

THESIS

IN-HOME AIR QUALITY CHANGES THROUGH REPORT-BACK OF PERSONAL DATA

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Olivia Cecil

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Ellison Carter

Frances Davenport  
Emily Fischer

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## ABSTRACT

### IN-HOME AIR QUALITY CHANGES THROUGH REPORT-BACK OF PERSONAL DATA

Indoor air quality (IAQ) is a critical determinant of health, yet households face limited practical strategies for improvement. This study tested whether multi-pollutant monitoring paired with personalized, plain-language Home Health Reports (HHRs) featuring data-informed recommendation for improving IAQ could prompt effective actions.

Results showed that ventilation-responsive pollutants—including CO<sub>2</sub>, NO<sub>2</sub>, and episodic volatile organic compounds (VOCs)—declined in treated homes, consistent with reported behaviors such as opening windows, using exhaust fans, and operating range hoods during pollutant-generating activities. NO<sub>2</sub> reductions were especially evident in gas-stove households, reflecting the uptake of provided low- to no-cost recommendations, especially where a clear source exists. In contrast, particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) showed no consistent treatment effect, likely due to episodic sources, outdoor infiltration, and limited adoption of higher-effort measures such as filtration. A subset of highly polluted homes did achieve PM reductions, echoing findings that the greatest reductions occur where baseline pollution is highest.

The VOC analysis reinforced the difference between pollutants diluted by ventilation and those requiring source removal. Episodic compounds such as carbon tetrachloride declined, while continuous emitters such as 1,4-dichlorobenzene were unaffected, underscoring the limits of ventilation-only strategies. Overall, findings align with prior work demonstrating that household behavior change can reduce short-term pollutant peaks, but structural or community-

level measures are needed where emissions are persistent or outdoor-dominated. Broader implementation could pair low-cost feedback with building or community measures, and future research should evaluate long-term adherence, optimize messaging strategies, and link pollutant reductions to health outcomes.

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## INTRODUCTION

Human exposure to air pollution remains a major contributor to respiratory, cardiovascular, metabolic, and neurological disease burdens worldwide. Both acute and chronic exposures to particulate matter (PM), nitrogen dioxide (NO<sub>2</sub>), and volatile organic compounds (VOCs) elevate risks across the life course. A 2009 study found that a decrease of 10  $\mu\text{g m}^{-3}$  to ambient PM<sub>2.5</sub> increased life expectancy by 0.61 years across all demographics (Pope *et al.*, 2009). Over time researchers have begun to focus on indoor air quality, as indoor environments dominate personal exposure profiles since people spend the majority of their time inside homes, workplaces, schools, and vehicles.

Due to the heterogenous nature of air quality in different indoor environments, Morantes *et al.* introduces a Harm Index (HI) to connect indoor air pollutant concentrations with chronic harm and thus rank and select contaminants of most concern (Koehler *et al.*, 2019, Morantes *et al.*, 2024). The HI metric is presented in disability-adjusted-life years (DALY) /  $\mu\text{g m}^{-3}$  / 10<sup>5</sup> persons / year. Concentrations of air pollutants vary between indoor environments, so HIs are designed to be combined with measured concentration to calculate the DALY/ 10<sup>5</sup> persons / year and assess the relative harm from a contaminant in an indoor environment. Some of the most harmful air pollutants are also the most common: PM<sub>2.5</sub>, PM<sub>10</sub>, and NO<sub>2</sub>. Representative indoor contaminant concentrations are presented from a review of peer-reviewed monitoring studies and are used as a comparison with this study.

Combustion-related gases and particles (e.g., NO<sub>2</sub> from gas stoves, ultrafine particles from candles, PM<sub>2.5</sub> from combustion) directly injure respiratory tissues and therefore function as primary health-risk drivers (Daouda *et al.*, 2024). Although PM<sub>2.5</sub> and NO<sub>2</sub> remain among the

most well documented indoor contaminants in terms of epidemiologic evidence, the indoor exposome encompasses a far broader spectrum of agents that serve different scientific and public-health purposes (Haddad *et al.*, 2019). Metabolic markers such as carbon dioxide (CO<sub>2</sub>), while not harmful at typical residential levels, act as occupancy and ventilation proxies, signaling when dilution of other pollutants is possibly insufficient (Park and Song, 2023). At the opposite end of the prevalence spectrum, special-case toxicants like paradichlorobenzene (PDCB), which is released from mothballs, deodorizers, and some types of flooring may occur in a minority of homes (or at least heterogeneously across the United States), yet can exceed reference exposure limits by orders of magnitude when present, posing acute and chronic toxicity risks (Huang *et al.*, 2018, Chin *et al.*, 2014). Finally, a miscellany of semi-volatile organic compounds (SVOCs), aldehydes, and bioaerosols from various products and sources contribute to sensory irritation, endocrine disruption, or allergenicity, although dose-response data remain limited (Lucattini *et al.*, 2018, Logue *et al.*, 2011, Liu *et al.*, 2022).

Recognizing this diversity of indoor pollutants informed our decision to center the Home Health Report (HHR) on concentrations of PM<sub>2.5</sub>, NO<sub>2</sub>, and CO<sub>2</sub>, and actions that households could take at low to no cost to reduce those concentrations if they were elevated, while the Home Health Box (HHB) air quality monitor simultaneously recorded a wider suite of particles, gases, and VOCs that can be used to contextualize and interpret the core metrics. Features of the HHB are described in detail in Tryner *et al.* (2021), as it was designed to provide high-resolution air quality data while remaining low-profile and unobtrusive in a home; Figure 1.1 shows an overview, and Appendix A details the mechanics.

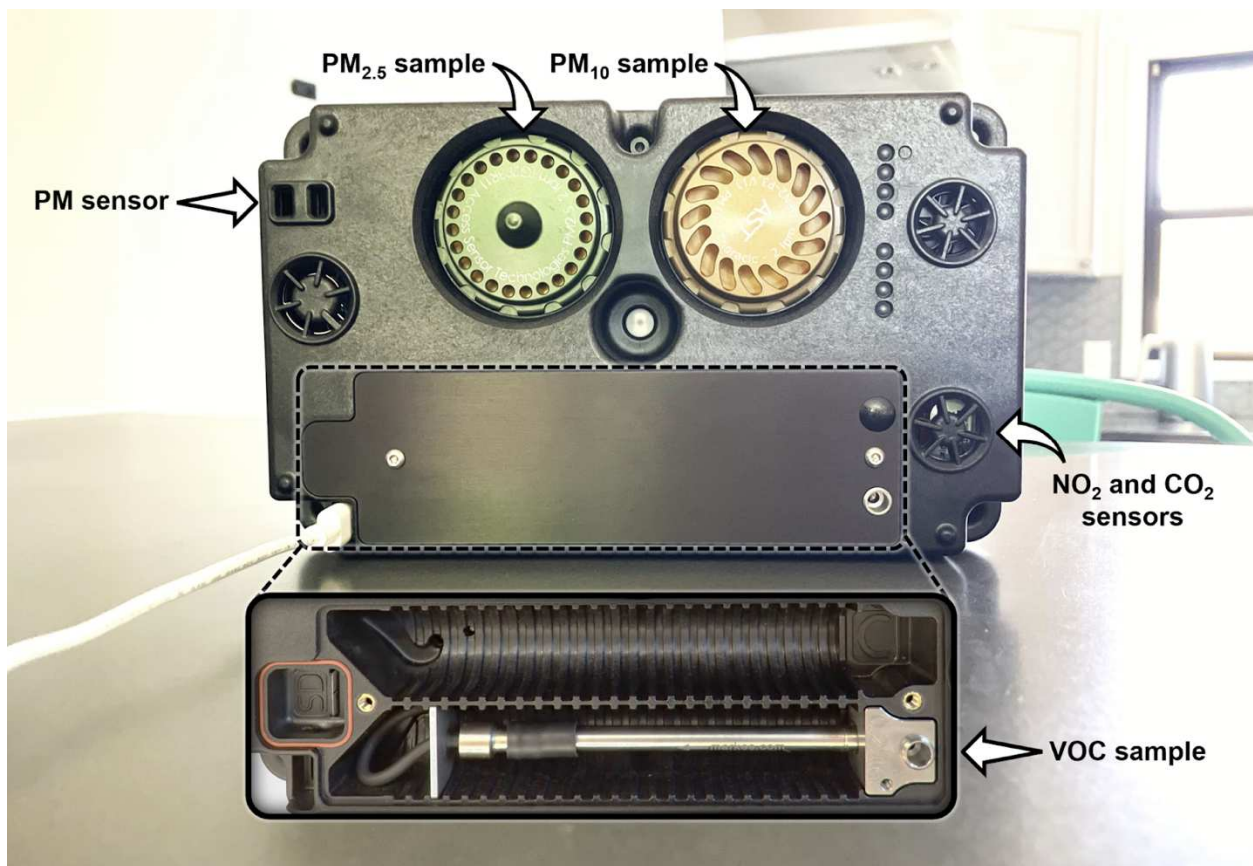


Figure 1.1 Home Health Box (HHB), courtesy of Access Sensor Technologies

Decades of discriminatory zoning, red-lining, and inequitable infrastructure investment have concentrated outdoor pollutant sources in communities of color and low-income neighborhoods (Lane *et al.*, 2022). These upstream factors have been associated with higher baseline ambient pollution, but the disparity widens once pollutants migrate indoors, where residents have fewer levers of control. National survey work shows that homes situated in socio-economically marginalized census tracts routinely record indoor PM and NO<sub>2</sub> levels two-to-three times higher than dwellings in neighboring, more affluent areas—even when outdoor monitors report similar readings. To illustrate how these structural forces materialize inside real bedrooms and kitchens, we highlight two well-characterized case studies. In Baltimore, Maryland, a campaign of 24-h integrated samples found that bedroom PM<sub>10</sub> concentrations in predominantly

Black, inner-city rowhouses averaged almost twice those measured in nearby suburban White households (McCormack *et al.*, 2008). Likewise, in Greater Boston, Massachusetts—a majority-Latinx community ringed by fuel-storage depots and major roadways—week-long indoor PM<sub>2.5</sub> levels in renter-occupied apartments exceeded those in owner-occupied single-family homes by 25–50% (Chu *et al.*, 2020). A similar story emerges along Colorado’s Front Range: pilot monitoring by Shretha *et al.* (2019) in Colorado residences provided evidence that long-range wildfire plumes, road proximity, and occupant behavior have a combined effect on indoor air quality in low-income homes. Taken together, these examples underscore how historical inequities translate into inhalable disadvantages today, providing a rationale for interventions targeted at the home microenvironment rather than solely at ambient sources.

High-resolution indoor air-quality data empower residents, clinicians, and advocates to target pollutant sources and evaluate mitigation efficacy. Researchers in France carried out a study where participants were either given generic information or personalized emission profiles, with in-home air quality monitoring both before and after distribution of the generic or personalized information and found the personalized emissions profiles led to higher reductions in concentrations of measured contaminants than generic educational information alone (Abdel Sater *et al.*, 2021). Household actions, such as optimized window-opening schedules, installation of MERV-13 filters, or replacement of gas stoves with induction—have demonstrated potential to reduce PM and NO<sub>2</sub> exposures when supported by clear, timely information (Nassikas *et al.*, 2024, Kureshi *et al.*, 2023, Daouda *et al.*, 2024). Housing characteristics and behaviors each contribute to indoor air-quality, for example, attached garages are a source of VOCs in the BTEX family (Benzene, Toluene, Ethylbenzene, and Xylenes) and NO<sub>2</sub> and building materials are found to relate to other VOCs and PM concentrations (Baeza\_Romero *et al.*, 2022). Survey

data can capture these household-level details that impact indoor air quality. The Home Health Box (HHB) pairs multi-pollutant sensing and reference-quality sampling with an automated, plain-language Home Health Report (HHR) designed to translate measurements into actionable recommendations.

While personalized environmental feedback has shown promise, robust evidence from randomized or quasi-experimental studies supported by monitoring remains sparse (Cibin *et al.*, 2025). Our study will test whether the HHB + HHR intervention can measurably lower indoor concentrations of PM<sub>2.5</sub>, NO<sub>2</sub>, CO<sub>2</sub>, and selected VOCs across diverse housing contexts. Findings will inform both household decisions and policy debates on gas appliance phase-outs, ventilation standards, and equity-focused housing upgrades. The remainder of this thesis will detail and assess concentration data collected throughout the study and evaluate group statistics to determine the success of the intervention.

## OBJECTIVES AND RATIONALE

This thesis is contained within the broader context of the Home Health and Air Pollution Study, a randomized control trial featuring multiple monitoring periods and personalized report-back of a suite of in-home air quality data. The study was ongoing as of August 2025 with 100 enrolled households and at least two, but up to three monitoring periods for every household. The unique design and dataset from this study allows for the testing of a comprehensive report-back strategy combined with repeated periods of high-quality monitoring of multiple pollutants for every home to address the shortcomings of existing indoor air quality-related behavior change studies. With the exception of analysis of VOC data, this thesis is constrained to data collected up to July 2025 and excludes any third period monitoring data for households from the primary analysis.

Building on the demonstrated health burden of indoor air pollutants, the inequities that magnify those burdens in marginalized communities, and the previous—but limited—empirical evidence of personalized feedback interventions, it was hypothesized that low- to no-cost interventions along with personalized report of monitored data could aid in the reduction of common indoor pollutants. This study positions the Home Health Box (HHB) indoor air quality monitor as both a measurement platform and a behavior-change catalyst.

By capturing multi-pollutant data in real homes and coupling those data with an intuitive, individualized Home Health Report (HHR), we seek to generate rigorous, policy-relevant evidence on whether real-time information can motivate occupants and landlords to reduce exposures and what avenues are most impactful to certain sources. We hypothesized that the feedback intervention could generate indirect impacts to some lesser-known in-home pollutants;

therefore, a more comprehensive suite of pollutants was collected in each household than was reported-back. Accordingly, this thesis pursues three interconnected objectives that translate the broader public-health rationale into testable research questions.

1. Quantify baseline indoor concentrations of CO<sub>2</sub>, NO<sub>2</sub>, PM<sub>2.5</sub>, and target VOCs (e.g., 1,4-Dichlorobenzene) across participant homes during an average week.
2. Evaluate the impact of treatment, as defined within this study (i.e., the Home Health Report: receiving in-home air quality information coupled with actionable recommendations to reduce pollutant levels) on those reported in-home air pollutant levels in households over a several-month intervention.
3. Expand preliminary evidence for the impact of treatment, as defined in this study, on in-home levels of air pollutants that were not directly reported via the treatment instrument (i.e., the Home Health Report).

To achieve these objectives, baseline monitoring data collected during an initial one-week sampling period was compared to data collected during a following one-week monitoring period, occurring after households in the treated group had been provided the intervention: a comprehensive and personalized report of their baseline data along with tailored recommendations to improve their indoor air quality. Since households were enrolled in the study on a rolling basis, these sampling periods took place across various seasons and times of year. Study workflows were designed such that both sampling periods should occur within the same season. These data were used to achieve the study objectives stated above, and in-home pollutant trends were analyzed at the household-level.

## LITERATURE REVIEW

### **Outdoor vs. Indoor Exposure Disparities 2.1**

Indoor pollutant concentrations are shaped by a dynamic interchange between outdoor sources, building characteristics, and indoor activities. In many U.S. cities, outdoor PM<sub>2.5</sub> and NO<sub>2</sub> peaks align with traffic density and industrial plumes—but infiltration efficiencies vary widely between types and ages of homes, and temporally within the same home (MacNeill *et al.*, 2012). Consequently, households in the same census tract can experience markedly different indoor burdens even when outdoor monitors report identical readings. Building use also influences indoor pollutant concentrations; a 2020 review of studies measuring or modeling indoor/outdoor (I/O) ratios for NO<sub>2</sub> in various building types found that residential structures have the highest I/O ratios (compared with offices and schools) due to numerous indoor NO<sub>2</sub> sources (Hu and Zhao, 2020).

