified using multipoint calibration standards that were available for 77 specific VOCs listed in indoor air guidelines and chemical regulatory programs including the California Department of Public Health Standard Method v1.2–2017 (CDPH SM), California Proposition 65 (Prop 65), California's Chronic Reference Exposure Levels, Occupational Safety and Health Administration's Permissible Exposure Limit, and American Conference of Governmental Industrial Hygienists' Threshold Limit Values (ACGIH TLVs®). The other VOCs without authentic standards were calibrated relative to toluene. Total VOC (TVOC) levels were determined by converting the total GC-MS scan response and calculating a concentration based on a toluene equivalent.

Aldehyde samples on DNPH cartridges were analyzed by high-performance liquid chromatography (HPLC) following methods in U.S. EPA TO-11A, ISO 16000–3, and ASTM D5197.[17–19] The sampled DNPH reagent in the cartridge reacted with collected carbonyl compounds to form derivatives that were then eluted from the cartridge with acetonitrile. Analysis was done using reverse-phase HPLC with ultraviolet (UV) detection. Multipoint calibrations were available for the target analytes that include formaldehyde; acetaldehyde; 2-propenal; acrolein; propanal; 2-butenal; butanal; benzaldehyde; 3-methylbutanal; pentanal; 2-methylbenzaldehyde; 3- and 4-methylbenzaldehyde; hexanal; and 2,5-dimethylbenzaldehyde.

The limit of detection is typically less than 2 µg/m^3, usually ranging from 0.2 µg/m^3 to 0.5 µg/m^3 for most VOCs and aldehydes, but the limit of quantification was defined as 2 µg/m^3 in this study.

SETTLED DUST SAMPLING

Household settled dust samples were collected with a Eureka Mighty-Mite vacuum cleaner (model 3670) with crevice tool fitted with a pre-weighed Whatman cellulose extraction thimble sealed into the vacuum hose with a rubber o-ring. For both indoor and outdoor areas, the entire floor-surface area for a indoor/outdoor area was vacuumed by gently drawing the crevice tool across the top of all surfaces. The thimbles containing the settled dust samples were weighed and placed in sealed labeled plastic bags for downstream chemical and toxicological analysis.

3.0 RESULTS AND DISCUSSION

VOCS AND ALDEHYDES

Chemical analysis data was aggregated into a master datafile that reported the identity and levels of chemicals detected in the indoor and outdoor air samples. **Figure 3** shows indoor and outdoor TVOC levels of each home for both the 1-hour and 4-hour samples. The data demonstrate that the indoor TVOC and aldehyde levels are tens to over a hundred times higher relative to outdoors and that the sample duration of 1-hour vs. 4-hour results in a similar concentration.

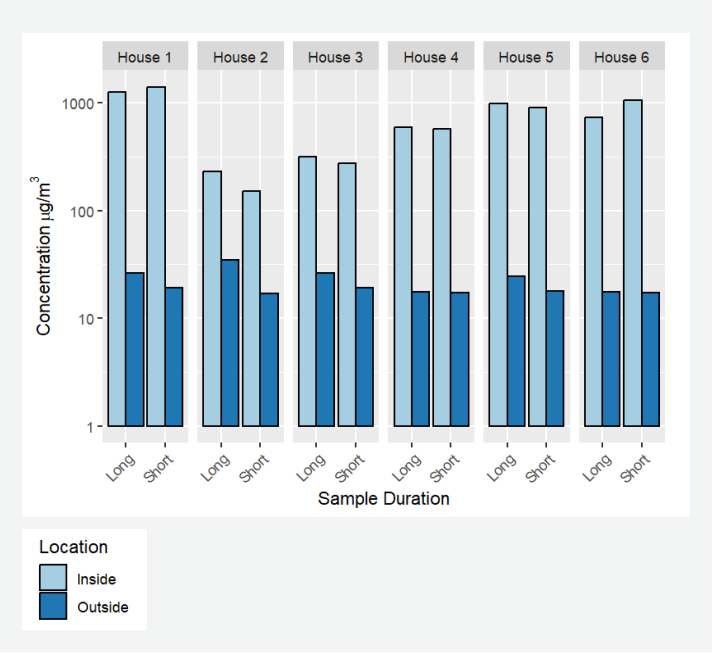


Figure 3: Indoor and outdoor TVOC levels from long (4-hour) and short (1-hour) active air sampling

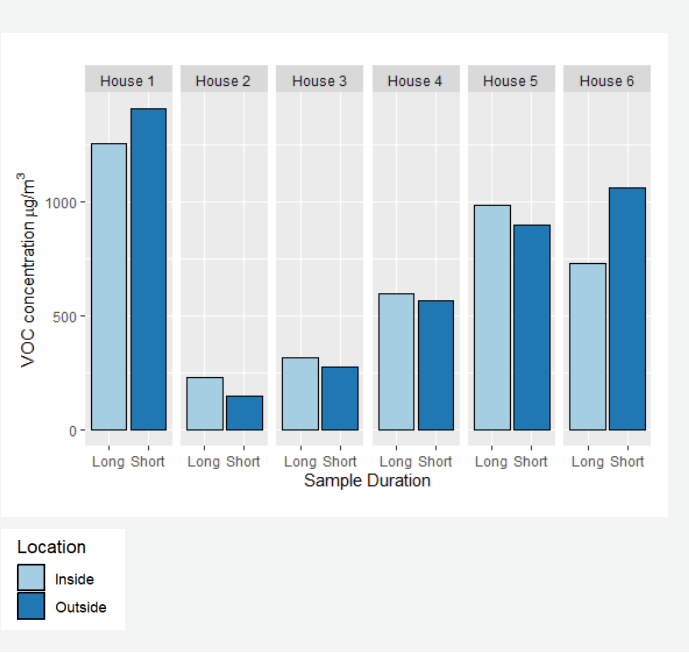


Figure 4: Indoor TVOC levels from long (4-hour) and short (1-hour) active air sampling

Figure 4 shows the difference between 1-hour and 4-hour sample concentrations for the indoor samples. The two sampling durations produced comparable results and there was variability in the TVOC levels from home to home. In order to test for significant differences between the 1-hour and 4-hour samples, the indoor and outdoor data from all homes was pooled and a paired t-test was conducted with R for statistical computing.[20]
The result of the statistical analysis showed that there were no significant differences ($p > 0.05$) between the reported concentrations of the indoor or outdoor air samples based on the duration of sampling. **Figure 5** shows the mean and 95% confidence interval for indoor and outdoor samples taken with a 1-hour and 4-hour duration. The findings related to the optimal sampling time will be used to inform the design of the sampling strategy for phase 2 of the study.

The VOC chemical landscape was evaluated within each home. TVOC levels were above the LEED green building criteria of 500 µg/m^3 in four of the six evaluated homes. There were 8 specific VOCs and aldehydes; acetaldehyde, acetic acid, decamethyl cyclopentalsiloxane, decanal, ethanol, formaldehyde, hexanal, and hexanoic acid that were consistently detected in all 6 homes. These eight chemicals were queried against other publicly available household level air monitoring data to determine if the levels reported in the current study were comparable to VOC levels reported in previous studies. For example, the Relationships of Indoor, Outdoor, and Personal Air (RIOPA) study was conducted by the Health Effects Institute (HEI) and the National Urban Air Toxics Research Center (NUATRC) in three cities with different air pollution source profiles including Los Angeles, California; Houston, Texas; and Elizabeth, New Jersey in 1999 - 2000. Of the 8 VOCs detected in all homes in the current study, three compounds, formaldehyde, acetaldehyde, and hexanal, were also reported in the RIOPA data set.