Combustion appliances, cooking practices, and resident behaviors add complexity to monitoring, as pollutant concentrations vary both spatially and temporally in the home (Singh *et al.*, 2024). Cooking-related emissions from gas stoves can increase in-home concentrations of NO<sub>2</sub> well above outdoor standards, and both gas and electric cooktops produce large amounts of PM<sub>2.5</sub> (Singh *et al.*, 2024, Nassikas *et al.*, 2024). Cleaning products, scented candles, oil diffusers, and hobbies like crafting or woodworking contribute to in-home PM-load (Nassikas *et al.*, 2024, ALA, 2023) Building characteristics such as attached garages or art studios can contribute to pollution levels, and unknown reservoirs of emissions can originate from leaks or spills (Mannan and Al-Ghamdi, 2021). Since US adults spend up to 90% of their time indoors, this exposure environment has a significant impact on human health (Klepeis 2001).

## Low-Cost Sensor Technologies 2.2

Advances in micro-electromechanical systems have produced a wave of low-cost, low-power sensors that promise democratized air-quality monitoring. Optical particle counters (e.g., Plantower, Sensirion) infer PM mass from light-scattering intensity but can overestimate mass in high-humidity or high-PM environments (Levy Zamora *et al.*, 2019). Electrochemical NO<sub>2</sub> cells offer ppb-level sensitivity yet historically suffer from cross-interference with ozone and temperature drift (Mead *et al.*, 2013). Testing has shown that electrochemical sensors used in the Home Health Box (HHB) are strongly correlated with reference NO<sub>2</sub> concentrations and successfully predict gas concentrations, likely due to the less variable environment indoors (Tryner *et al.*, 2021). Non-dispersive infrared (NDIR) detectors reliably quantify CO<sub>2</sub> but challenges associated with conversion of raw output into pollutant concentrations is complex and can increase cost when monitoring in variable conditions; conversely, the HHB operates indoors, where linear mixed models were able to produce accurate results without the computing cost of random forest calibration models (Tryner *et al.*, 2021).

Balancing accuracy, affordability, and usability guided sensor selection for the HHB. The deployed suite costs approximately USD 5000 yet achieves field performance comparable to those from reference monitors after multi-point calibration and humidity correction (Reilly *et al.*, 2022, Tryner *et al.*, 2021).

## Ventilation & Occupancy Metrics 2.3

Ventilation dictates the rate at which indoor pollutants are diluted or removed, making it a foundational determinant of exposure. Hu and Zhao (2020) found that seasonal variations in residential NO<sub>2</sub> concentrations could be attributed to the changing air exchange rate as people

alter behaviors according to weather. Residences in the US are overwhelmingly ventilated by leaks in the building envelope or manually by opening windows, unlike commercial buildings which adhere to airflow guidelines with mechanical ventilation throughout the year (Sherman and Matson, 2002). With this in mind, carbon dioxide (CO<sub>2</sub>) is not toxic at typical residential levels, yet its concentration closely tracks occupant density and air-exchange rate, providing a practical proxy for ventilation adequacy (Kabirikopaei and Lau, 2020). Persily (2022) cautions against CO<sub>2</sub> being used alone to quantify air exchange, rather the metric should be used as an indicator in reference to a standard or state, or combined with building and occupancy details to evaluate air exchange.

At shorter time scales, transient CO<sub>2</sub> peaks > 1,500 ppm flag high-occupancy events (e.g., dinner preparation), since human metabolism and burning of fuel are the main sources of indoor CO<sub>2</sub>; combustion by-products and cooking aerosols may also spike (Shen *et al.*, 2020). Because occupants can correct ventilation deficits rapidly by taking actions such as opening windows or engaging exhaust fans, CO<sub>2</sub> feedback offers an actionable lever for behavior change.

#### **Building Characteristics & Source–Sink Dynamics 2.4**

The built environment shapes indoor pollutant dynamics through both source intensity and removal capacity. Gas stoves, unvented space heaters, and kerosene lamps introduce combustion by-products directly; carpeting and soft furnishings act as sinks that adsorb semivolatile organics and later re-emit them when temperatures rise (Nassikas *et al.*, 2024, Weschler and Nazaroff, 2008). A California study monitored NO<sub>2</sub> concentration throughout nine homes with gas cookstoves, taking measurements with and without venting to determine that gas-cooking without venting elevations NO<sub>2</sub> levels in the kitchen to over 100 ppb, with increases observed in all other rooms as well. When the vent was activated, reductions of up to 95% were

recorded throughout the home (Singer *et al.*, 2017). Building characteristics such as room interconnectedness can impact pollutant circulation through the home, while building age, retrofitting activities, and finishing material can contribute emissions, such as paradichlorobenzene (PDCB) from solid wood flooring (Baeza\_Romero *et al.*, 2022, Huang *et al.*, 2018). Research has shown that ventilation alone does not robustly impact VOC emissions from constant emitters like building materials (Wolkoff, 1998).

Envelope airtightness and infiltration rate modulate how quickly outdoor pollutants penetrate indoors and how fast indoor emissions are flushed out (MacNeill *et al.*, 2012, Hu and Zhao, 2020) Although the present study does not measure airtightness directly, we collect data on building age, construction type, ventilation system, and presence of combustion appliances so that post-intervention recommendations in the Home Health Report (HHR) can be tailored (e.g., advising portable HEPA units in older, leakier homes versus range-hood upgrades in newer but tightly sealed kitchens).

### **Health Evidence for VOCs & SVOCs 2.5**

Beyond criteria pollutants, a range of volatile and semivolatile organic compounds (VOCs/SVOCs)—formaldehyde, benzene, phthalates, flame-retardant by-products—affects endocrine, neurological, and respiratory health (Logue *et al.*, 2011). 1,4-dichlorobenzene (PDCB) warrants special attention: while detected heterogeneously in U.S. homes, measured concentrations can exceed the U.S. EPA reference concentration ( $RfC = 800 \mu\text{g m}^{-3}$ ) by orders of magnitude, elevating cancer risk (EPA 1994, Chin *et al.*, 2013). The 1999 – 2000 National Health and Nutrition Examination Survey (NHANES) included a VOC personal exposure study carried out on the adult subset via badges worn for 2 – 3 days with 10 VOCs sampled. PDCB was the predominant VOC in 15% of the measurements, with the median concentration of these

measurements exceeding  $60 \mu\text{g m}^{-3}$ . Though PDCB is not ubiquitous like the highly studied BTEX compounds (Benzene, Toluene, Ethylbenzene, and Xylenes), the inclusion in a population-level survey alongside BTEX, and the notable results flag this compound for additional observation (Jia *et al.*, 2008).

The HOMEChem study highlights the diversity in overall mass and combinations of VOCs within the home, which can increase above background by 300% during cooking or cleaning and contain known and potential air toxics (Hodshire *et al.*, 2022). Existing epidemiology is thinner than for extensively studied pollutants such as  $\text{PM}_{2.5}$  or  $\text{NO}_2$ , but mechanistic toxicology and weight-of-evidence assessments justify precautionary exposure reductions and monitoring to determine possible harm—hence the HHB’s inclusion of passive sorbent tubes to screen for a broader chemical panel (Monantes *et al.*, 2024).

## **Behavior-Change Theory & Feedback 2.6**

### *Environmental Feedback 2.6.1*

Pollutant monitoring alone seldom translates into exposure reduction; effective interventions leverage behavior-change frameworks. The COM-B model posits that Capability, Opportunity, and Motivation interact to produce Behavior. Personalized feedback can enhance psychological capability (by improving risk comprehension) and reflective motivation (by linking actions to measurable outcomes) (Michie *et al.*, 2011). Feedback must be placed in context for participants, such as ranked from low to high concern, or displayed against all data collected (Samon *et al.*, 2023). A randomized control trial in Chile showed that participants provided information and guidance on reducing in-home exposures when using wood-burning cookstoves (sign affixed to stove vent indicating level of pollution entering home at various

degrees of open) did follow recommendations to open the exhaust vents farther and reduced household PM<sub>2.5</sub> pollution over the control group (Ruiz-Tagle and Schueftan, 2021). Evidence shows that tailored, context-specific messages outperform generic advice, but few air-quality trials have incorporated multi-pollutant feedback or evaluated durability beyond a few weeks. By nesting the HHR within these theories and measuring outcomes over multiple months, this thesis addresses a critical gap in environmental-health intervention science.

### *Personalized Feedback 2.6.2*

A 2025 review of communication interventions in air quality awareness found that top-down communication strategies tend to increase awareness but have limited influence on behavior, whereas participatory approaches are increasingly adopted and more effective in fostering meaningful action (Cibin *et al.*, 2025). Personalized feedback goes one step farther and shows promising impacts to engagement – Brody *et al.* (2021) found that a subgroup given personalized exposure reports spent approximately twice as much time viewing their reports as compared to the group provided only overall summary results.

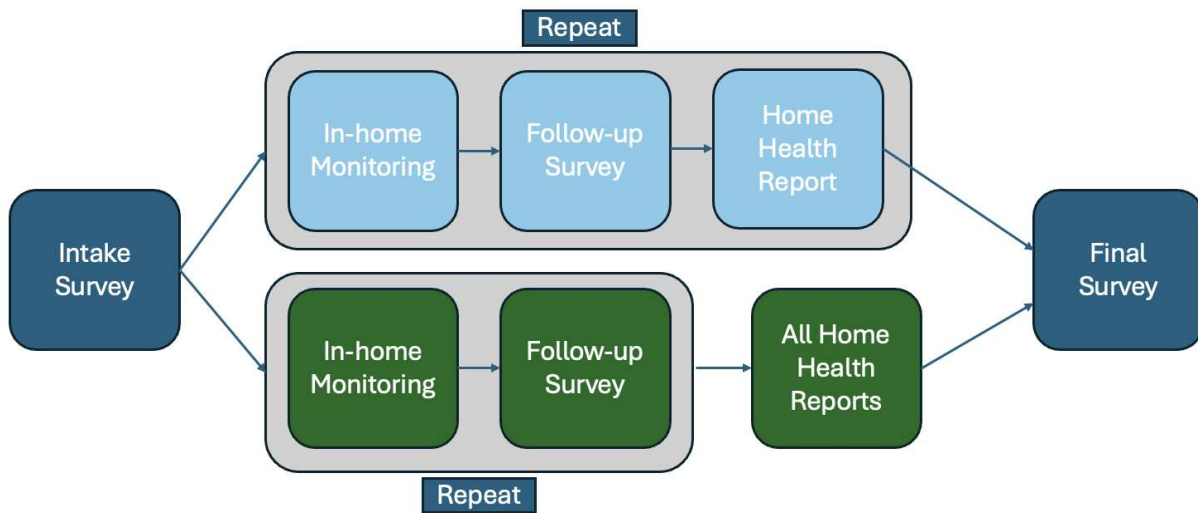
A 2021 study in France tested the effectiveness of generic versus personalized information as treatment in a randomized control trial of indoor air quality monitoring – households were equipped with a PM monitor for four months and randomized into three groups: control, generic information treatment, and weekly personal emission profile with the same generic information. Though focused only on PM<sub>2.5</sub> pollution from combustion activities, special emphasis given to wood-burning, authors found the personalized treatment to reduce indoor PM<sub>2.5</sub> levels by 20% compared to the control group (Abdel Sater *et al.*, 2021). Despite promising signals, the evidence base remains thin: few studies cover more than one pollutant, randomization is rare, and outcome measures vary (mean 24-h concentration vs. peak reductions

vs. self-reported behavior change). No prior work, to our knowledge, has simultaneously tracked PM<sub>2.5</sub>, NO<sub>2</sub>, CO<sub>2</sub>, and select VOCs while providing a plain-language, visually oriented report akin to the Home Health Report (HHR). This thesis therefore addresses a critical gap in scientific literature to date by testing a multi-pollutant, theory-informed feedback tool over a multi-month period—long enough to observe sustained habits or regression to baseline.

## METHODS

### Study Design and Timeline 3.1

The Home Health and Air Pollution Study followed a longitudinal, two-arm design consisting of (i) an Intake Survey, (ii) up to three rounds of in-home monitoring, each paired with a self-administered Follow-Up Survey and, for treated participants, a Home Health Report (HHR), and (iii) a Final Survey. Figure 3.1 depicts the full workflow for control (green) and treated (blue) groups; each grey box represents one complete monitoring “deployment” or sampling period.



*Figure 3.1 Study timeline and participant flow for control (green) and treated (blue) groups. Grey clusters indicate a single deployment cycle, repeated up to three times per participant.*

### Study Population and Recruitment 3.2

Eligible households included adults  $\geq 18$  years who (i) spoke English or Spanish, (ii) expected to remain in their residence for  $\geq 4$  months, and (iii) provided informed consent.

Exclusion criteria included address change during the study, voluntary withdrawal, failure to

return monitor, or decline to provide a means of contact such as mailing address, email address, or phone number.

Participants were recruited via three pathways: (1) Dr. Fernando Holguin's asthma clinic at the University of Colorado Anschutz Medical Campus, (2) outreach by Colorado State University (CSU) researchers in Fort Collins (flyers at public libraries, Healthy Homes networks, and a local food-rescue site), and (3) the City of Las Cruces Sustainability Office.

All participants recruited through CSU were read a recruitment script in person or over the phone and given the opportunity to ask questions before providing required demographic information which was recorded in REDCap (Research Electronic Data Capture), a secure, web-based software platform designed to support data capture for research studies. Demographic information collected for each participant record included: name, date of birth, home address (where sampling would take place), race, and ethnicity. For participants not in the Las Cruces subgroup, a method of communication was also required: email and/or phone number. Additional demographic questions were included on the Intake Survey, but answers were not required for continued participation.

### **Home Health Box (HHB) Preparation 3.3**

All preparations for sampling were carried out at Access Sensor Technologies, and included: (1) CO<sub>2</sub> sensor calibration outside to ambient concentration of 417 ppm, (2) organizing and checking o-rings on sample media, and recording serial numbers of two filters and one thermal desorption tube per monitor in a deployment-tracking-log, (3) installing clean inlets and 37-mm-diameter polytetrafluoroethylene (PTFE) sample filters (PT37P-PF03, Measurement Technology Laboratories, Minneapolis, MN, USA) for particulate matter sampling, (4) installing

a clean Carbopack X SafeLok stainless steel thermal desorption tube (C1-DXXX-5020, Markes, Bridgend, UK) for total volatile organic compound (tVOC) sampling, (5) flow rate validation of all pumps activated for sampling against an external flow rate meter (MWB-5SLPM-D/GAS: 99.9% Air + 0.1% H<sub>2</sub>O, HC for filter samples and MWB-50SCCM-D/GAS: 99.9% Air + 0.1% H<sub>2</sub>O for VOC samples, Alicat Scientific, Tucson, AZ, USA), and (6) programming sample settings, updating file dates, and reviewing all filter serial numbers are correctly recorded into software.

Once HHBs were assembled, they were sealed into static-shielding plastic bags and packed into cardboard boxes with layers of foam inserts. Included in each shipping box were (1) USB-C charging cable, (2) pre-paid return shipping label, (3) adhesive strips of packing tape for return shipping, and (4) instructions detailing repacking of the box. HHBs were shipped overnight directly to participants home address, to a centralized pickup location, or hand-delivered to local participants. A shipping alert was emailed including tracking information and instructions for setting up the monitor.

## **Field Procedures 3.4**

### *Deployment and Retrieval 3.4.1*

Each HHB operated autonomously for one week (168 h), signaled by a solid green LED. Boxes were shipped to participants' homes, exchanged at a central pickup site, or hand-delivered in Fort Collins. Las Cruces residents collected and returned units through city staff. Participants were instructed to unpack the HHB and place it in a main living area of their home, on a flat surface between knee and head height where it could be plugged in, activated, and left undisturbed for the sampling duration. Once the HHB turned off automatically, signaling sample

completion by no longer displaying a green LED light, participants were instructed to place the HHB back in the original packaging, including plastic static shield bag, and either (1) ship box to AST using the provided pre-paid shipping label, (2) contact CSU for home pickup, or (3) return HHB to Las Cruces staff at City Hall. Automated email reminders were issued at 21- and 30-days post-shipment; non-responsive participants then received personalized emails and phone calls.

Field blanks were collected at a rate of 10% - blanks were prepared as though it were an active sample, then either shipped to the CU Anschutz Clinic in Denver, Las Cruces City Hall, or hand carried home by a CSU team member. Every field blank was stored at the location, in the original packaging, for at least one week and then returned by the same pathway, to simulate regular sampling and transit.

Upon return to AST sample unloading process included (1) both PM filters were removed, placed into clean plastic clam-shells, and stored in a freezer at -20°C before post-processing, (2) the thermal desorption tube containing the VOC sample was removed from the HHB, capped (SS-400-C, Swagelok, Solon, OH, USA), wrapped in aluminum foil, placed inside a sealed plastic bag, and stored in a freezer at -20 °C to await analysis (storage for up to a few months before analysis), (3) mirco-SD card extracted from HHB and the sample-LOG file was transferring the a Dropbox folder of raw data, (4) PM inlets were cleaned with water and cotton swabs, air dried, and then stored in a clean, resealable box. Each HHB was retained in the AST office for subsequent deployments to the same household as much as feasible.

### *Surveys and Report Delivery 3.4.2*

Several surveys were distributed to participants through REDCap during the study. An initial Intake Survey was automatically emailed to each participant when the first HHB was prepared for shipping, and Follow-Up Surveys were distributed once each HHB was received at AST and unloaded. The Las Cruces subgroup completed all surveys on a tablet during HHB handoff at the designated exchange location with a city representative.

Surveys differed between the treated and control groups, with the treated group surveys including questions about reactions to the treatment with all else the same. Blank versions of all surveys are including in Appendix B. Participants were automatically reminded of outstanding surveys every three days, up to three times, but after 2 weeks had elapsed, HHRs were generated in the absence of survey data. HHRs were delivered by email, through REDCap as a PDF link or as a printed copy (Las Cruces participants only).

### **Home Health Report (HHR) Detail 3.5**

Every Home Health Report (HHR) was four pages long, delivered by email as a PDF (Las Cruces subgroup reports were printed and handed to participants by city representative), and contained the following information: cover page, description of how to read the report and relevance of recorded parameters, detailed air quality data recorded during sampling, and personalized tips from standardized list that correspond to each participant's unique home and air quality data. Two reports are included as Appendix C, which encompass the general range of indoor air quality found in the study from low pollution-level to high, and a HHR is included as Figure 3.2.

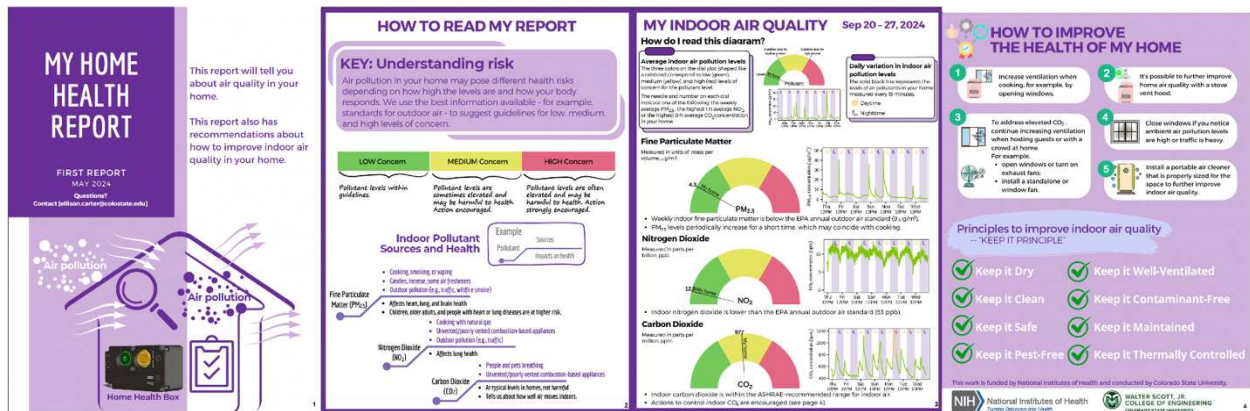


Figure 3.2. The Home Health Report is a four-page document detailing and summarizing each week-long sampling period for a household.

- Page 1: cover page with dates of sampling and which monitoring period (first - third) is described.
- Page 2: directions for understanding plots, acronyms defined, and general information on air quality data included in report.
- Page 3: a representative maximum average concentration was shown as a dial plot and time-series plots for Carbon dioxide, Nitrogen dioxide, and PM<sub>2.5</sub> (Las Cruces subgroup also includes PM<sub>10</sub> data average on dial plot, but no time-series).
- Page 4: six personalized recommendations to reduce pollutants found by monitoring data and the general “Keep it” principles from the National Institute of Health. A complete list of recommendations can be found in Appendix D.

### Representative Concentrations 3.5.1

Dial plots were utilized to concisely communicate the calculated representative pollutant levels for a household in reference to selected standards for outdoor air quality from either US Environmental Protection Agency (US EPA) or World Health Organization (WHO). Threshold values and the basis for comparison to HHB pollutant level are detailed in Table 3.1.

*Table 3.1. Criteria selected for rating in-home pollutant levels measured by HHB, and basis for calculations of representative pollutant concentrations presented in HHRs.*

Pollutant	Unit	Basis	Low	Medium	High	Source
PM <sub>10</sub>	µg m <sup>-3</sup>	168-h averaged derived from filter sample	< 45	45 – 150	> 150	WHO, US EPA
PM <sub>2.5</sub>	µg m <sup>-3</sup>	168-h averaged derived from filter sample	< 9	9 – 35	> 35	US EPA
NO <sub>2</sub>	ppb	1-h block average	< 53	53 – 100	> 100	US EPA
CO <sub>2</sub>	ppm	8-h rolling average	< 800	800 – 1200	> 1200	

Dial plots featured sections colored green, yellow, and red, corresponding to low, medium, and high threshold exceedance, and the participant’s in-home concentration during the sampling period was shown as a black line labeled with the numeric value. Representative concentrations were calculated during post-processing according to the HHB User Manual and astr package Reference and are described in Section 3.6.1.

### *Time-Series Plot 3.5.2*

Time series plots were shown for each air quality parameter, smoothed to a 15-minute rolling average; PM<sub>2.5</sub>, NO<sub>2</sub>, and CO<sub>2</sub> concentrations were plotted over the duration of each sample. The 15-minute rolling average line on the PM plots were color-coded according to the PM<sub>2.5</sub> low to high rating for the full sample. Each segment of the 15-minute rolling average lines on the NO<sub>2</sub> and CO<sub>2</sub> plots was color coded according to the low to high rating for the associated hour or gray if a rating was unavailable due to incomplete data.

## Measurements 3.6

### *Real-Time Sensor Data 3.6.1*

HHBs logged 30-s readings of PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, CO<sub>2</sub>, temperature, and relative humidity. The electrochemical NO<sub>2</sub> sensor's limit of detection (LOD) is 30 ppb. Post-processing of chemical sensor data recorded on the LOG-file was completed by Dr. Jessica Tryner, Director of Research at AST, according to steps described in the HHB User Manual and the github reference for the *astr package* (AST, 2025). In short, time-resolved pollutant samples were validated and corrected according to quality assurance criteria described in the *astr package* documentation before 1-h block, then 8-h rolling averages were calculated for the full duration of the sample, in reference to the sample start time. Blocks were considered valid if 30-s data were captured for at least 75% of the hour, and 8-h rolling averages were such if at least six of the eight 1-h blocks were valid.

### *Outdoor Air Quality Data 3.6.2*

Hourly outdoor PM<sub>2.5</sub>, PM<sub>10</sub>, and NO<sub>2</sub> levels measured at regulatory monitoring sites across Colorado and in Doña Ana County, New Mexico were downloaded from either the United States Environmental Protection Agency (US EPA) Air Quality System (AQS) or the Colorado Department of Public Health and Environment and New Mexico Environment Department websites for validation of data collected by the HHB, or to replace values recorded below LOD. Nearest outdoor regulatory monitors were located according to GPS latitude and longitude of the address provided upon enrollment.

### Gravimetric Particulate Matter 3.6.3

Particulate matter samples were collected on filters at a pump rate of  $2 \text{ L min}^{-1}$ . Two size-selective inlets separated particulate matter into  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  to be deposited onto pre-weighed filters. Filters were pre- and post- weighed on a microbalance (Mettler Toledo Inc., XS3DU, USA) in triplicate, and stored in vacuum-sealed bags before being placed into filter inlets on a HHB for sampling. After sampling, filters were removed, replaced into plastic storage clam-shells, and stored in a freezer at  $-20^\circ\text{C}$  before post-weighing within approximately one week. The 168-hour average PM concentrations for both  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were calculated by dividing the difference in mass by the total airflow through the inlet during the sampling period, this is included below as Equation 3.1.

$$[PM_{AVG,168-hr}] = \Delta mass / [(2 \text{ L min}^{-1})(168 \text{ hour})(60 \text{ min hour}^{-1})] \quad \text{Eq 3.1}$$

### Volatile Organic Compounds 3.6.4

VOC samples were analyzed in batches of 30 to 40 using thermal desorption gas chromatography–mass spectrometry (TD GC-MS) (UNITY-ULTRA-xr, Markes, Bridgend, UK, Trace 1310, Thermo Fisher Scientific, Waltham, MA, USA, ISQ QD, Thermo Fisher Scientific). The gas chromatograph was equipped with a 30 m ZB-5HT Inferno column (Phenomenex, Torrance, CA, USA; 0.25 mm internal diameter, 0.25  $\mu\text{m}$  film thickness); processing is described in Tryner *et al.* (2023). In brief, each tube was pre-purged with room-temperature nitrogen (50 mL/min for 1 minute), then desorbed at  $300^\circ\text{C}$  for 10 minutes with a nitrogen flow of 100 mL/min. The trap was heated at  $40^\circ\text{C/s}$  to  $300^\circ\text{C}$ , initiating GC analysis. The desorbed VOCs were introduced to the GC with a split flow of 30 mL/min. Blanks and calibration sample tubes

were placed at the start and end of a sampling sequence, and at predetermined intervals throughout the sample. All analysis was carried out at Colorado State University at the Analytical Resources Core (ARC), and processing of TD GC-MS data was carried out in Chromeleon by Colorado State University ARC facility personnel. VOC data were excluded from HHRs due to analysis lag and batching of samples.

### **Data Management 3.7**

All participant records and survey responses resided in REDCap, which provided validated entry fields, audit trails, and automated exports. Raw sensor files were stored in secure Dropbox folders; subsequent processing employed the astr R package per HHB User Manual guidelines.

### **Statistical Analysis 3.8**

#### *Summary Statistics 3.8.1*

Summary statistics were calculated for only those participants with data for both deployments one and two ( $n = 74$ , [treated = 35, control = 39]). Calculations for arithmetic mean, standard deviation, and median were completed by column for each air quality parameter recorded ( $\text{CO}_2$ ,  $\text{NO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10-2.5}$ ). Geometric mean and the 95% confidence interval of the geometric mean were also calculated in this way. Values were calculated within treated and control groups, and for each sample period (1 and 2).

#### *Change metrics 3.8.2*

The average change in concentration for each air quality parameter recorded ( $\text{CO}_2$ ,  $\text{NO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10-2.5}$ ) was calculated by finding the change in each pollutant concentration for each participant, then averaging this column within the treated and control groups. Percent change in

each pollutant was calculated by first creating a change ratio (CR) of the concentration during sampling period 2 to concentration during sampling period 1 for each participant (Equation 3.2), then taking the geometric mean ( $GM_{CR}$ ) of the change ratios for each pollutant and finally calculating the percent change according to Equation 3.3.

$$CR = c_{HHB2} / c_{HHB1} \quad \text{Equation 3.2}$$

$$\text{percent change} = (GM_{CR} - 1) * 100 \quad \text{Equation 3.3}$$

Output tables for both summary and change statistics are displayed in the results section corresponding to the evaluated pollutant.

### *Group Comparisons 3.8.3*

Unpaired t-tests were carried out for comparison between treated and control groups for both sampling periods. This analysis was completed to observe differences between sample 1 data for the two groups – testing the success of randomization, and to test for any differences in sample 2 data for the groups – evaluating success of the intervention. Output tables are shown in Section 4.3.5 and include the following parameters: mean difference, upper and lower confidence intervals, p-value, n treated, and n control.

Additionally, paired t-tests were performed for intra-group sample comparison. This analysis is needed to confirm that any significant differences observed in sample 2 from the unpaired t-tests are not only significant between the groups but are also significant when compared within-group to sample 1. Output tables are shown in Section 4.3.5 and include the following parameters: mean difference, upper and lower confidence intervals, p-value, and sample size.

Wilcoxon tests were carried out for CO<sub>2</sub> data after a Shapiro-Wilks Normality test confirmed the data is not normally distributed. The same comparisons were made and the results also presented in Section 4.3.5.

### **Ethical Considerations 3.9**

The study protocol received approval from the Colorado State University Institutional Review Board (IRB # 23 – 0817). All participants provided informed consent and received monetary compensation upon completion of surveys and monitor returns.

## RESULTS

### Participant Summary 4.1

Data collection was conducted for this analysis from November 2023 to July 2025. In total, 84 participants had completed sampling period 1 (treated n = 41, control n = 43), and 74 participants had completed sampling periods 1 and 2 (treated n = 35, control n = 39). The average time to return HHBs was 22 and 25 days for sampling periods 1 and 2, respectively.

Households were recruited in both Colorado and Las Cruces, New Mexico, and these locations are used as subgroup divisions for some analyses. Table 4.1 shows the overall participant summary and any subgroups created by region or housing characteristic.

*Table 4.1 Participant summary including subgroups and demographic details used for analysis.*

Randomization	HHB 1 (n = 84)				HHB 1 and 2 (n = 74)			
	n	Colorado	New Mexico	Gas stove	n	Colorado	New Mexico	Gas stove
Treated	41	33	8	12	35	29	6	10
Control	43	34	9	16	39	33	6	15

Across all participants, 28% were renters and 72% were homeowners. Housing types included 77% single-family detached homes, with the remaining 23% split evenly between apartments and townhouses or duplexes. Household sizes ranged from single occupants to households with six or more members (median household size: 2). The median building age was 42 years (1983) (IQR: 74 – 16 years), and 39% of households reported at least one combustion appliance (gas stove, gas fireplace, or unvented space heater).

Geographic and environmental context also differed between sites. Colorado households were more likely to be located in suburban or exurban areas, with varied proximity to major

roadways. Las Cruces households were more frequently located in arid, dust-prone environments and in neighborhoods with higher reliance on evaporative cooling systems. Both regions experience wildfire smoke seasonally, though no sampling period coincided with a major wildfire event. Maps of participating households are included as Appendix E and have been generated with a random jitter added to home coordinates to protect privacy. One household was located in Garfield County, in the Rocky Mountains, but all other Colorado households were concentrated in the Denver area and Fort Collins.

#### **In-Home Air Quality and Survey Data Collection Summary 4.2**

Between November 2023 and July 2025, the study collected both in-home air quality and survey data from participating households. This included 150 filter samples for coarse particulate matter (PM<sub>10</sub>) and 158 filter samples for fine particulate matter (PM<sub>2.5</sub>). We collected field blanks at a rate of approximately 10%, which served as controls to check for any contamination during handling and storage. For volatile organic compounds (VOCs), we obtained 198 samples using pre-conditioned Carbo-pack X thermal-desorption tubes.

We also gathered survey data at multiple points in the study. Across all participants, there were 77 completed intake demographic surveys (92% completion rate), 61 follow-up surveys after the first sampling period (73%), and 63 follow-up surveys after the second sampling period (85%). In the second round of data collection, treatment-group specific surveys were distributed, with 27 treated households completing surveys, and 36 control households. These survey responses helped with data interpretation in the context of participant behaviors, housing characteristics, and any changes made in response to the Home Health Reports.