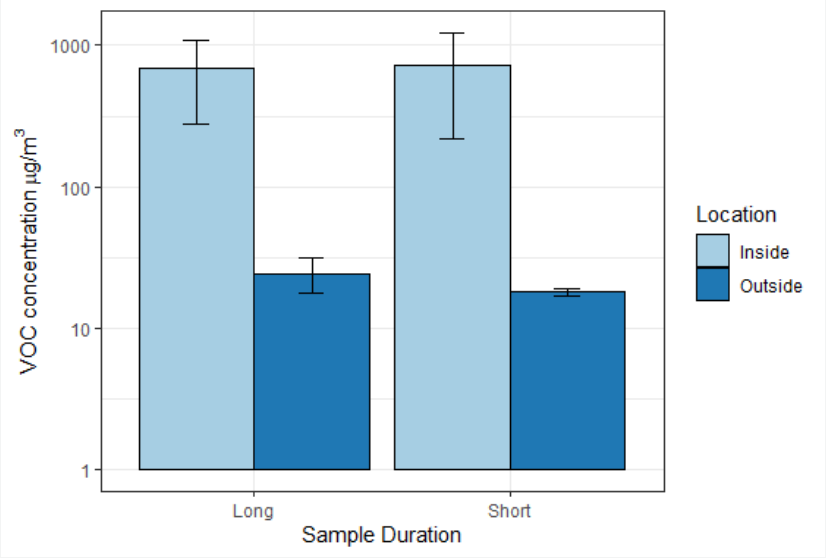


Figure 5: Average concentration of VOCs in homes by location and sample duration (means and 95% confidence intreval)

Figure 7 shows the comparative levels of these three chemicals in indoor air samples from RIOPA and the current study. The average levels for the three chemicals in the present study were consistently higher than the values reported in the literature. The levels of the three chemicals were evaluated for statistical differences across locations with a one-way analysis of variance with post-hoc comparisons. The differences between formaldehyde levels in the current study and the other RIOPA locations were not statistically significant. The formaldehyde levels detected in 50% of the homes in the present study exceeded the NIOSH recommended exposure limit (REL) of 0.016 ppm (23.6 µg/m3). In addition, 100% of the homes exceeded the Cal/EPA Office of Environmental Health Hazard Assessment Chronic Recommended Exposure Level (CREL) of 0.006 ppm (9 µg/m3) for airborne levels of formaldehyde indoors.[21,22] One home exceeded the CREL of 70 µg/m3 for acetaldehyde.[22] The levels of acetaldehyde and hexanal were not significantly different in the present study compared to the Houston Texas samples from RIOPA but they were significantly different compared to the RIOPA Los Angeles and New Jersey results. It should be noted that the statistical readout was influenced by the large difference between the sample size of the current study (n=6) and that of the RIOPA study (CA, n=173; NJ, n=169; and TX, n=145). Due to the differences in sample size in mind, it is appropriate to interpret the limited pilot data from the current study as in a comparable range to the levels of VOCs in the existing air monitoring literature.

Figures 8-19 list the individual VOCs and aldehydes detected in each home and show a Venn diagram to annotate the number of chemicals that are unique to the indoor and outdoor environments and the ones that are common to both indoor and outdoor samples. There were 66 different individual VOCs detected among the indoor air samples. Twenty-seven of the 66 individual VOCs do not have established regulatory or health guidance criteria for indoor air levels. Two of the VOCs detected in all the homes, formaldehyde and ethanol, are recognized human carcinogens (IARC Group 1). Styrene, a probable human carcinogen (IARC group 2A), was detected in one home. Acetaldehyde was detected in all homes and is classified as a possible human carcinogen (IARC Group 2B). It is important to recognize that cancer is not a typical endpoint for the basis of acceptable exposure criteria and other endpoints such as respiratory irritation or other acute health effects are often used to derive regulatory and health-based guidance values. Formaldehyde is an exception to this trend, but the basis of the airborne limits for ethanol, styrene, and acetaldehyde is based on respiratory and dermal irritation and their impacts on the central nervous system. There are no statutory or universally accepted methods for deriving acceptable exposure limits for chemicals in indoor air. Given the amount of time that people spend in their homes, it is reasonable to consider exposures occurring in homes to be chronic, or long-term, types of scenarios. In general, it is health-protective to keep exposure to carcinogens as low as possible. Therefore, it is important to consider if

a chemical is a known or suspected carcinogen in addition to cross-checking the various environmental and occupational limits established for primarily non-cancer health effects when evaluating health risks associated with indoor air.

Individual chemicals detected in each home were queried with the chemical and product database embedded within the PubChem web portal in order to identify common product use categories of the detected VOCs and aldehydes.[23,24]

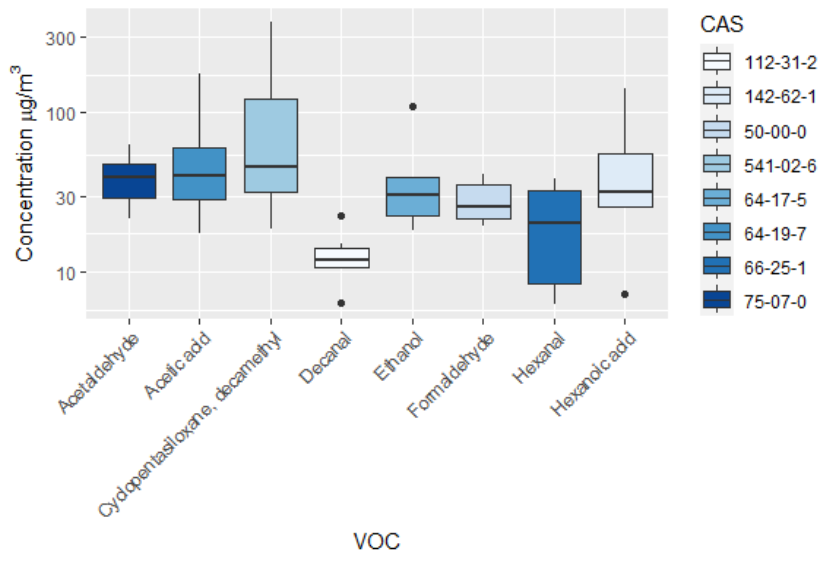


Figure 6: VOCs and aldehydes detected in all homes

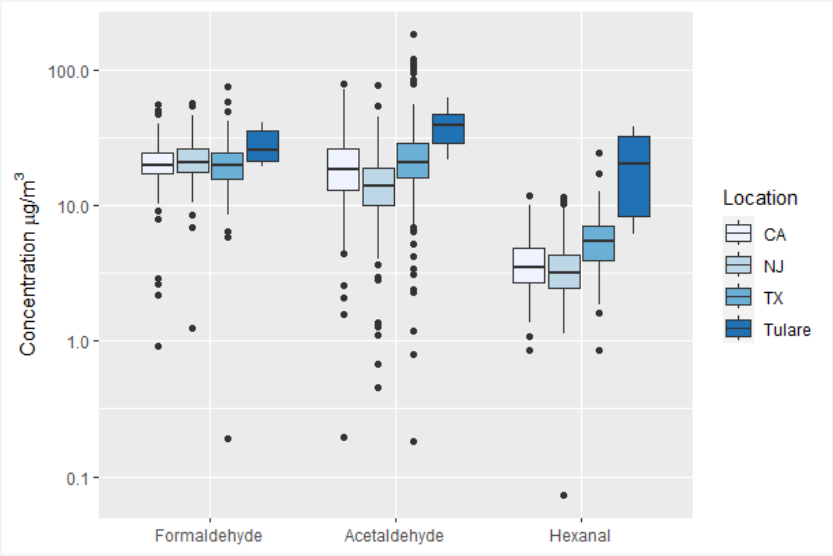


Figure 7: VOCs and aldehydes detected in Tulare and RIOPA study

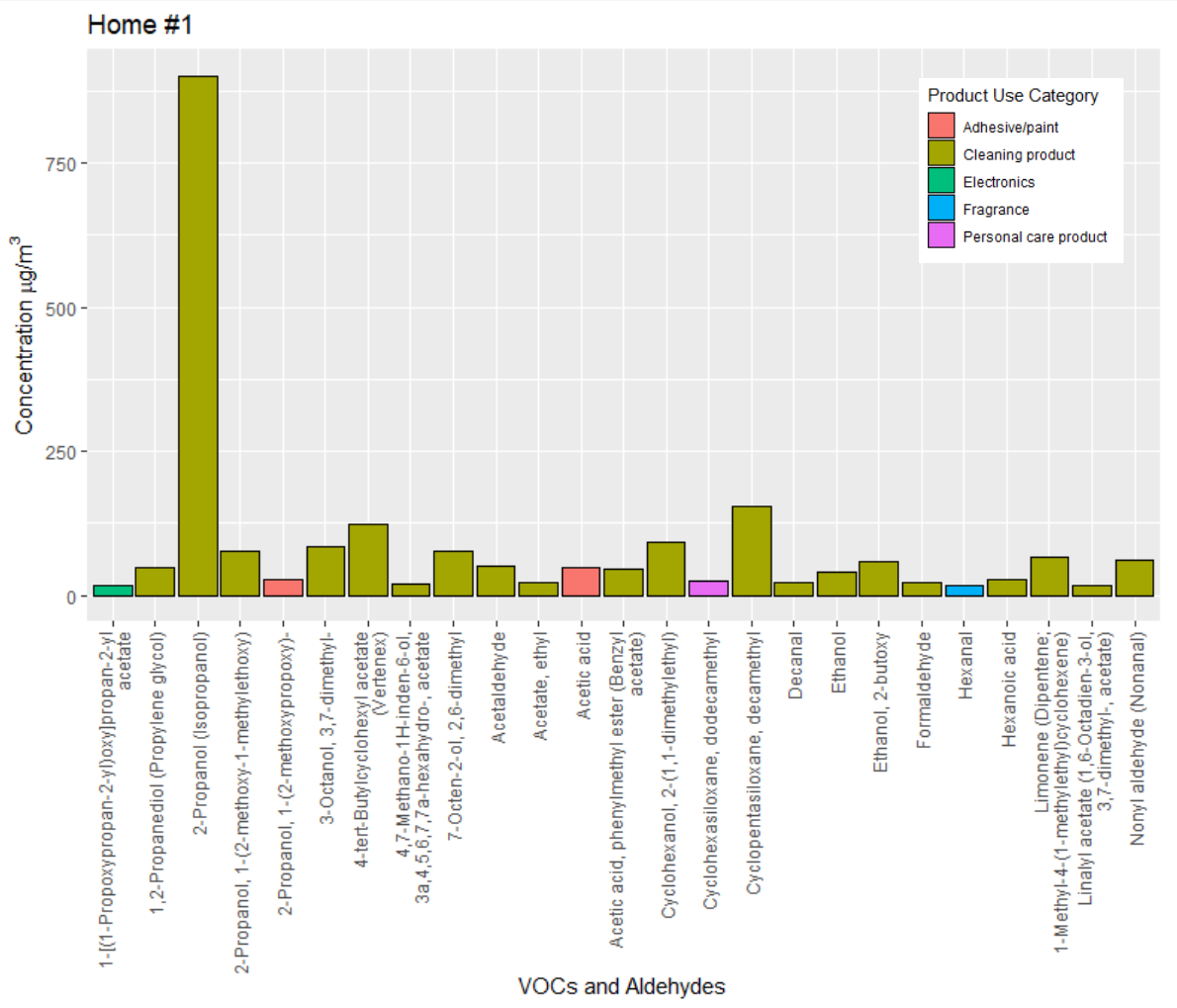


Figure 8: Home #1 VOC and aldehyde levels

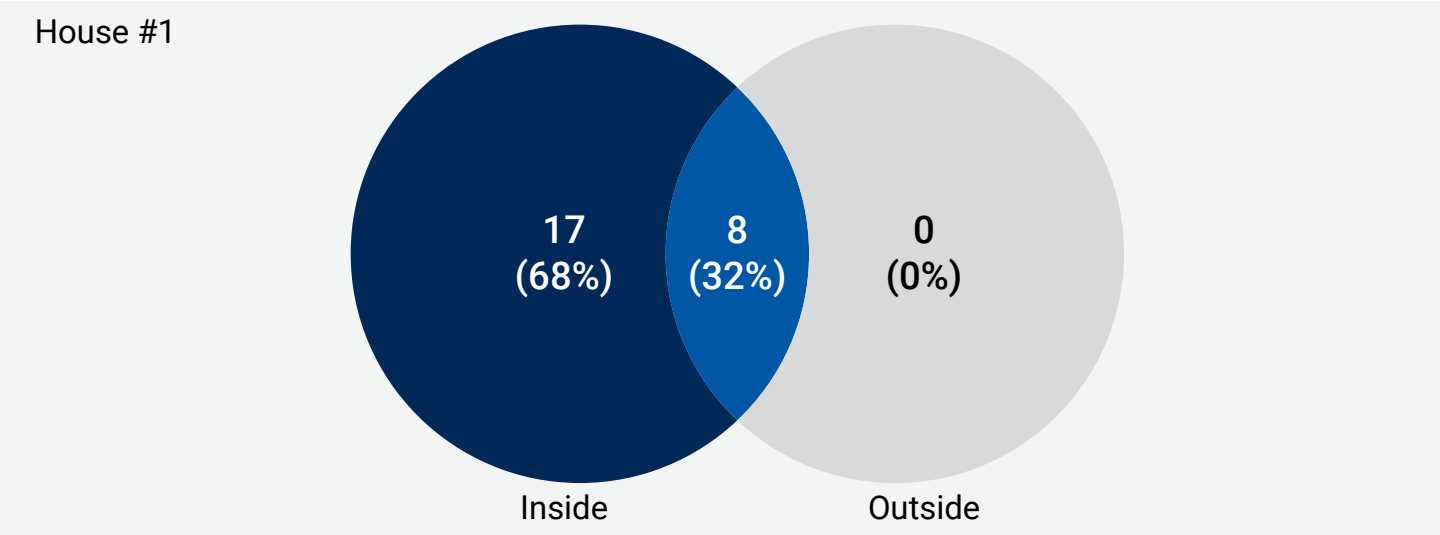


Figure 9: Home #1 Venn diagram of inside vs. outside

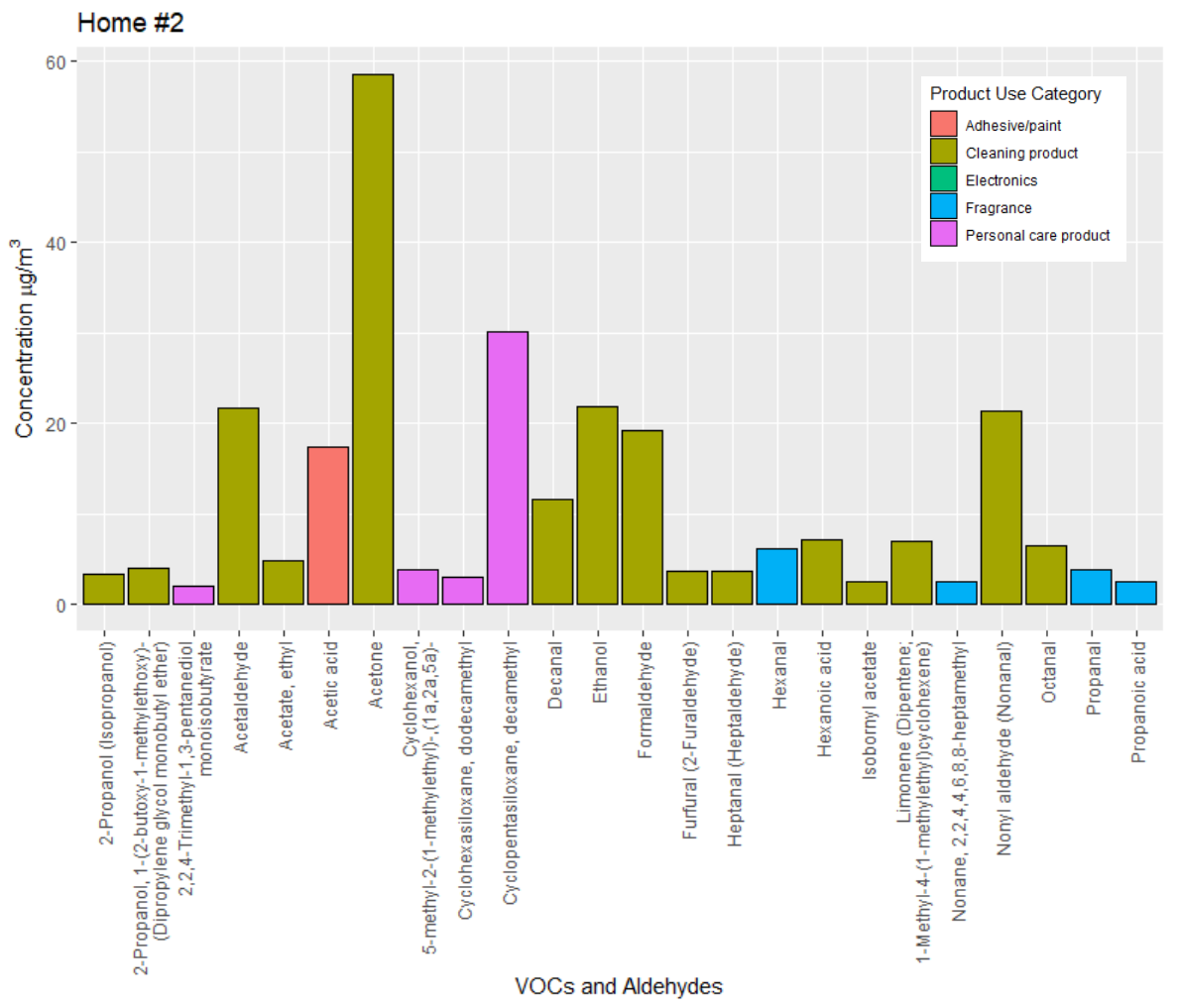


Figure 10: Home #2 VOC and aldehyde levels

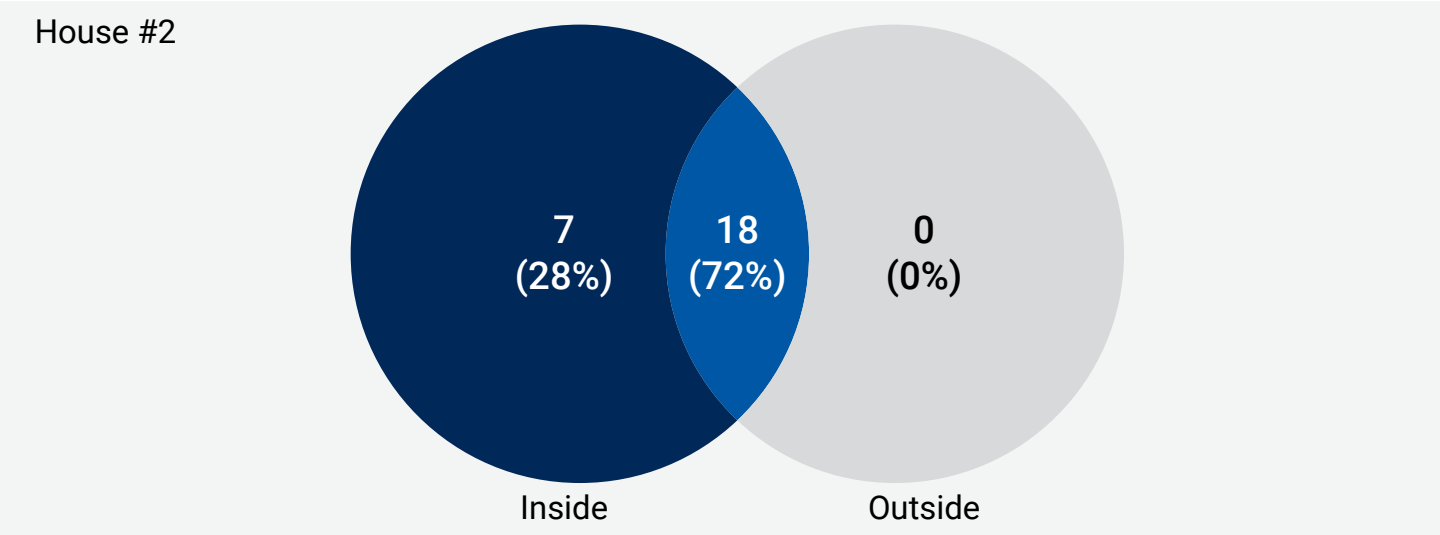


Figure 11: Home #2 Venn diagram of inside vs. outside

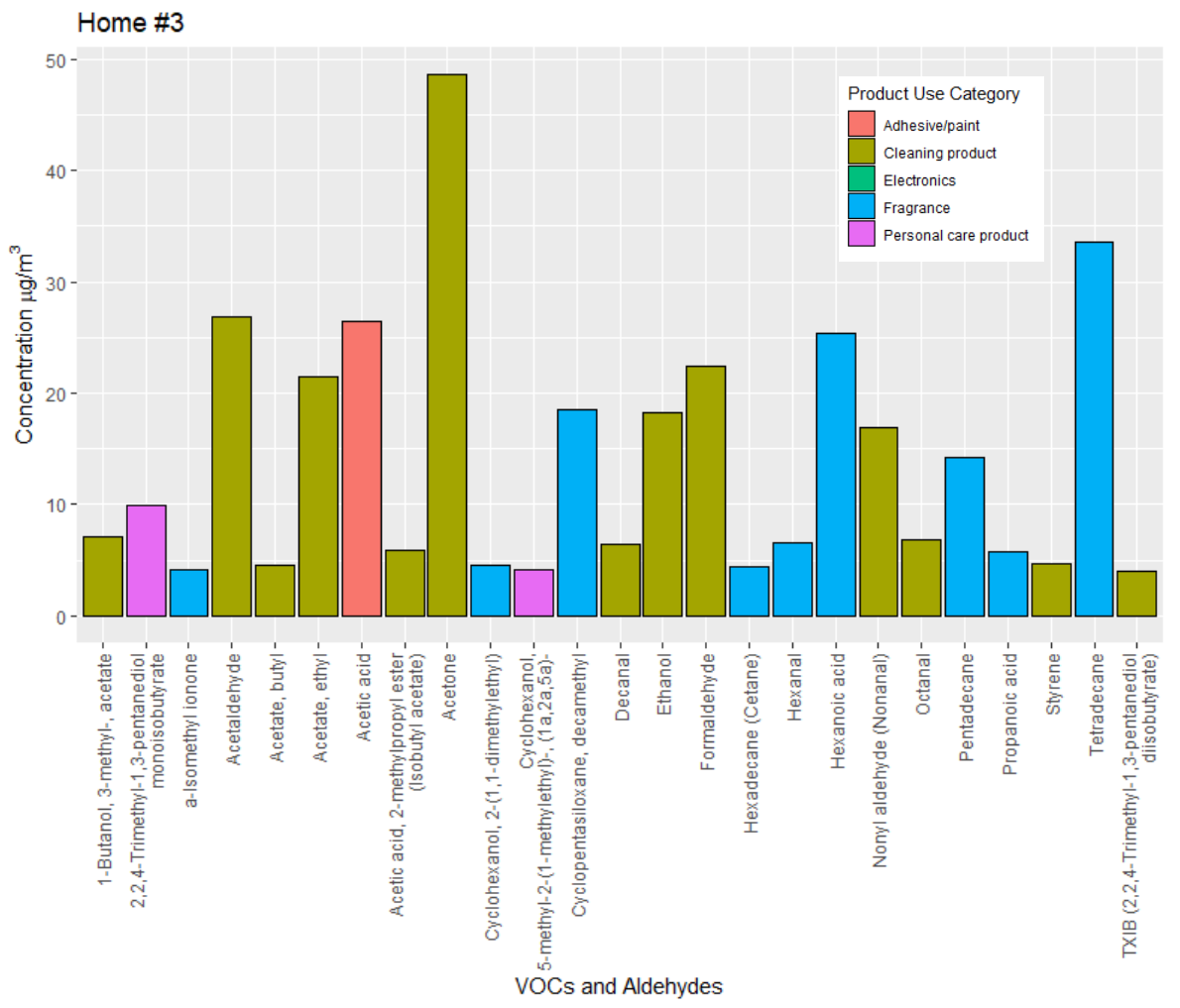


Figure 12: Home #3 VOC and aldehyde levels

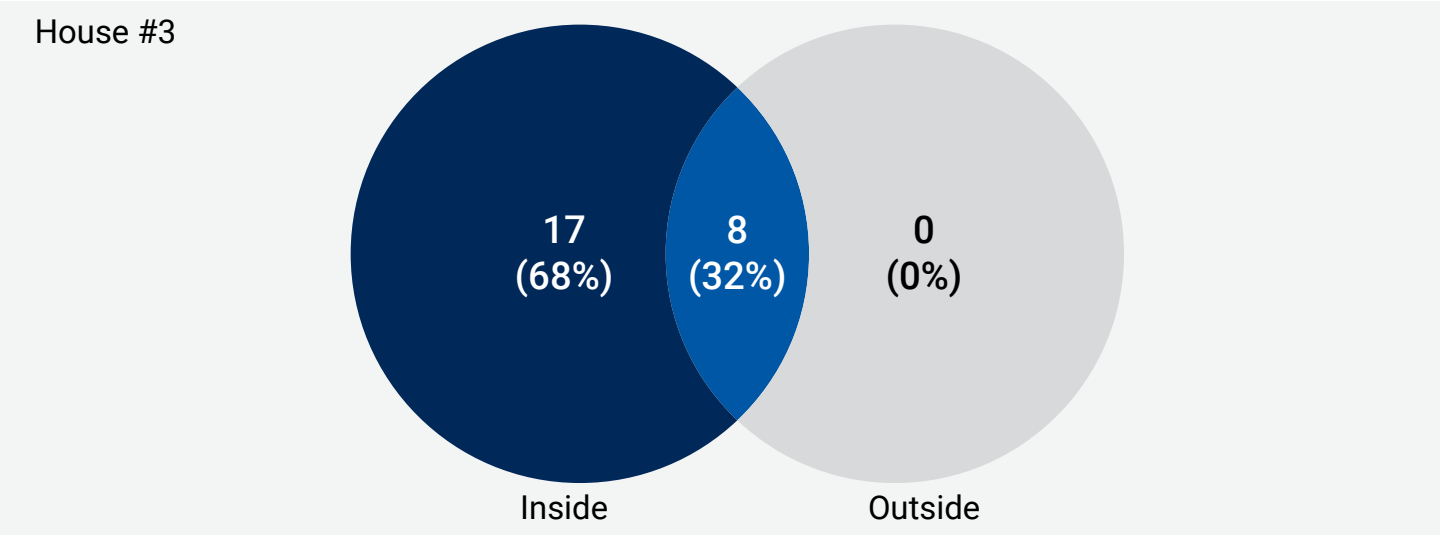