All Home Health Reports (HHRs) provided to participants included clearly labeled time-series plots for each pollutant measured. Each report also summarized the data into a single representative concentration for the sampling week. This representative value was calculated using one of several approaches, depending on the pollutant: a maximum rolling average, a maximum block average, or an integrated average. The representative concentration was then displayed on a dial-style graphic and categorized from “low” to “high” based on health-based thresholds. These thresholds were drawn from either the U.S. Environmental Protection Agency (EPA) standards or the World Health Organization (WHO) guidelines, depending on the pollutant. Table 3.1 in Section 3.5.1 provides these threshold values, their definitions, and the sources from which they were derived.

### **Analysis of Intervention Impacts Among Select Measured In-Home Pollutants 4.3**

All data collected and returned to participants as Home Health Reports (HHRs) were analyzed according to consistent methods. Details of each pollutant’s calculation method are provided in its respective section.

#### *Fine Particulate Matter (PM<sub>2.5</sub>) Concentrations and Trends 4.3.1*

Fine particulate matter (PM<sub>2.5</sub>) was reported to all participants in HHRs. The representative concentration for fine particulate matter was calculated as the 168-hour average derived from the filter sample (collected via size-selective inlet with a constant flow rate of 3 L min<sup>-1</sup>). Figure 4.1 shows overall PM<sub>2.5</sub> concentration distributions by deployment and group. The concentrations measured for PM<sub>2.5</sub> were typically low, with many values being below the EPA annual outdoor standard of 9 µg m<sup>-3</sup>. Median concentration across all samples collected were 6.3 µg m<sup>-3</sup> (sample 1, HHB1) and 5.8 µg m<sup>-3</sup> (sample 2, HHB2), but the range extended from 0.6 to 679 µg m<sup>-3</sup>,

consistent with high household-to-household variation reported in other indoor air quality studies (Mannan and Al-Ghamdi, 2021).

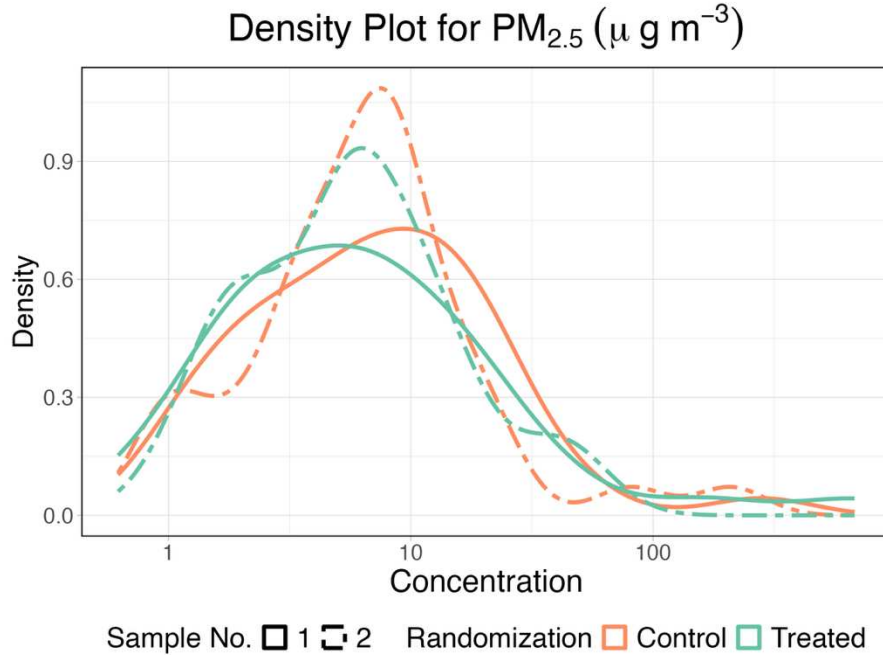


Figure 4.1. PM<sub>2.5</sub> concentration distribution of filter-derived 168-hour average concentrations for each deployment, by treatment group.

In a meta-analysis of 107 monitoring studies (i.e., individual research efforts documented globally in which indoor air quality was directly measured via sensors or samplers in homes or other environments), Morantes *et al.* (2024) reported a representative median PM<sub>2.5</sub> concentration of 26 µg m<sup>-3</sup>. Our lower medians may reflect the U.S.-only scope of our work and comparatively lower ambient levels during the study period. A meta-analysis by Logue *et al.* (2011) that primarily used empirical data from studies conducted in the United States, but did not report medians, found a mean of 15.9 µg m<sup>-3</sup>, which is closer to our study means of 22.3 µg m<sup>-3</sup> (HHB1) and 12.0 µg m<sup>-3</sup> (HHB2).

Trend plots displayed as Figure 4.2 show the direction of change in PM<sub>2.5</sub> concentrations between HHB1 and HHB2 for each participant, separated into treated and control groups. The

background tinting of the plot aligns with low, medium, and high thresholds provided in HHRs. Bases for these thresholds can be found in Table 3.1. Only households that completed both sampling periods ( $n = 74$ ) can be included in this analysis, and of those, only households with PM data for both HHB1 and HHB2 are included ( $n = 74$ ).

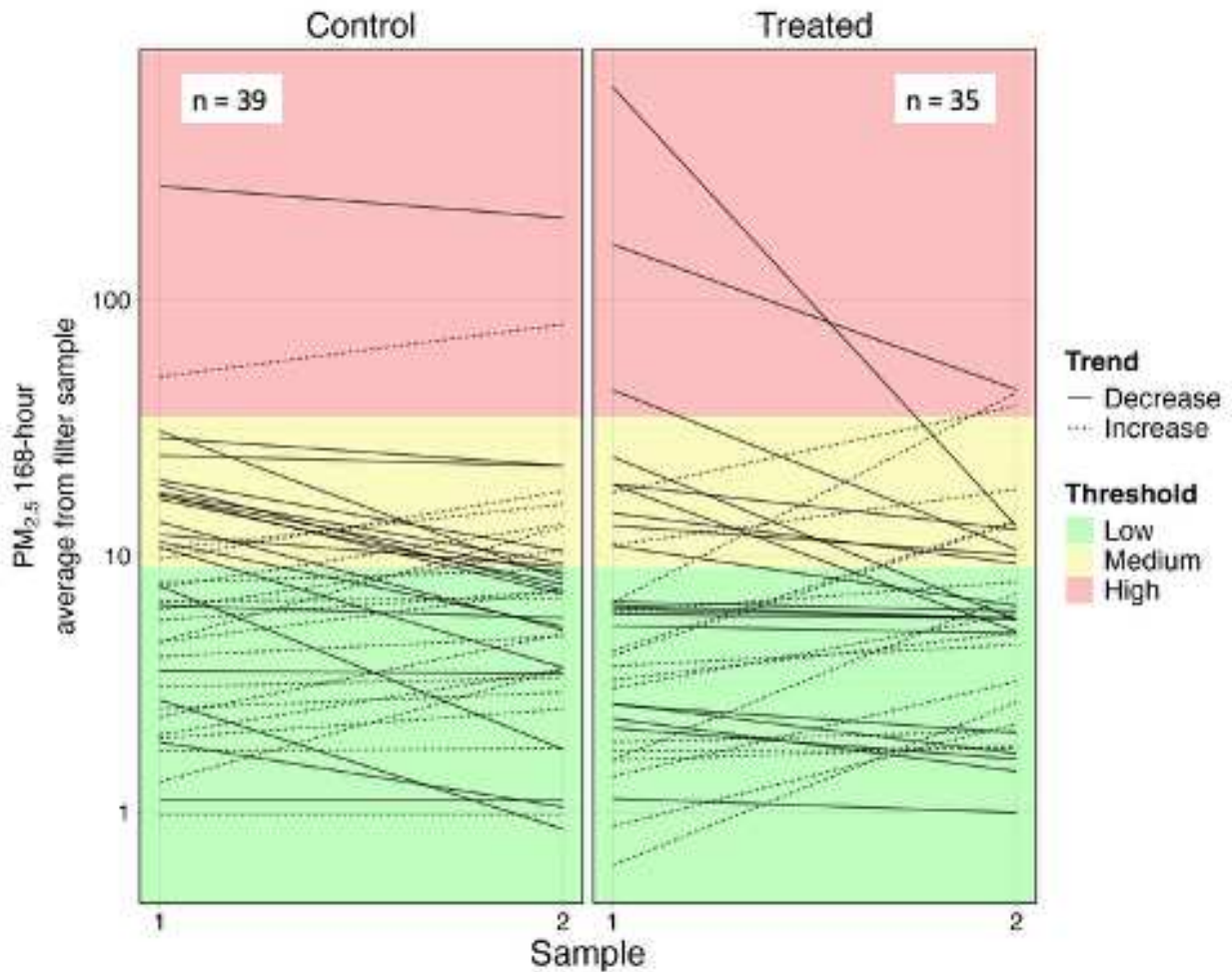


Figure 4.2. Trend plot for  $PM_{2.5}$  data illustrating changes from deployments 1 to 2 for each household, separated by treatment status. Background tinting is shown according to thresholds presented to participants in HHRs, and y-axis is on a log-scale.

Although fine particulate matter concentrations were most often classified as low—defined here as below  $9 \mu\text{g m}^{-3}$ —a notable subset of samples were considerably higher. In total, 55 out of 158 samples (35%) fell into the medium or high classification, with 25 of these samples from treated households and 30 from control households. The distribution of results indicates

that while most households maintained relatively low PM<sub>2.5</sub> levels, a substantial minority experienced elevated indoor particle concentrations at least once during the study period.

Across the treated group, 54% of households showed decreases of varying magnitudes between HHB1 and HHB2. Among treated households with the highest initial concentrations, progress was particularly evident: all three households classified as high in HHB1 recorded lower concentrations in HHB2. Similarly, six of the eight treated households initially ranked as medium decreased to a lower category by HHB2; to restate, 82% of treated high/medium ranked households demonstrated a reduction. This trend is consistent with the hypothesis that targeted, actionable recommendations could produce measurable improvements in indoor air quality over a relatively short period, yet only the most polluted end of the spectrum is showing these results. A similar pattern was reported by Abdel Sater *et al.* (2021).; they found the most polluted households experienced a 40% reduction in PM<sub>2.5</sub> levels by the conclusion of their wood-burning stove intervention study, while the average household reduction in PM<sub>2.5</sub> was 20%.

Because the HHR served as the primary communication tool for study participants, it is important to describe the nature of the recommendations they received, as this context helps interpret the results reported here. As a reminder, HHRs for each household included pollutant-specific observations drawn from the monitoring data, a visual dial indicating the household's classification (low, medium, or high), and practical recommendations tailored to that home's results. For households with elevated PM<sub>2.5</sub>, these recommendations often included advice to restrict smoking or vaping to outdoor areas, reduce or eliminate the use of candles and incense, increase ventilation during cooking (e.g., by using exhaust fans or opening windows), and consider installing a portable air cleaner to reduce particle load. In some cases, recommendations

were combined, for example, advising both behavior changes and specific equipment upgrades to address likely sources.

The survey responses collected after the second sampling period provide additional insight into how participants engaged with the HHR feedback. In one illustrative case, the participant with the highest PM<sub>2.5</sub> concentration in HHB1 reported taking action based on their HHR—specifically, implementing one or more of the recommended changes—and successfully reduced their concentration to fall within the medium classification by HHB2. These results underscore that the changes reported here likely reflect a combination of natural variability and participant action, with the HHR serving as both a diagnostic and motivational tool. Table 4.2 provides additional descriptive statistics for PM<sub>2.5</sub>, illustrating both central tendencies and variability that informs statistical significance testing.

*Table 4.2. Statistics for fine and coarse particulate matter calculated for each sample and between samples 1 and 2.*

Parameter	Units	Randomization	Sample	Calculated per Sample				Calculated between Samples 1 and 2	
				n	AM <sup>a</sup> (±SD <sup>b</sup> )	Median	GM <sup>c</sup> (CI <sub>1</sub> , CI <sub>2</sub> ) <sup>d</sup>	Average Δ <sup>e</sup> (±SD) [unit]	GM %Δ <sup>f</sup> (CI)
PM <sub>10-2.5</sub>	μg/m <sup>3</sup>	Control	1	39	7.7 (5.2)	6.3	6.1 (4.9, 7.6)	-0.7 (3.9) [μg/m <sup>3</sup> ]	-13.2% (-24, -1)
			2	39	6.8 (5.4)	5.5	5.3 (4.2, 6.6)		
PM <sub>2.5</sub>			1	39	17.3 (44.1)	7.5	7.3 (5, 10.5)	-3 (13.5) [μg/m <sup>3</sup> ]	-12.5% (-27, 5)
			2	39	14.4 (34.6)	7.1	6.3 (4.5, 8.9)		
PM <sub>10-2.5</sub>		Treated	1	35	8.7 (8.4)	6.4	5.9 (4.4, 8)	-1.5 (4.4) [μg/m <sup>3</sup> ]	-10.3% (-22, 3)
			2	35	5.8 (4.4)	5.1	4.4 (3.4, 5.7)		
PM <sub>2.5</sub>			1	35	31.4 (116.1)	5.3	5.9 (3.7, 9.5)	-22.1 (114.4) [μg/m <sup>3</sup> ]	14.6% (-13, 51)
			2	35	9.3 (11.1)	5.7	5.7 (4.2, 7.9)		

AM<sup>a</sup>: Arithmetic Mean

SD<sup>b</sup>: Standard Deviation

GM<sup>c</sup>: Geometric Mean

(CI<sub>1</sub>, CI<sub>2</sub>)<sup>d</sup>: Confidence Intervals, Low and High

Average Δ<sup>e</sup>: Average change in pollutant concentration between Sample 1 and 2

GM %Δ<sup>f</sup>: Geometric mean of ratios used to calculate percent change

Both the treated and control groups exhibited a negative average change in PM<sub>2.5</sub> concentrations between HHBs 1 and 2, indicating an overall downward trend. However, the

variability in these changes was substantial; large standard deviations in both groups indicate that these differences are not statistically significant. For the treated group, the percent change is positive while the average change is negative, indicating that a small number of large decreases are present in the data, but more frequently, low values are increasing by small amounts.

#### *Coarse Particulate Matter (PM<sub>10-2.5</sub>) Concentrations and Trends 4.3.2*

Changes in coarse particulate (PM<sub>10-2.5</sub>) concentrations between sampling periods are considered *indirect* outcomes in this study, as only the Las Cruces subgroup received their in-home measures of coarse particulate matter and accompanying recommendations addressing potential sources of coarse particles. While a small separate analysis for this subgroup is presented later, the main dataset still provides useful context for understanding overall household concentrations. Figure 4.3 presents a density plot for PM<sub>10-2.5</sub> concentrations from 150 valid samples; eight additional measurements were excluded due to mechanical failure during sampling.

Median concentrations for HHBs 1 and 2 were 6.4 and 5.3  $\mu\text{g m}^{-3}$ , respectively—both well below the WHO 24-hour air quality guideline of 45  $\mu\text{g m}^{-3}$ , which serves as the threshold between the “low” and “medium” pollutant rankings in the HHR classification system. Unlike PM<sub>2.5</sub>, no extremely high values were recorded, with the highest recorded concentration of 38.5  $\mu\text{g m}^{-3}$  falling below the medium threshold in our study. For context, Morantes et al. (2024) reported a worldwide median of 35  $\mu\text{g m}^{-3}$ , while Logue *et al.* (2011) did not provide a representative PM<sub>10-2.5</sub> mean. Compared to these references, our study’s median concentrations suggest that most participating households experienced relatively clean conditions with respect to coarse particulate matter.

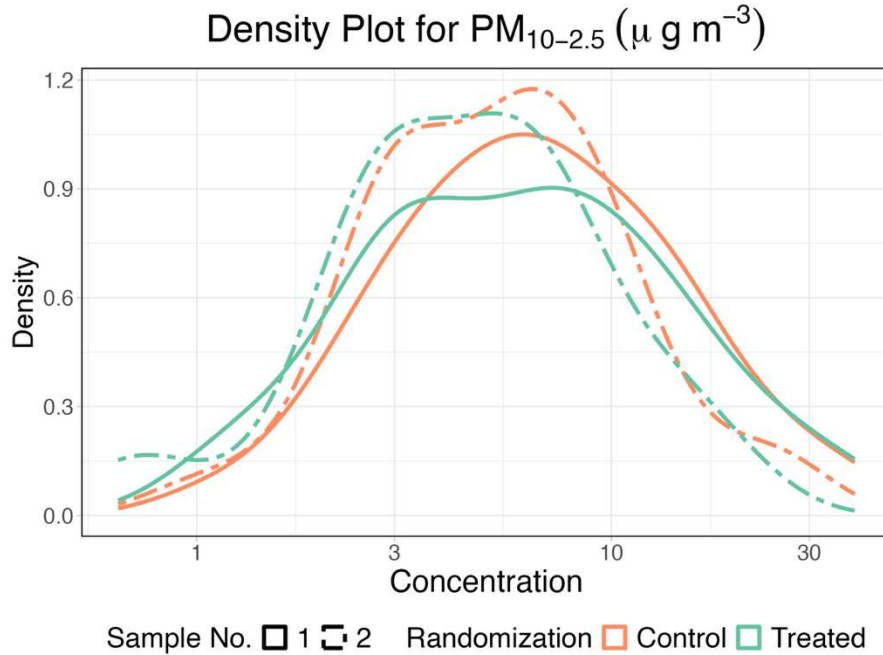


Figure 4.3. PM<sub>10-2.5</sub> concentration distributions of 168-hour average calculated from filter-derived averages of PM<sub>10</sub> and PM<sub>2.5</sub> plotted by treatment status and deployment.

Elevated PM<sub>10-2.5</sub> readings may result from local dust storms, nearby construction, heavy indoor cleaning activities, or unvented heating sources, all of which could exist or not in or around each home and is controlled for by randomization. In some cases, these peaks could also be related to short-term events such as moving furniture, deep cleaning carpets, or other activities that resuspend settled dust. The HHB was not designed to provide time-resolved coarse particulate data, so self-reporting in the survey is the best way to determine sources of coarse particles to provide guidance.

#### *Analysis of In-Home PM<sub>10-2.5</sub> Concentrations in Las Cruces Subset of Homes 4.3.2.1*

Within the Las Cruces, NM subgroup, PM<sub>10-2.5</sub> medians were somewhat higher than in the full dataset: 15.4  $\mu\text{g m}^{-3}$  for HHB1 and 8.8  $\mu\text{g m}^{-3}$  for HHB2 (full dataset = 6.4 and 5.3  $\mu\text{g m}^{-3}$ ). Figure 4.4 illustrates these distributions for the 17 participants with valid HHB1 measurements and the 10 with valid HHB2 measurements. Two HHB2 samples were excluded

from analysis due to equipment failure. Concentration density plots for Las Cruces are not separated by treatment status, but only by sample number due to small sample size.

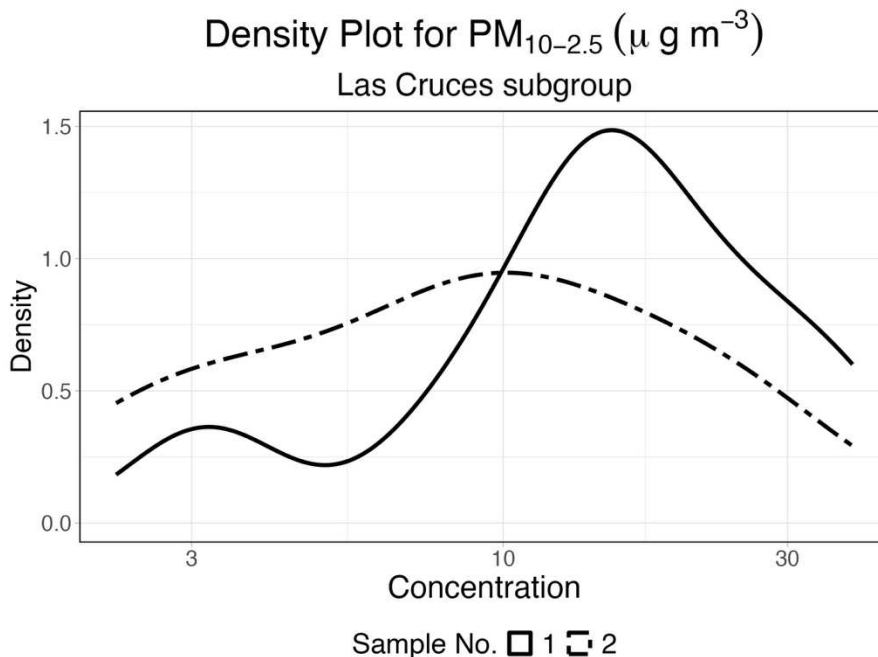


Figure 4.4. Density plot of PM<sub>10-2.5</sub> concentrations as filter-derived 168-hour average for each household – Las Cruces subgroup. Data separated by deployment, not treatment status due to sample size constraint.

Coarse particulate matter is often dominated by outdoor sources and is capable of medium- to long-range atmospheric transport (Wang *et al.*, 2024). In regions such as southern New Mexico, this includes windblown dust from surrounding arid landscapes, resuspended road dust, and particles carried into neighborhoods from agricultural or construction activities (City of Las Cruces, 2025). Because these sources are largely external to the home and often occur on a community or regional scale, coarse particles can be challenging to control through actions taken solely within a single household. This was one of the reasons coarse particulate matter was not included in the original HHR feedback: household-level interventions, such as increased ventilation or source control, are generally less effective for reducing coarse particles that originate outdoors. These results were added to the feedback for Las Cruces participants after our

local partners expressed a specific interest in receiving this information, particularly given the regional prevalence of dust events.

Several factors may contribute to the higher median values observed in Las Cruces as compared to Colorado. The region's arid climate and frequent seasonal winds can transport fine dust into homes, especially those with less airtight building envelopes. Common building designs—such as single-story layouts with direct outdoor access—may also facilitate particulate ingress. Landscaping choices, including bare soil or gravel near windows and doors, can further increase indoor coarse particle levels. Given these contextual factors, dust-control measures such as sealing air leaks, installing higher-efficiency filters in HVAC systems, and using doormats or shoe-removal policies could be considered in future interventions. However, these approaches are likely to provide only partial mitigation when the dominant sources are regional in scale.

#### *Nitrogen Dioxide (NO<sub>2</sub>) Concentrations and Trends 4.3.3*

The representative NO<sub>2</sub> value reported in the HHR and used for analysis was the maximum 1-hour block average during the week of sampling (see Table 3.1 for basis, threshold values, and sources). The HHB's limit of detection (LOD) for NO<sub>2</sub> is 30 ppb; in our dataset, 76% of recorded values fell below this threshold.

In U.S. homes without indoor biomass combustion—such as wood stoves or unvented kerosene heaters—gas stoves are typically the most significant source of indoor NO<sub>2</sub>. Given that only a portion of households in our study reported having a gas stove, it is not surprising that many recorded NO<sub>2</sub> concentrations fell below the LOD. Nevertheless, we considered it unlikely that the true concentration was zero in these cases. To avoid underestimating exposure potential, we adopted a conservative approach: all concentrations below 30 ppb were replaced with the

maximum 1-hour block average from the nearest outdoor monitor during the sampling week. This method assumes that these homes still experienced at least background NO<sub>2</sub> levels from outdoor infiltration, even if indoor sources were minimal. The replacement values therefore reflect low, but nonzero, concentrations consistent with the absence of major indoor sources (Hu and Zhao, 2020). Figure 4.5 shows the NO<sub>2</sub> concentration distributions for HHBs 1 and 2 for each treatment group.

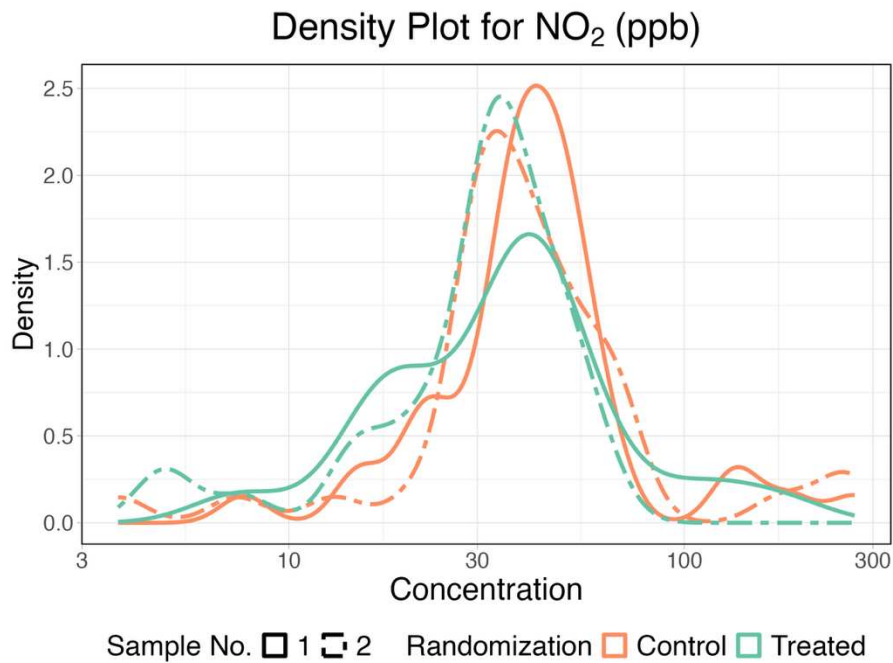


Figure 4.5. NO<sub>2</sub> concentration distributions for HHB 1 and 2, Treated and Control groups, with values below LOD replaced with nearest outdoor sensor value calculated by the same block-average basis as the indoor value.

Across all households, median NO<sub>2</sub> values were 39 ppb in sample 1 and 35 ppb in sample 2. These medians are higher than the 12 ppb equivalent reported in Morantes *et al.* (2024) for a global dataset of residential monitoring studies but remain below the U.S. EPA’s annual standard of 53 ppb, which serves as the threshold between “low” and “medium” classification in the HHR system designed to provide context to the values given to participants.

Although most households recorded low to moderate NO<sub>2</sub>, a small subset of homes recorded high levels, with 7% of samples exceeding U.S. EPA’s 1-hour outdoor standard of 100 ppb. Figure 4.6 presents trends in household-level changes between sampling periods (HHB1 to HHB2). Only households that completed both sampling periods (n = 74) can be included in the plot, and of those, only households with NO<sub>2</sub> data for both samples are included (n = 73).

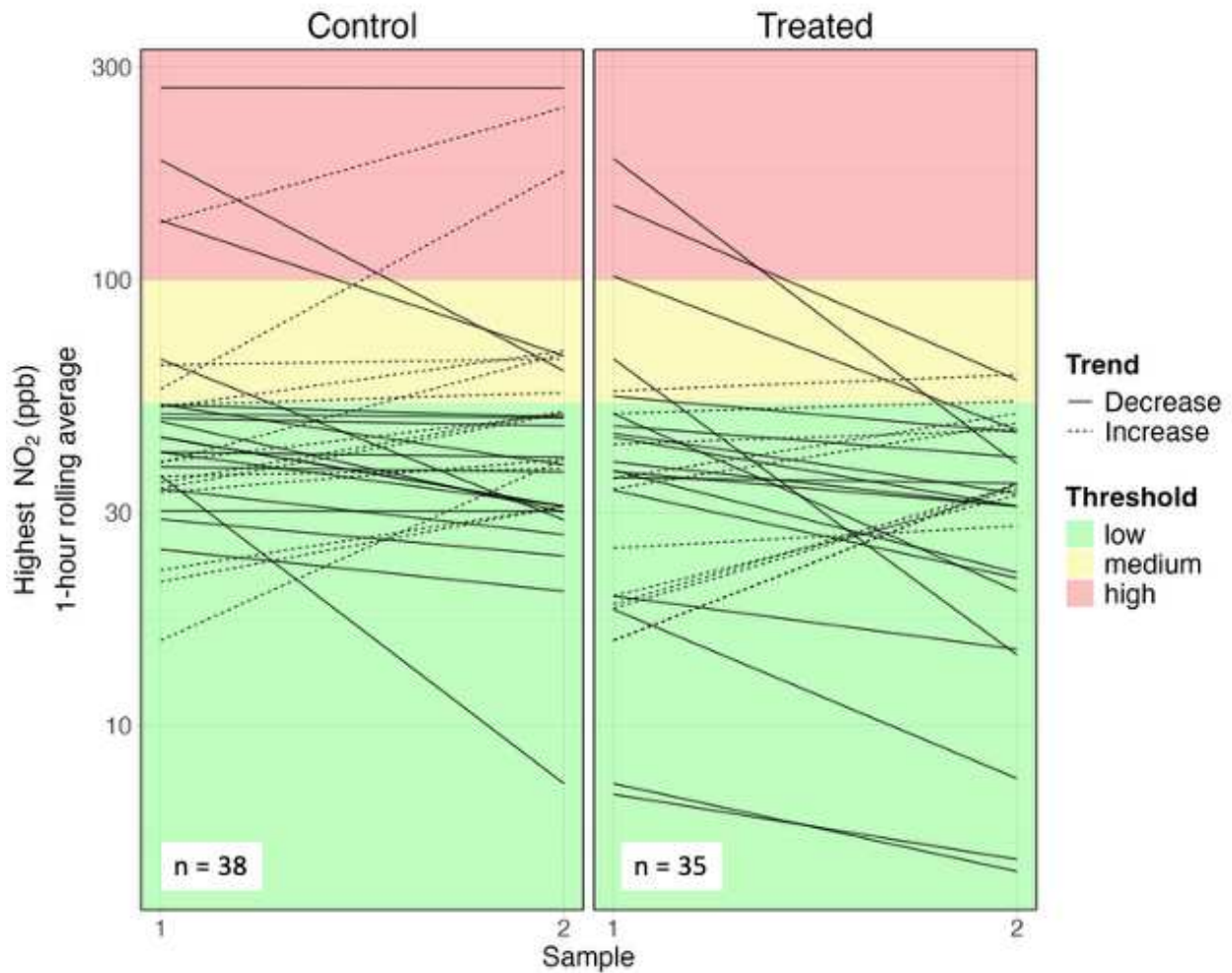


Figure 4.6. Trend plot for NO<sub>2</sub> data illustrating changes from deployments 1 to 2 for each household, separated into Control and Treated groups. Background tinting is shown according to thresholds presented to participants in HHRs, and y-axis is on a log-scale.

Of the 35 treated households, six exceeded the medium threshold in HHB1. By HHB2 five of these six had reduced concentrations into the low range; this is in contrast to the control

group, where households generally remained above the medium threshold or newly exceeded it in HHB2.

Households with elevated NO<sub>2</sub> received straightforward recommendations targeting the most common indoor sources. These included avoiding idling vehicles in attached garages, increasing ventilation while cooking, opening fireplace flues during gas fireplace use, and restricting smoking or vaping to outdoor areas. Because these actions are both low-cost and easy to implement, they can be adopted quickly. The reductions observed in treated households—particularly among those with medium or high initial concentrations—suggest that providing residents with clear data, relevant context, and practical recommendations can result in measurable NO<sub>2</sub> improvements over short timeframes.

Table 4.3 presents descriptive statistics for NO<sub>2</sub> by group and sampling period. The treated group exhibited a greater negative percent change in NO<sub>2</sub> between samples 1 and 2, with relatively wide confidence intervals but below zero, again reflecting the high household-to-household variability of in-home air quality, but overall more of a decrease for the treated group compared to control. The percent change calculation is detailed in Section 3.8.2, but in brief, percent change was calculated from the geometric mean of the ratio of HHB2/HHB1 for each participant, thus providing a providing a measure of change that is less sensitive to outliers than the tradition means of calculating an average percent change. Statistical tests for significance are reported in Section 4.4.