Figure 13: Home #3 Venn diagram of inside vs. outside

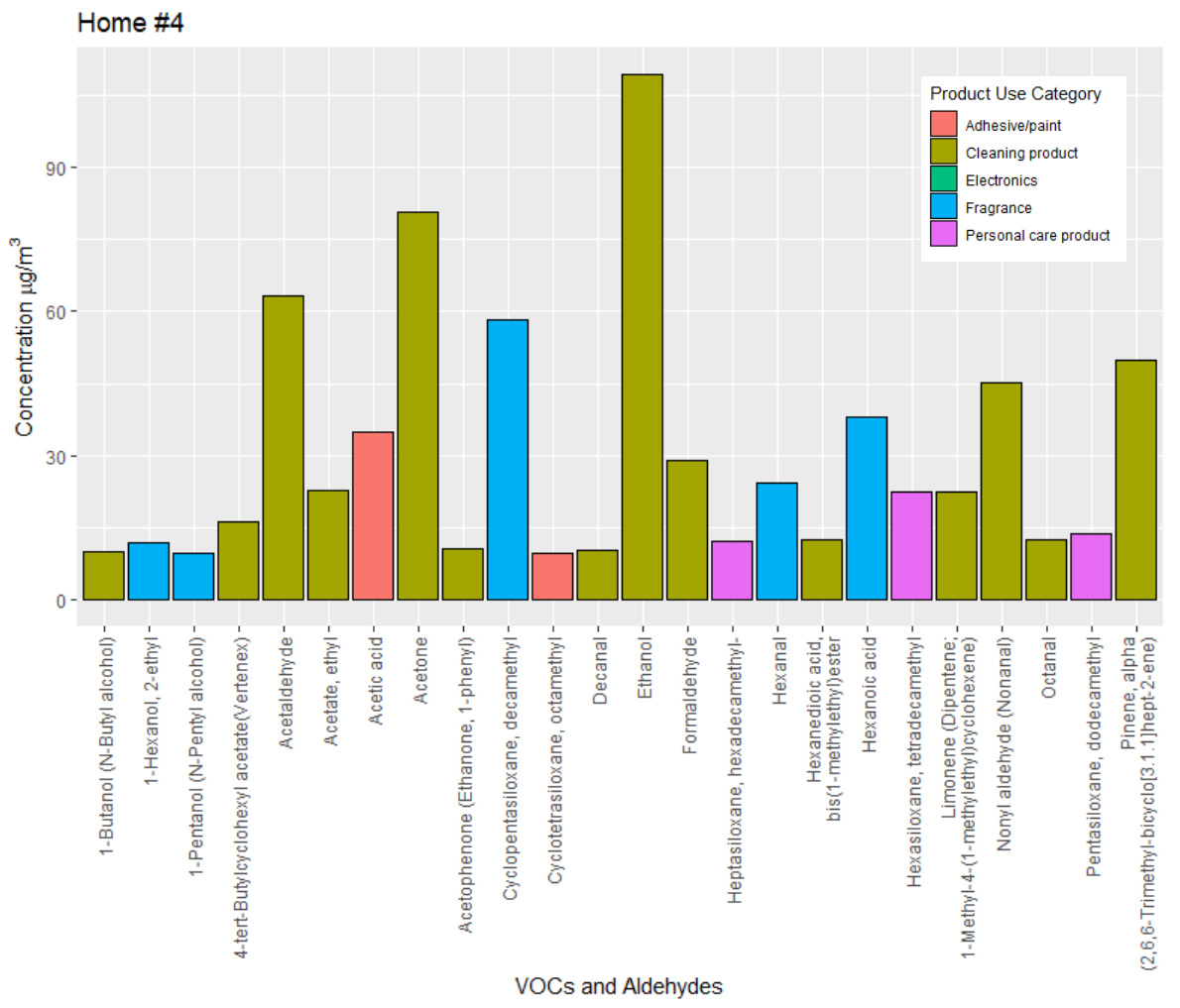


Figure 14: Home #4 VOC and aldehyde levels

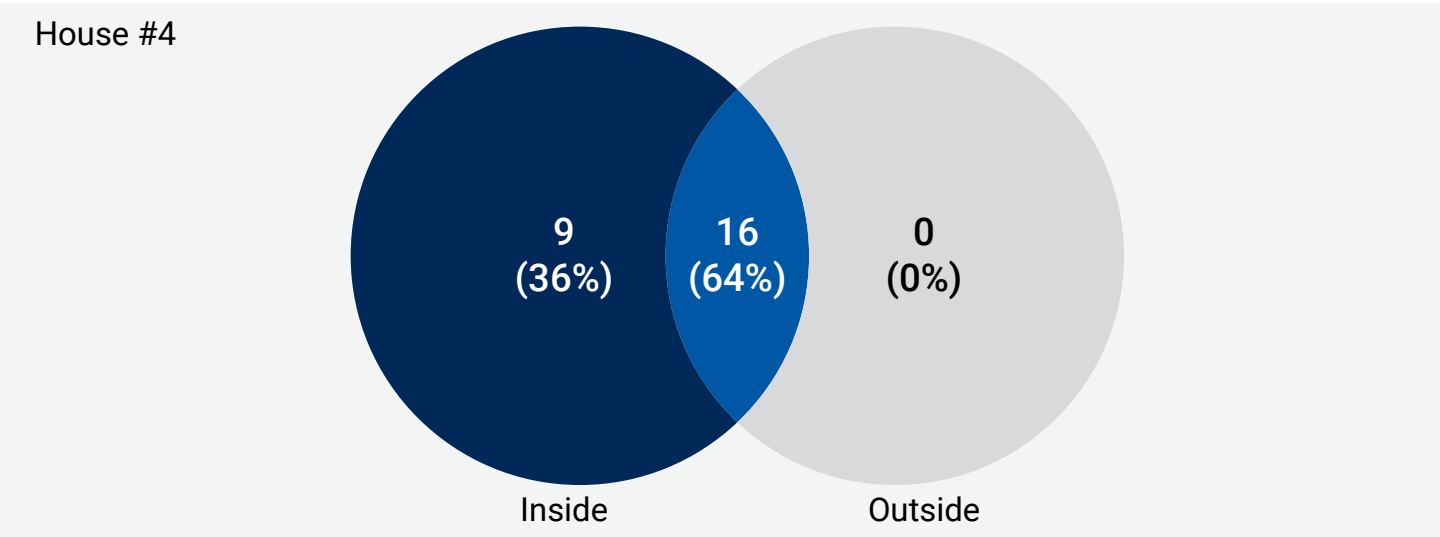


Figure 15: Home #4 Venn diagram of inside vs. outside

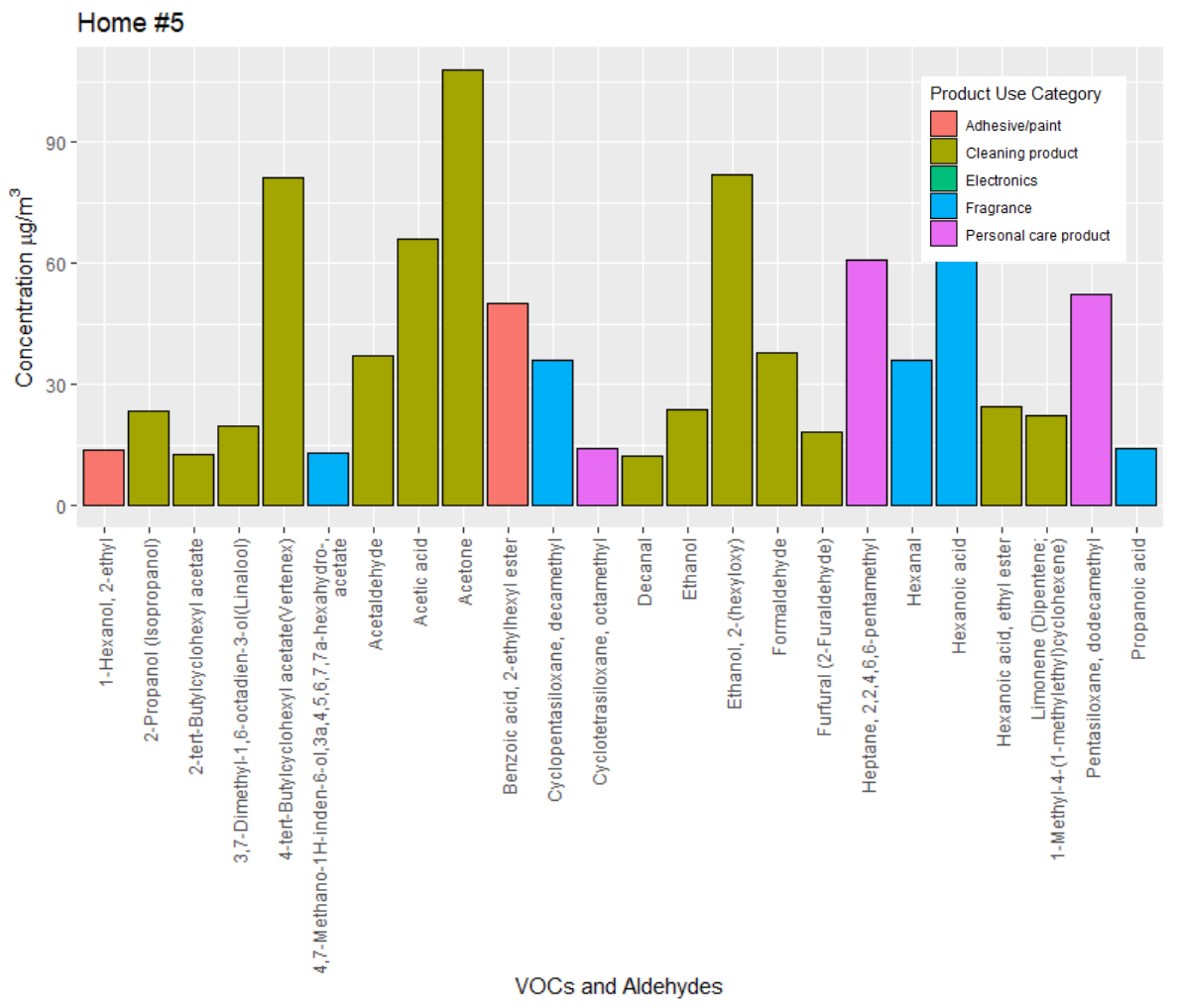


Figure 16: Home #5 VOC and aldehyde levels

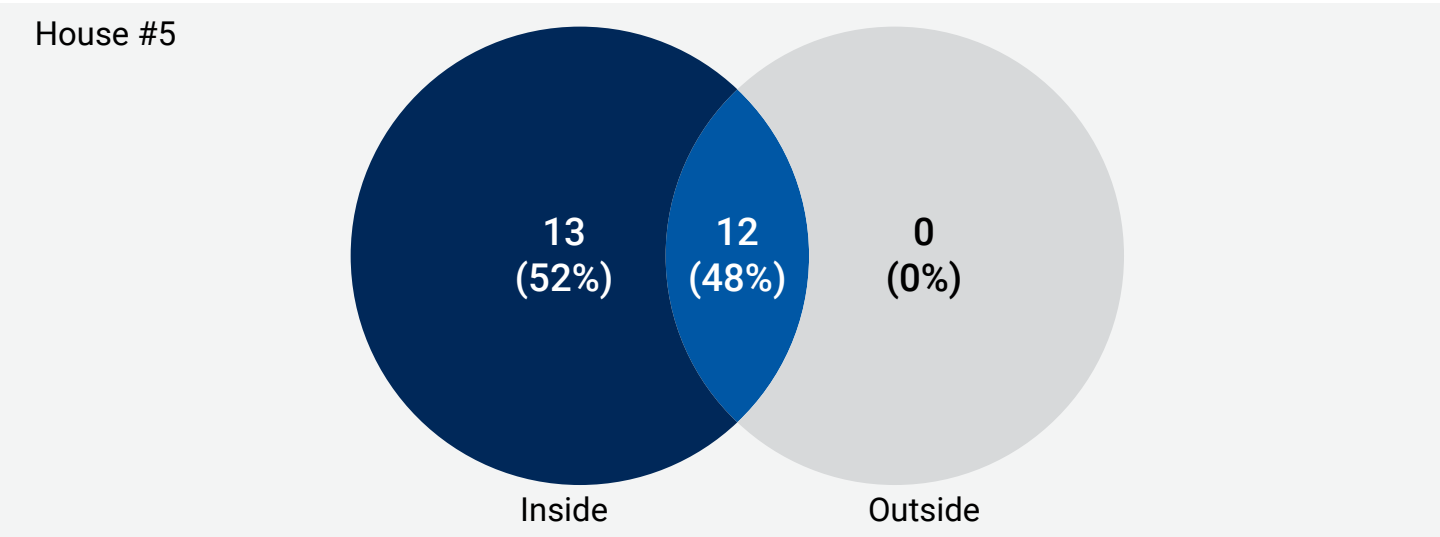


Figure 17: Home #5 Venn diagram of inside vs. outside

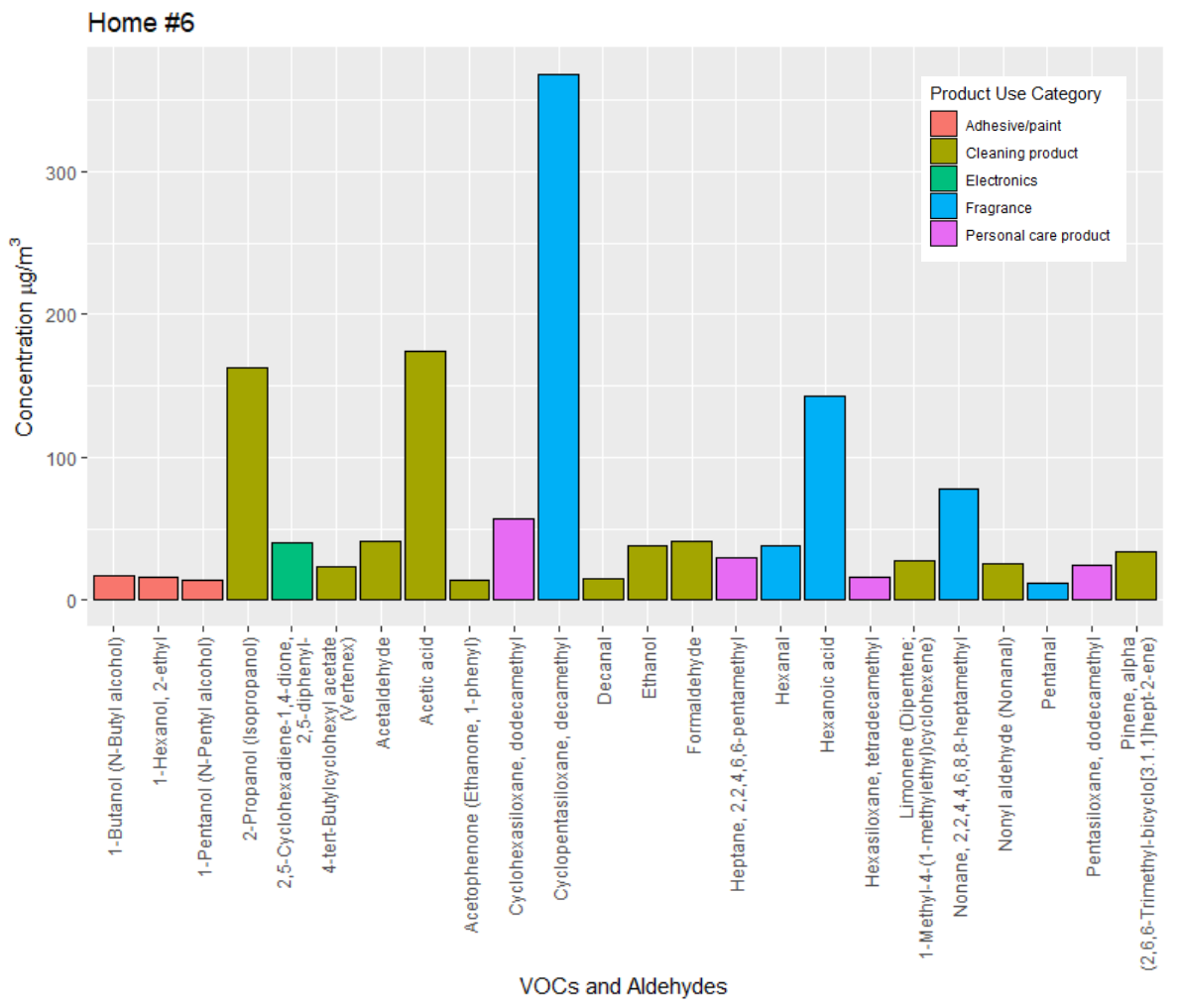


Figure 18: Home #6 VOC and aldehyde levels

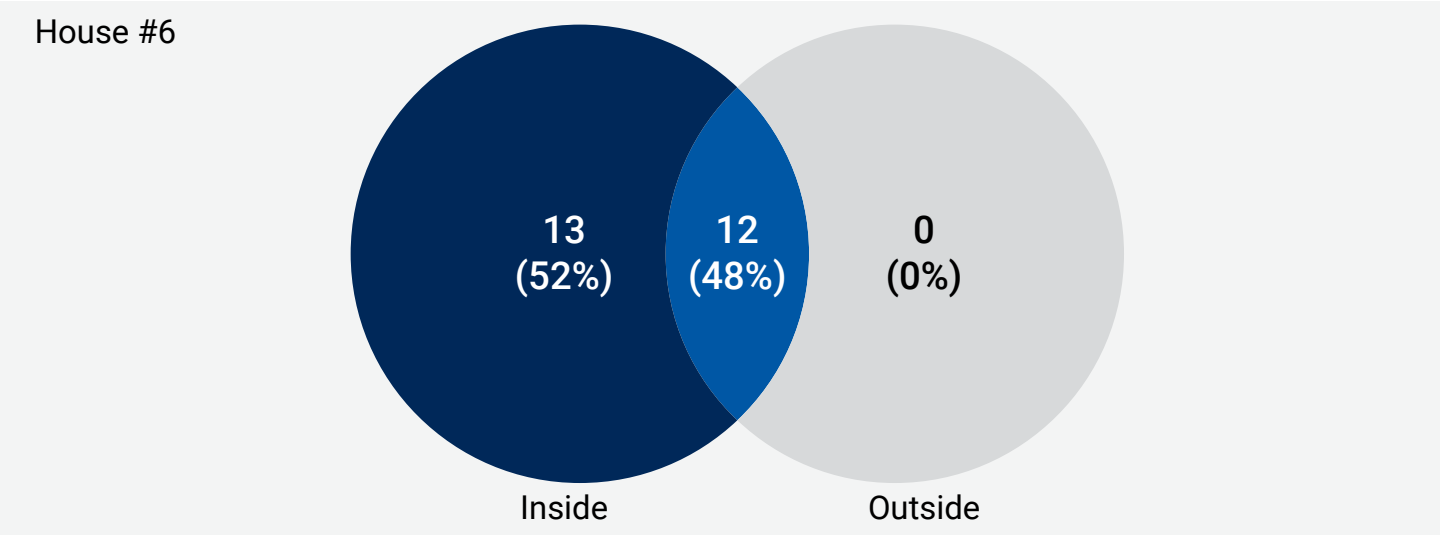


Figure 19: Home #6 Venn diagram of inside vs. outside

Based on these results, the predominate chemical classes detected in the indoor air are likely associated with cleaning products and fragrances. The Venn diagrams of the household levels show that there are no detected chemicals unique to the outdoor environment in any of the homes, while 36%- 68% of the detected chemicals are unique to the indoor environment. A range of 32% - 72% of the detected chemicals were present in both indoor and outdoor samples, indicating that the indoor environment is influenced by the chemicals present in the outdoor air.

During phase 2 of the study, CIRI will collect (1-hour) air samples with active sampling techniques for VOCs and aldehydes and will conduct longer-term passive sampling (6-day) in individual homes. This approach is based on the evaluation of the pilot data set. In addition to air monitoring CIRI will collect settled dust samples from the indoor environment of the participants' homes. The settled dust samples will be sieved, weighed, and analyzed for metals, VOCs, semi-volatile chemicals, and cellular toxicity.

4.0 Conclusions and Future Work

The study found that there was house to house variability among both the indoor and outdoor air samples. The statistical analysis of the air sampling duration variable will allow CIRI to design a sampling strategy based on a 1-hour sample collection duration for future phases of this project. This will add flexibility to the sampling plan for phase 2 of the study, which will involve conducting air and settled dust sampling in 50 homes in Tulare County, California. During the next phase of the study CIRI scientists will be embedded in the sample collection team at each household. During phase 2, CIRI will collect 1-hour air samples with active sampling techniques for VOCs and aldehydes and will conduct longer-term passive sampling (6-day) in individual homes. This approach is based on the evaluation of the pilot data set. In addition to air monitoring, CIRI scientists will collect settled dust samples from the indoor environment of the participants' homes. The settled dust samples will be sieved, weighed, and analyzed for metals, semi-volatile chemicals, and cellular toxicity. Phase 2 will also capture information related to the differences in chemical profiles of air and dust samples before and after a WUI/wildfire event and will allow for the assessment of the efficacy of personal air cleaners as it relates to VOC reduction. Phase 2 will consist of a baseline sampling trip where both passive and active paired indoor/outdoor air samples will be collected at participants' homes. An additional sampling trip will occur if/when there is a fire event in close enough proximity to impact community air quality in Tulare County, California.

5.0 REFERENCES

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