Table 4.3 Summary statistics for NO<sub>2</sub> calculated for each sample and between HHBs 1 and 2

Parameter	Units	Randomization	Sample	Calculated per Sample				Calculated between Samples 1 and 2	
				n	AM <sup>a</sup> ( $\pm$ SD <sup>b</sup> )	Median	GM <sup>c</sup> (CI <sub>1</sub> , CI <sub>2</sub> ) <sup>d</sup>	Average $\Delta$ <sup>e</sup> ( $\pm$ SD) [unit]	GM % $\Delta$ <sup>f</sup> (CI)
NO <sub>2</sub>	ppb	Control	1	39	54.3 (48.6)	43.4	43.4 (35.6, 52.9)	-0.7 (37.7) [ppb]	-6.6% (-19, 8)
			2	39	53.8 (55.4)	38.6	39.8 (31.4, 50.6)		
		Treated	1	35	46.4 (37.5)	39.3	36.5 (28.9, 46)	-13.8 (34.5) [ppb]	-21% (-32, -8)
			2	35	32.6 (14.2)	33.9	28.4 (23.1, 34.8)		

AM<sup>a</sup>: Arithmetic Mean

SD<sup>b</sup>: Standard Deviation

GM<sup>c</sup>: Geometric Mean

(CI<sub>1</sub>, CI<sub>2</sub>)<sup>d</sup>: Confidence Intervals, Low and High

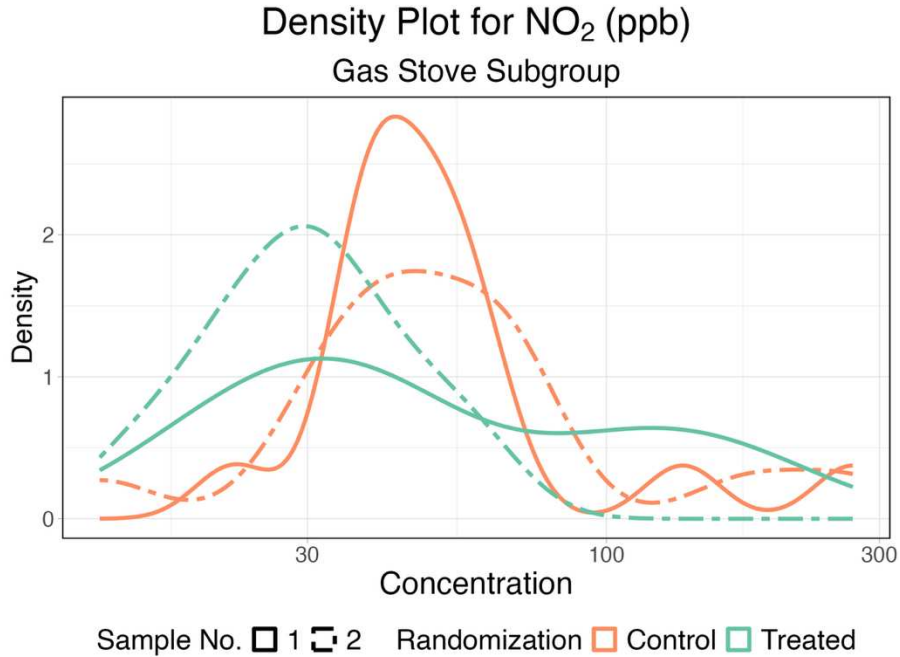
Average  $\Delta$ <sup>e</sup>: Average change in pollutant concentration between Sample 1 and 2

GM % $\Delta$ <sup>f</sup>: Geometric mean of ratios used to calculate percent change

### In-Home NO<sub>2</sub> Concentrations in Subset of Homes Reporting Use of Gas Stoves 4.3.3.1

A separate analysis was conducted for households reporting the presence of a gas stove in their Intake Demographics Survey. This subgroup analysis was motivated by the well-established role of gas cooking as a significant source of indoor NO<sub>2</sub> in U.S. homes (Singer *et al.*, 2017, Daouda *et al.*, 2024, Nassikas *et al.*, 2024).

In the gas stove subgroup, median NO<sub>2</sub> concentrations were higher than those of the overall sample: 44 ppb for HHB1 and 39 ppb for HHB2, compared to overall medians of 39 ppb and 35 ppb, respectively. These elevated medians are consistent with the presence of a strong indoor source and align with literature showing that kitchens with gas stoves can reach NO<sub>2</sub> levels up to two times higher than those with electric, with pollutant peaks in other parts of the home corresponding to cooking time (Singh *et al.*, 2024, Kornartit *et al.*, 2010). Figure 4.7 shows the distribution of NO<sub>2</sub> concentrations in gas stove households, then participant-level trends between sampling periods (HHB1 – HHB2) will be analyzed later.



*Figure 4.7. Distribution of representative NO<sub>2</sub> concentrations for HHB 1 and 2, Treated and Control groups for the subset of homes with gas cookstoves.*

Concentration distributions clearly show a shift away from the extreme high values in the treated group, but not in the control group; this can be seen by the lack of a tail on the right side for HHB2 – Treated, and the presence of this long tail for HHB2 – Control. Both groups have a few extreme concentrations in the initial sample.

The trend plot featured as Figure 4.8 shows that among treated households with gas stoves, nearly all showed decreases in NO<sub>2</sub> from HHB1 to HHB2 after receiving targeted recommendations, with no evident pattern for the control households. These recommendations focused on increasing ventilation during cooking (e.g., using an exhaust fan, opening windows, or both) and, where possible, reducing the frequency or duration of gas stove use. Although the sample size for this subgroup was relatively small (HHB1: n = 28 [treated = 12, control = 16]; HHB2: n = 25 [treated = 10, control = 15]), the consistency of decreases among treated households is pronounced.

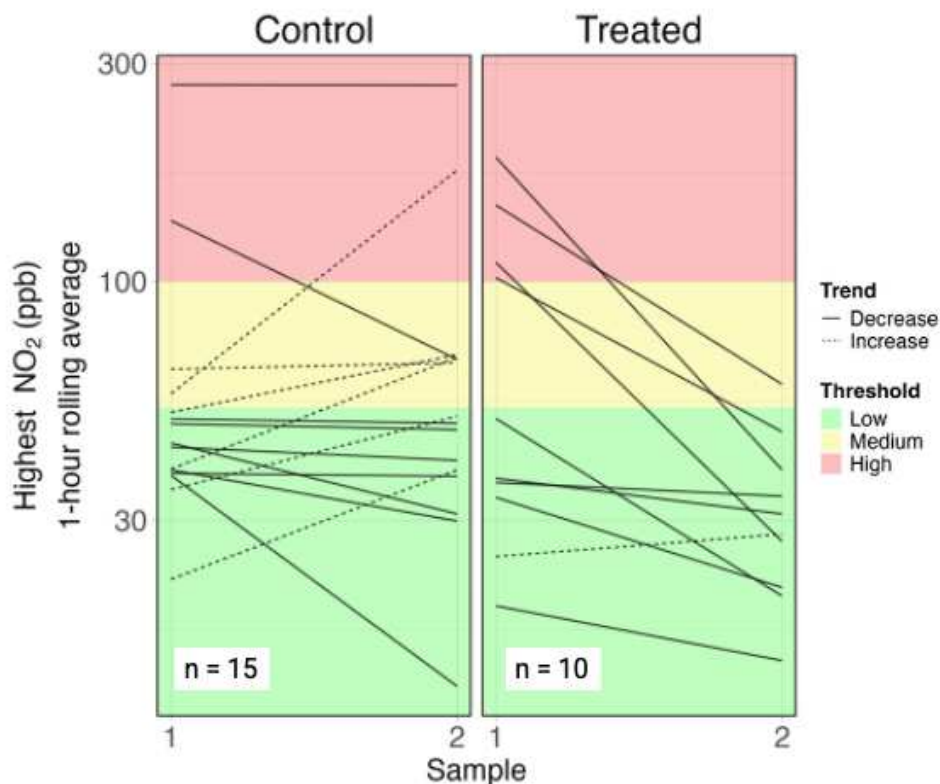


Figure 4.8. Trend plot for representative  $\text{NO}_2$  concentrations of the subset of households with gas cookstoves showing changes from HHB1 to HHB2. Background tinting is according to threshold values shown in HHRs for participants and y-axis is on a log-scale.

These results suggest that even modest changes in cooking-related ventilation practices can lead to meaningful reductions in  $\text{NO}_2$  exposure for homes with gas stoves. However, given the persistence of elevated medians compared to the overall sample, further reductions may require a combination of behavior changes and structural improvements, such as upgrading to a higher-efficiency range hood or transitioning to electric or induction cooking appliances.

#### Carbon Dioxide ( $\text{CO}_2$ ) Concentrations and Trends 4.3.4

Carbon dioxide ( $\text{CO}_2$ ) was measured in all participating households as an indicator of ventilation adequacy. While  $\text{CO}_2$  is not typically considered an indoor air pollutant at residential levels, it is a useful proxy for air exchange and occupancy patterns since elevated  $\text{CO}_2$  concentrations can indicate insufficient ventilation, which is often associated with the

accumulation of other indoor pollutants. At higher levels—generally above 1,000–1,500 ppm—CO<sub>2</sub> may also be associated with symptoms such as drowsiness, reduced cognitive performance, and impaired sleep quality (Satish *et al.*, 2012, Kang *et al.*, 2024).

Representative CO<sub>2</sub> values were calculated as the maximum 8-hour rolling average from the week of sampling, consistent with the approach used for other continuously (every 30s) monitored pollutants. Figure 4.9 shows the distribution of CO<sub>2</sub> concentrations for HHBs 1 and 2. Across the dataset, most households recorded concentrations below thresholds typically associated with poor ventilation, though a notable subset had elevated levels. The shape of the right side of the distributions is also notable: both treated and control groups show the presence of high values in HHB1, but for the treated group, these highest values are much less frequent in HHB2.

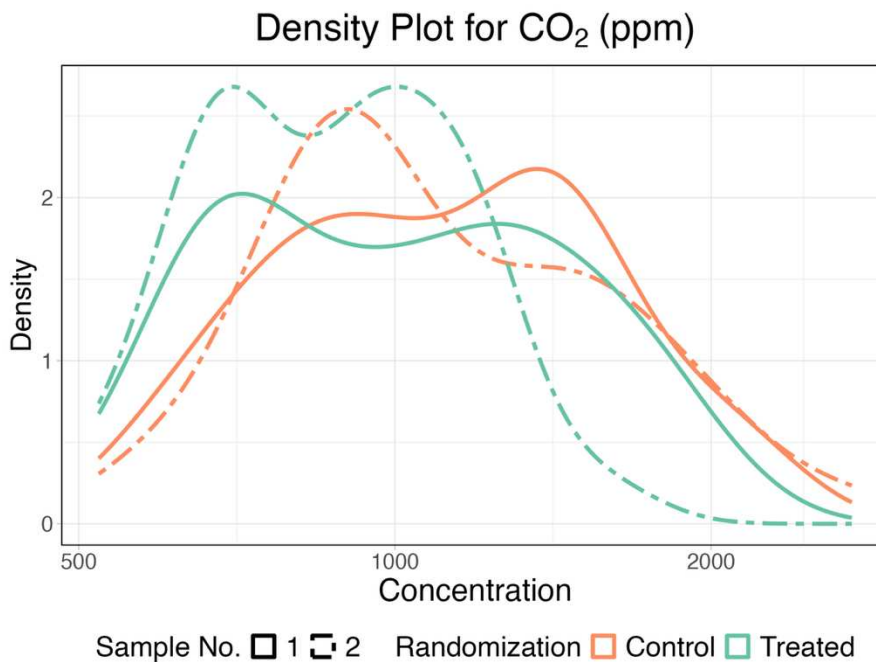


Figure 4.9. Distribution of CO<sub>2</sub> concentrations calculated as maximum 8-hour rolling average, by deployment and treatment status.

Medians for the combined dataset decreased from HHB 1 to 2 (1063 ppm and 954 ppm, respectively); trends will be analyzed both at the household-level and overall. Figure 4.10 illustrates household-level changes between sampling periods (HHB1 to HHB2), showing a general downward shift among treated households, while control households exhibited more mixed results.

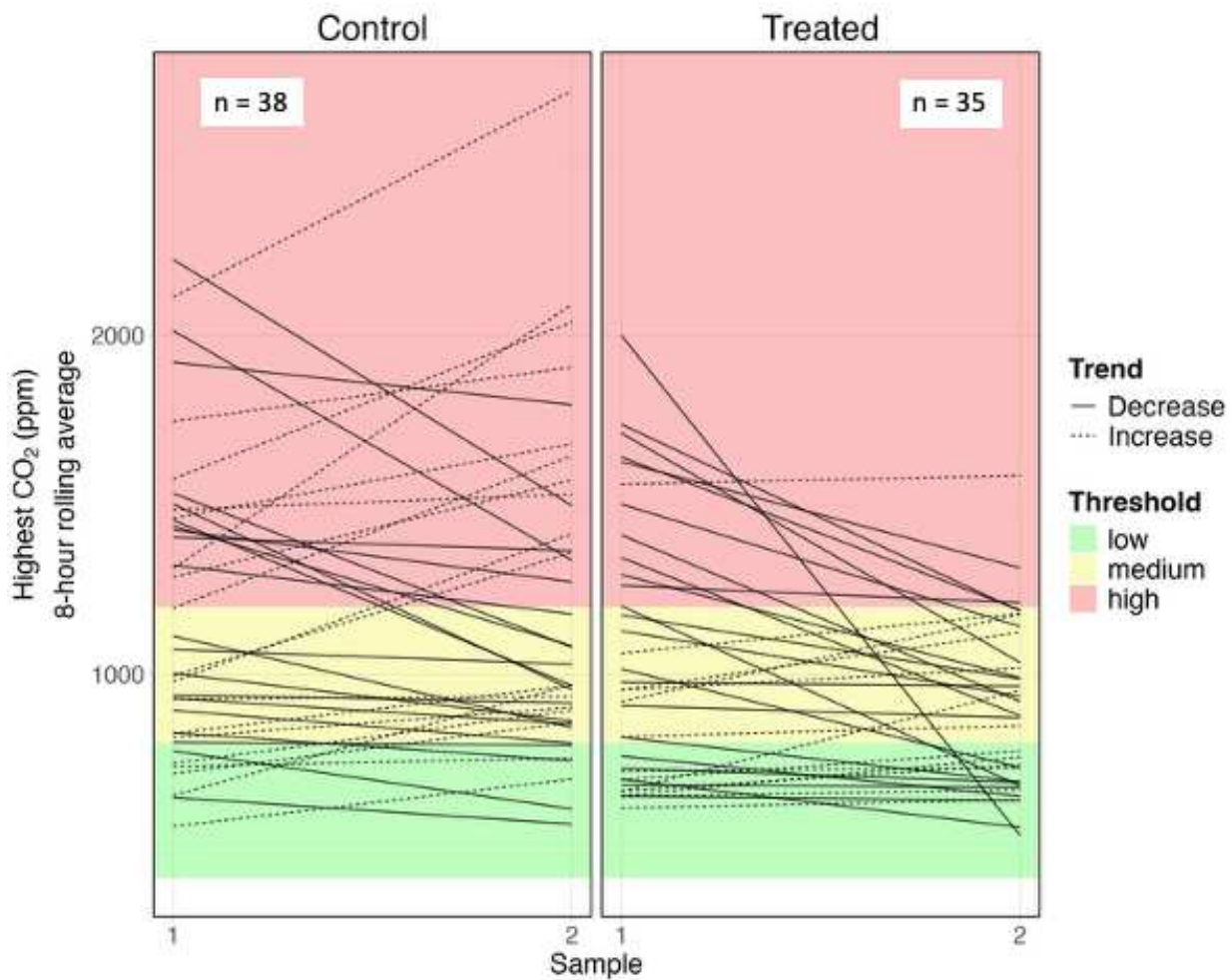


Figure 4.10. Trend plot for CO<sub>2</sub> data illustrating changes from deployments 1 to 2 for each household, separated into Control and Treated groups. Background tinting is shown according to thresholds presented to participants in HHRs, and y-axis is on a log-scale.

Within the treated group, 74% of households classified as high or medium for HHB1 displayed a decreasing trend to HHB2. On the very upper end of the treated group; 35%

exceeded the high threshold value in HHB1, yet after intervention, that had decreased to 9% of households, all of which had been ranked high for HHB1 – meaning no households entered the high threshold after treatment. As mentioned, trends were less distinct for the control group, with 46% increasing from HHB1 to HHB2, and only a 5% reduction in high rankings within the group (44% [HHB1] to 38% [HHB2]). Overall, 31 control households were ranked as high or medium for HHB1 and 32 ranked as such for HHB2.

Households with elevated CO<sub>2</sub> received recommendations aimed at improving ventilation, particularly during periods of high occupancy or pollutant-generating activities such as cooking, cleaning, or entertaining guests. Common recommendations included increasing window opening frequency, using portable or window fans to improve airflow, and operating mechanical ventilation systems (if available) during and after high-occupancy events. For homes with heating or cooling systems equipped with air handling units, recommendations also included setting fans to “on” rather than “auto” to improve continuous air circulation.

The statistical summary in Table 4.4 shows that the treated group experienced an average decrease in CO<sub>2</sub> between sampling periods, while control group results were more variable. Although the standard deviation in the treated group was large—reflecting wide variability between homes—the downward trend suggests that even low-cost, behavior-based interventions can measurably improve ventilation in some households. The percent change calculated from the geometric mean is negative for the treated group, and positive for the control group, showing the downward trend for the treated group persists when calculated from the geometric mean.

Table 4.4. Summary statistics for CO<sub>2</sub> calculated per sample and between HHB1 and HHB2

Parameter	Units	Randomization	Sample	Calculated per Sample				Calculated between Samples 1 and 2	
				n	AM <sup>a</sup> (±SD <sup>b</sup> )	Median	GM <sup>c</sup> (CI <sub>1</sub> , CI <sub>2</sub> ) <sup>d</sup>	Average Δ <sup>e</sup> (±SD) [unit]	GM %Δ <sup>f</sup> (CI)
CO <sub>2</sub>	ppm	Control	1	39	1193 (437)	1094	1119 (998, 1254)	3.8 (334.6) [ppm]	1.9% (-4, 9)
			2	39	1187 (474)	970	1108 (987, 1244)		
		Treated	1	35	1061 (392)	955	996 (885, 1121)	-158.5 (332.9) [ppm]	-11.1% (-18, -4)
			2	35	902 (248)	879	871 (796, 953)		

AM<sup>a</sup>: Arithmetic Mean

SD<sup>b</sup>: Standard Deviation

GM<sup>c</sup>: Geometric Mean

(CI<sub>1</sub>, CI<sub>2</sub>)<sup>d</sup>: Confidence Intervals, Low and High

Average Δ<sup>e</sup>: Average change in pollutant concentration between Sample 1 and 2

GM %Δ<sup>f</sup>: Geometric mean of ratios used to calculate percent change

In several cases, participants reported in follow-up surveys that they had begun to implement the recommended changes regularly, such as opening windows during gatherings or running fans for longer periods after cooking.

The variability in outcomes highlights the influence of contextual factors on the effectiveness of CO<sub>2</sub> reduction strategies. For example, some households may have had physical or environmental constraints—such as lack of operable windows, concerns about outdoor air quality, or extreme weather—that limited their ability to implement certain recommendations. Others may have already had relatively low baseline CO<sub>2</sub> levels, leaving less room for measurable improvement.

Combined with the household-level trends, CO<sub>2</sub> results indicate that providing clear, personalized feedback on ventilation can prompt meaningful changes in household practices, even in the absence of major equipment upgrades. These changes can be implemented quickly, incur minimal cost, and may also have co-benefits for reducing other indoor pollutants that respond to improved ventilation.

## Testing the Impact of the Intervention on In-Home Air Quality Metrics 4.4

To evaluate whether the Home Health Box (HHB) plus Home Health Report (HHR) intervention produced measurable changes in indoor pollutant levels, we conducted three types of statistical tests. The first was an unpaired t-test comparing pollutant concentrations between the treated and control groups within each sampling period (HHB1 and HHB2). This test assesses whether there were systematic differences between groups at a given time point. The second was a paired t-test comparing pollutant concentrations within the same households across the two sampling periods (HHB1 to HHB2). This approach tests whether changes occurred over time within a group, which is important for detecting the effect of the intervention in treated households. The third statistical test was a Wilcoxon test since the CO<sub>2</sub> data was found to not be normally distributed by a Shapiro-Wilks Normality test. Wilcoxon tests were carried out as paired and unpaired to test correlations between sampling periods and groups, like the t-tests discussed above.

The unpaired t-test results in Table 4.5 show no significant differences between treated and control households in HHB1 for any pollutant measured, and Table 4.6 shows statistical test results for CO<sub>2</sub>, for which the same result can be observed for HHB1. This lack of significant difference is desirable at baseline, as it indicates that randomization was successful and the two groups were comparable before the intervention. In contrast, for HHB2, statistically significant differences emerged for both CO<sub>2</sub> and NO<sub>2</sub> concentrations, with treated households having lower mean values than controls. This finding suggests that the intervention had an effect, at least for these pollutants.

Table 4.5. Unpaired t-test between groups for each sample with significant p-values bolded. Mean difference, confidence intervals, and sample sizes are included for treated and control.

Parameter	HHB1 - Treated v Control						HHB2 - Treated v Control					
	Mean Difference	Lower CI	Upper CI	p-value	Treated n	Control n	Mean Difference	Lower CI	Upper CI	p-value	Treated n	Control n
NO <sub>2</sub>	-7.9	-27.9	12.2	0.437	35	39	-21.2	-40.0	-2.5	<b>0.028</b>	35	38
PM <sub>2.5</sub>	14.1	-28.0	56.2	0.502	35	39	-5.1	-16.8	6.7	0.390	35	39
PM <sub>10-2.5</sub>	1.0	-2.4	4.4	0.558	32	37	-1.0	-3.3	1.3	0.397	33	38
PM <sub>10-2.5</sub> (NM only)	2.3	-11.1	15.8	0.694	6	6	-6.7	-17.6	4.2	0.196	4	6

Table 4.6. Wilcoxon test results for CO<sub>2</sub> data – each test has p-value provided and significant results are bolded.

Wilcoxon Test Results for CO <sub>2</sub>		
Relationship Tested	p-value	paired/unpaired
HHB1 - Treated v Control	0.174	unpaired
<b>HHB2 - Treated v Control</b>	<b>0.00697</b>	unpaired
Control - HHB1 v HHB2	0.909	paired
<b>Treated - HHB1 v HHB2</b>	<b>0.0137</b>	paired

While unpaired t-tests establish between-group differences, they do not reveal whether those differences are due to changes over time in the treated group, the control group, or both.

For that reason, paired t-tests (Table 4.7) were performed.

Table 4.7. Paired t-test between samples for each group with significant p-values bolded, mean difference, confidence intervals and sample size are included.

Parameter	Treated - HHB1 v HHB2					Control - HHB1 v HHB2				
	Mean Difference	Lower CI	Upper CI	p-value	n	Mean Difference	Lower CI	Upper CI	p-value	n
NO <sub>2</sub>	13.8	2.0	25.7	<b>0.024</b>	35	0.7	-11.7	13.1	0.910	38
PM <sub>2.5</sub>	22.1	-17.1	61.4	0.260	35	3.0	-1.4	7.3	0.179	39
PM <sub>10-2.5</sub>	1.7	-0.1	3.6	0.067	30	0.7	-0.7	2.1	0.308	36
PM <sub>10-2.5</sub> (NM only)	8.9	-7.2	25.4	0.183	4	1.4	-7.2	10.0	0.680	6

In the treated group, paired t-tests confirmed significant decreases in NO<sub>2</sub> concentrations from HHB1 to HHB2, whereas the control group did not show similar reductions. These results strengthen the inference that the decreases observed in the treated group were due to the intervention rather than to unrelated temporal or seasonal factors. The Wilcoxon tests for CO<sub>2</sub> confirm this same pattern: HHB1 and HHB2 are significantly different for the treated group, but not the control group.

When interpreting these results, it is important to note that the intervention recommendations were designed to be low-cost, behavior-based changes—such as increasing ventilation during cooking or high-occupancy events—that could be implemented immediately by participants. The statistical evidence that these measures reduced CO<sub>2</sub> and NO<sub>2</sub> concentrations supports the feasibility of using personalized monitoring feedback to achieve measurable indoor air quality improvements without requiring major equipment upgrades.

PM<sub>10-2.5</sub> data from Las Cruces, NM was tested separately since these participants received treatment for PM<sub>10</sub> in addition to the other three pollutants; the sample size is small, and no significant trend exists for either test.

#### **VOCs: Exploring Potential Indirect Effects of the Intervention 4.5**

Volatile Organic Compounds (VOCs) were monitored in all participating households using passive sorbent tubes deployed for the full one-week sampling period. These compounds arise from a range of sources, including building materials, consumer products, cleaning agents, and occupant activities. From an exposure science perspective, they can be broadly categorized as continuous emitters, where emissions occur steadily over time from a persistent source (e.g., solid air fresheners, certain stored chemicals), and episodic emitters, where releases occur during specific events or activities (e.g., cleaning, painting, cooking).

This secondary analysis focused on a subset of VOCs identified by Logue *et al.* (2011) as chronic indoor health hazards found in most homes. Our aim was to assess whether the intervention might also have indirect effects on VOC levels, particularly for episodically emitted compounds. We did not provide recommendations specifically targeting VOC sources, but because ventilation can dilute short-term peaks, some reduction might occur incidentally.

Conversely, continuous emitters are less likely to be affected by ventilation, and their mitigation typically requires source removal.

Formaldehyde (HCHO) and the BTEX group (benzene, toluene, ethylbenzene, xylenes) were excluded from this analysis, either because we did not measure them (in the case of HCHO) or because our samples fell outside the primary research scope of alterable indoor source control. A complete dataset of all VOC measurements is provided in Appendix F, but a subset of six target compounds from Logue *et al.* (2011) is evaluated. Figure 4.9 presents boxplots for these six VOCs across three sampling rounds. The y-axes in each panel are scaled independently to highlight trends within each compound, so comparisons should not be made between compounds on absolute concentration. Data points are shown behind the boxplots to illustrate the number of detections for each compound in our study, an overall study mean for each compound is shown as a solid line, and a reference mean from Logue *et al.* is displayed as a dashed line.

Hexachlorobutadiene and Vinyl chloride were classified as present in most homes by Logue but were not frequently detected in our study above the limit of detection. For three of the remaining four compounds, which were detected frequently, data is grouped near the reference mean and the study means align well with the references. A notable exception is PDCB, the reference mean for which is much higher. This will be discussed in Section 4.5.1.

## Concentrations of select species

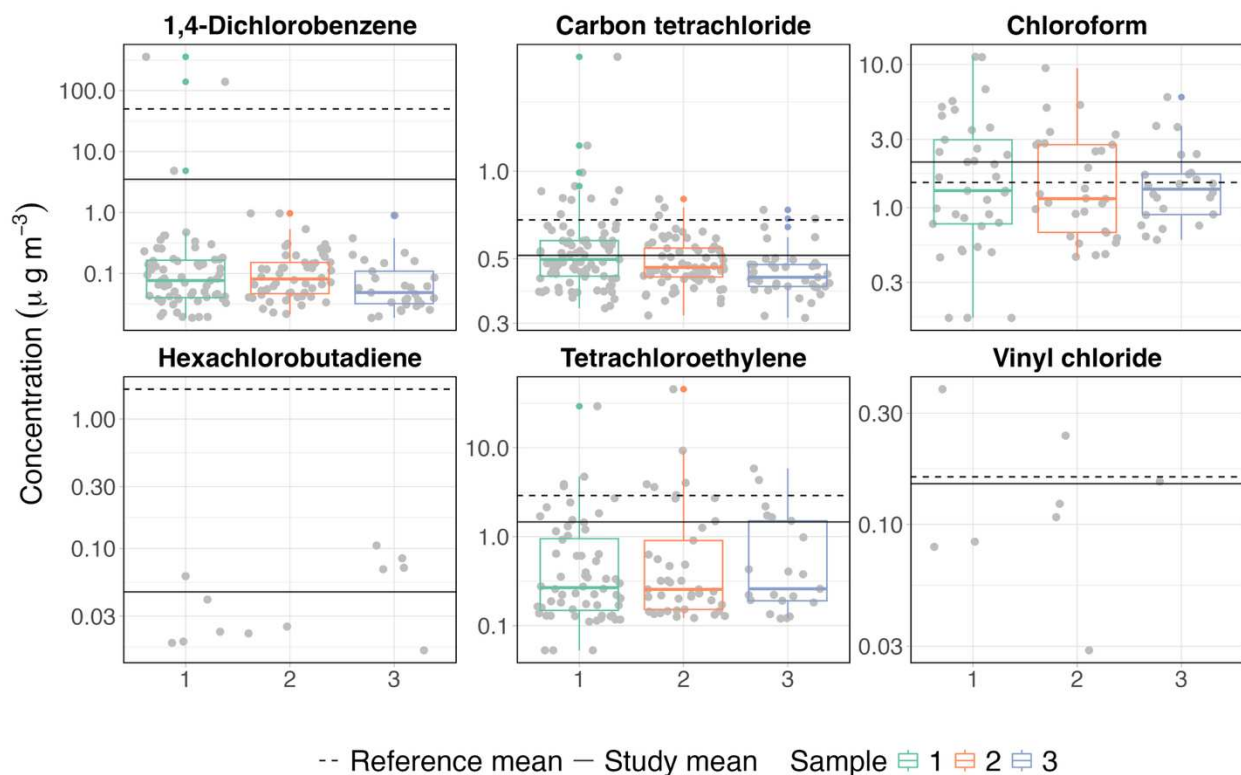


Figure 4.11. Boxplots and data points of six VOCs included in Logue 2011 as chronic health hazards. Those compounds with few study detections do not have boxplots shown, only data points.

### 1,4-Dichlorobenzene: A Continuous Emitter Requiring Source Control 4.5.1

PDCB was detected in 148 of the 198 total samples (75%), making it one of the more prevalent VOCs in our dataset. It is typically emitted from consumer products such as mothballs, solid air fresheners, urinal or toilet blocks, and solid wood flooring (Chin *et al.*, 2013, Huang *et al.*, 2018). Because these products off-gas steadily over time, PDCB is considered a continuous emitter—meaning that, once present, it will contribute to indoor concentrations until the source is removed, and the wide range of sources lead to highly variable concentrations between homes (Huang *et al.*, 2018).

From a toxicological standpoint, PDCB is important due to its classification as a possible human carcinogen and its prioritization in indoor air hazard rankings. In the NHANES 1999

personal exposure study, which remains one of the most comprehensive VOC exposure assessments in the U.S., participants wore passive sampling badges for 2–3 days, and PDCB was among the 10 VOCs measured directly in personal air samples. The compound’s inclusion underscores the level of concern about its prevalence and potential health effects. No comparable large-scale study using personal air sampling has been conducted since; more recent NHANES assessments have relied on biomonitoring rather than direct air measurements.

In our study, median PDCB concentrations were lower than that reported in NHANES, as shown in Figure 4.12. This difference may reflect changes in consumer product formulations, reduced use of PDCB-containing products, or regional variation in purchasing habits. We observed differences between Colorado and New Mexico households, suggesting that local availability and preferences could also influence PDCB prevalence – this phenomenon was reported in Huang *et al.* (2018) where researchers found extremely high PDCB levels in one Japanese town, only to discover that 88% of the population used mothballs.

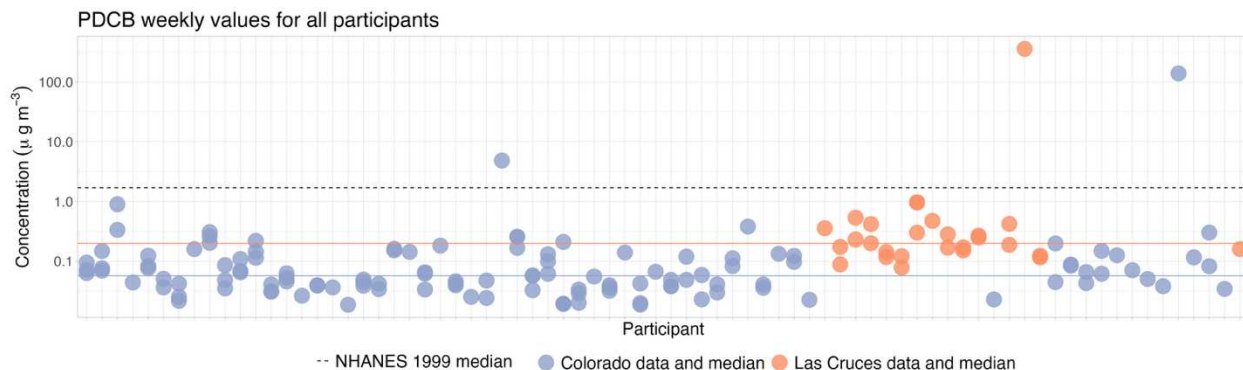


Figure 4.12. PDCB data detected in study for each household with geographic groups differentiated by color. Households with multiple measurements have all detections plotted. Study medians are calculated for each geographic group and can be compared to NHANES 1999 median value shown as dotted line.

As illustrated by the boxplots in Figure 4.13, PDCB levels remained largely unchanged between sampling periods. This aligns with the expected behavior of a continuous emitter, where

ventilation alone is unlikely to produce meaningful reductions. The implication is that for compounds like PDCB, occupant education and direct source removal are the only effective strategies for reducing exposure.

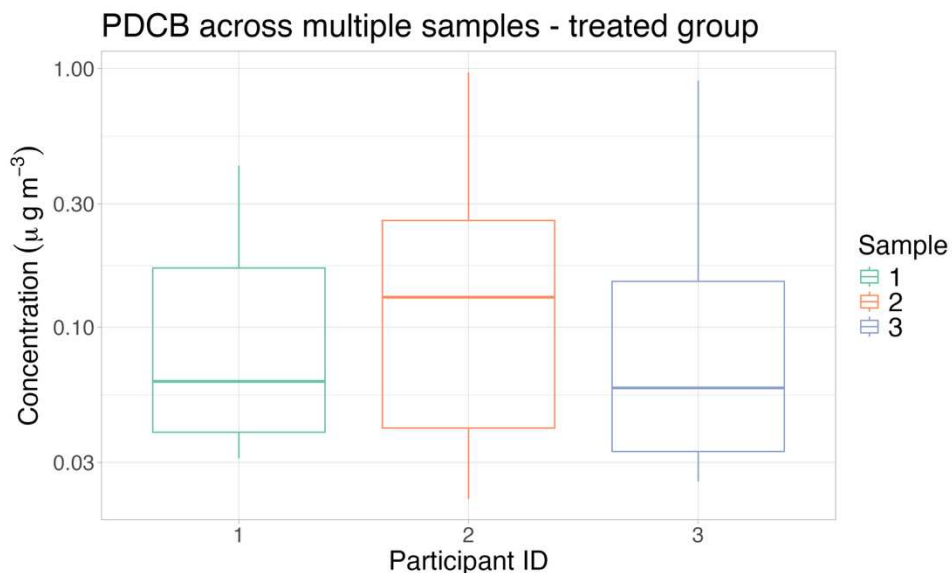


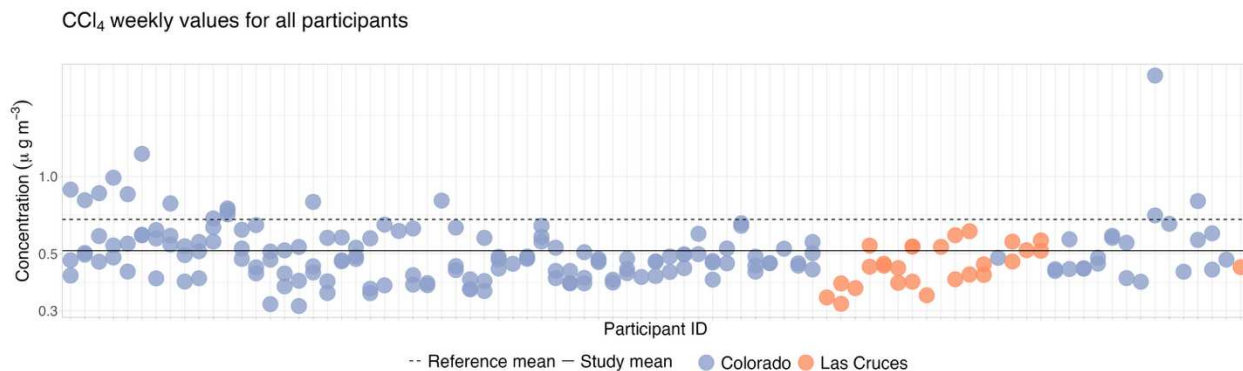
Figure 4.13. Boxplot of PDCB concentrations across multiple samples for the Treated group, showing constantly emitted compounds may not respond to changes in ventilation.

#### Carbon tetrachloride: An Episodic Emitter with Potential Ventilation Co-benefits 4.5.2

Carbon tetrachloride ( $\text{CCl}_4$ ) is classified as an episodic emitter in residential settings, with emissions primarily associated with cleaning activities that involve certain bleach-based products. Laboratory and field studies, including work by Obadasi *et al.* (2014), have shown that carbon tetrachloride often co-occurs with chloroform in these products, and both compounds can be released during typical cleaning events.

In our study,  $\text{CCl}_4$  was detected in both Colorado and New Mexico homes at similar levels, but the mean concentration was below the reference value reported in Logue *et al.* (2011). Figure 4.14 shows the comparison, along with a dashed line representing the reference mean from Logue. Since  $\text{CCl}_4$  was not included in the NHANES personal exposure study, the Logue

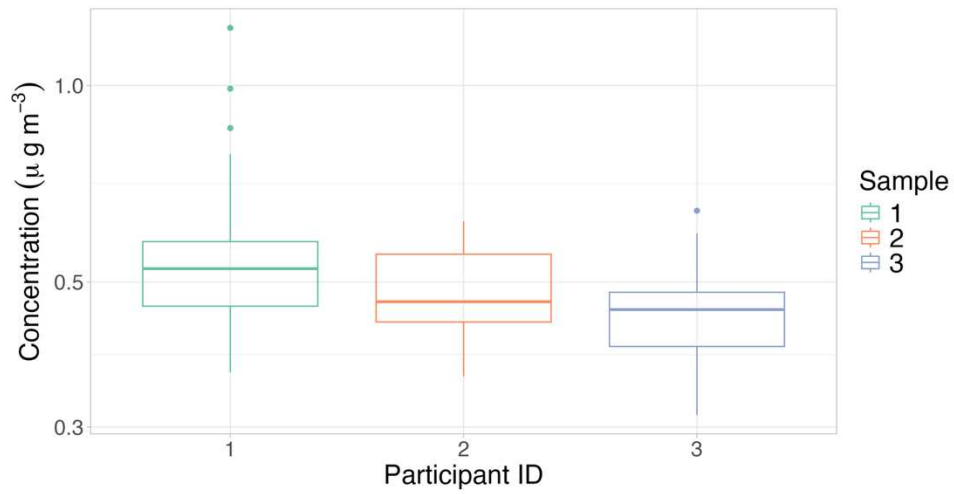
reference is the best available data for comparison. No consistent differences emerged between regions, suggesting that bleach product usage may be relatively similar across study sites.



*Figure 4.14 Concentrations of CCl<sub>4</sub> detected in study for each household with geographic groups differentiated by color. Households with multiple measurements have all detections plotted. Study mean was calculated across all samples and can be compared Logue et al. reported mean.*

As shown in Figure 4.15, there was a downward trend in CCl<sub>4</sub> concentrations over successive sampling periods in treated households. While we did not provide guidance to reduce VOC product use, the ventilation practices recommended to reduce CO<sub>2</sub> and NO<sub>2</sub>—such as opening windows or running exhaust fans—could plausibly contribute to reducing the short-term peaks associated with episodic cleaning events. The magnitude of these changes was not tested for statistical significance, but the direction of the trend supports the hypothesis that ventilation interventions can offer co-benefits for certain episodic VOCs, even when those pollutants are not a primary focus of the intervention.

CCl<sub>4</sub> across multiple samples - treated group



*Figure 4.15 CCl<sub>4</sub> concentrations across multiple samples for Treated group. The downward trend shown is representative of an episodic emitter, concentrations of which can be controlled by increasing ventilation during and after VOC use.*

## DISCUSSION

Indoor air quality (IAQ) is a recognized determinant of respiratory, cardiovascular, and neurological health (Logue *et al.*, 2011), yet practical approaches for improving it at the household level remain limited. People spend most of their time indoors, where pollutant levels vary widely from home to home (Kornartit *et al.*, 2010). Some of this variation comes from factors such as building characteristics and local outdoor conditions (Baeza\_Romero *et al.*, 2022). Occupants typically have limited control over these elements. Other variation arises from the many indoor sources and activities that generate emissions (Nassikas *et al.*, 2024, Kornartit *et al.*, 2010). This combination of fixed and changeable influences makes universal prescriptions ineffective and underscores the need for household-specific information that converts measurement data into feasible actions. The present study evaluated whether a practical scheme comprised of multi-pollutant monitoring with the Home Health Box (HHB) paired with a personalized, plain-language Home Health Report (HHR) could help households reduce common pollutants and, secondarily, whether those same behaviors might have co-benefits for selected volatile organic compounds that were not the subject of the HHRs.

While the overall analysis points to measurable improvements for ventilation-responsive pollutants (NO<sub>2</sub> and CO<sub>2</sub>), the patterns for individual pollutants reveal how different sources and household behaviors must be the starting point for updates. For NO<sub>2</sub>, both in the full treated group and in the gas-stove subgroup, declines were consistent with targeted guidance such as increasing ventilation during cooking, using range hoods when available, opening flues when operating gas fireplaces, and avoiding idling vehicles in attached garages. These actions were representative of the low- to no-cost recommendations that made up the majority of HHR

guidance. Although the reports did include some higher-effort suggestions that could influence NO<sub>2</sub> and PM, such as changing HVAC filters, purchasing portable air cleaners, or using HEPA-filtered vacuum cleaners, there was no clear evidence from participant follow-up that higher-effort measures were adopted during the study period. Given this and considering that many particulate matter events in our dataset could have associated, at least some of the time, with outdoor infiltration, it is not surprising that PM<sub>2.5</sub> and PM<sub>10-2.5</sub> levels did not show consistent treatment effects.

Within this context, PM distributions in the study were low on average and characterized by large, short-lived spikes, which aligns with the episodic nature of their sources and the lack of evidence that participants implemented the higher-effort, filtration-based controls. On the other hand, a small subset of household with the highest measured PM<sub>2.5</sub> succeeded in decreasing in-home PM<sub>2.5</sub> concentrations. The tendency for the most polluted environments to respond more robustly to intervention is also noted in a French study of in-home PM (Abdel Sater *et al.*, 2021).

In contrast, the VOC analysis underscored the difference between pollutants amenable to dilution through short-term ventilation actions and those requiring source elimination. Continuous emitters such as 1,4-dichlorobenzene (PDCB) remained stable across sampling periods, while episodic emitters such as carbon tetrachloride (CCl<sub>4</sub>) trended downward in treated homes, mirroring CO<sub>2</sub> decreases. The latter pattern is consistent with the kinds of behaviors participants reported adopting, primarily those that increased ventilation. Broadly, these results suggest that where it is pollutant sources can be mitigated through straightforward, low-cost, and context-specific actions, households are able to respond quickly and effectively. Where sources are persistent or dominated by outdoor events, substantial improvement without investment in filtration or structural modifications is unlikely.

These results are broadly concordant with prior work showing that feedback and simple changes can reduce indoor pollutant peaks during activities such as cooking (Kureshi *et al.*, 2023). Our contribution extends the literature in several ways. First, we evaluated multiple pollutants simultaneously and linked them to one integrated set of recommendations; therefore, rather than focusing on a single source or adaptation, we presented participants with a comprehensive and more realistic understanding of their in-home environment (Singer *et al.*, 2017, Ruiz-Tagle and Schueftan, 2021). Second, we paired a randomized, two-arm design with repeated household measurements, allowing us to test both between-group differences and within-household changes over time. Third, we explicitly examined whether actionable recommendations coupled with the participant's in-home air quality measures for specific pollutants (i.e., CO<sub>2</sub>, NO<sub>2</sub>, and PM) might carry over to VOCs. This connection may have been discussed conceptually in prior work, but it has rarely been tested in homes (Cibin *et al.*, 2025).

It marks mentioning, our particulate matter results differ from some meta-analytic summaries that report higher indoor PM<sub>2.5</sub> averages (Logue *et al.*, 2011, Morantes *et al.*, 2024). Plausible explanations include regional outdoor baselines during our study period, housing stock differences, and the absence of extended wildfire smoke episodes. Although these discrepancies in particulate matter findings are noteworthy, they do not alter the core result: the HHR intervention was associated with lower CO<sub>2</sub> and NO<sub>2</sub> concentrations in treated households compared to controls at the second measurement, along with within-household declines in the treated group. While we cannot directly attribute these changes to specific behaviors due to the hands-off nature of the study; the recommendations provided, specifically targeted ventilation during pollutant-generating activities, remain the most plausible mechanisms for the observed improvements.

Viewed in the broader ecosystem of IAQ research and practice, the findings highlight where household action is most likely to succeed and where alternative approaches are warranted. Ventilation-responsive pollutants, including CO<sub>2</sub>, NO<sub>2</sub> from combustion, and some episodic VOCs, respond to timely and feasible behaviors such as using range hoods, opening windows strategically, operating exhaust fans, and increasing air circulation during and after higher-emission activities and crowded gatherings. Recent studies have also shown that occupant behavior changes of this kind can reduce exposure peaks and lower average concentrations in real-world homes, particularly when feedback or targeted messaging is provided (Ruiz-Tagle and Schueftan, 2021, Kureshi *et al.*, 2023). Continuous emitters such as PDCB, in contrast, require source identification and removal because ventilation alone cannot address steady emissions. The persistence of PDCB in our study is consistent with other work documenting the limited effect of ventilation on continuously emitted pollutants (Wolkoff 1998, Huangfu *et al.*, 2020). Further illustrating the limits of household actions, coarse PM in the Las Cruces subgroup is likely dominated by regional outdoor sources and longer-range transport and did not respond to intervention in our study (City of Las Cruces, 2025). In such cases, community or building-level strategies, such as filtration upgrades or dust-control practices, may be more appropriate avenues. Our results reinforce the conclusion from prior multi-scale intervention studies that successful IAQ improvement often requires aligning household-level actions with broader structural or community interventions (Cibin *et al.*, 2025).

The framework can be applied across many environments – programs in public health, weatherization, asthma management, and rental housing could incorporate HHB/HHR-style feedback to prompt low-cost behaviors with documented benefits for NO<sub>2</sub> and CO<sub>2</sub>. The caveat being, these benefits are most likely to impact pollution from cooking and high-occupancy

events. Messaging must be pollutant-informed. For example, guidance to “increase ventilation by opening windows during cleaning” is appropriate for episodically emitted VOCs, like CCl<sub>4</sub>, in contrast, constant emitters like PDCB require “remove the product” recommendations and product-substitution lists. Both compounds are included in the broad category of VOCs, and oversimplification of messaging will not lead to equal benefits. For jurisdictions debating appliance standards and ventilation codes, these data support a both-and approach. Structural measures such as capture-efficient range hoods, minimum ventilation rates, and electrification should be complemented by household education that improves day-to-day practices. Community partners in dust-prone regions may wish to pair household feedback with neighborhood-scale dust mitigation and filtration initiatives which acknowledges the limited leverage of individual actions on coarse particulates.

### **Future Work 5.1**

Several avenues for future research can build on this pilot study, which was designed as an initial test of a novel multi-pollutant feedback intervention. Extending follow-up periods would make it possible to assess the durability of behavior change and pollutant reductions beyond the initial novelty effect. However, longer-term monitoring may face challenges such as participant attrition, seasonal changes in pollutant sources, and the need to maintain engagement over extended periods. Real-time or near-real-time prompts could be compared with periodic reports to determine which feedback cadence is most effective for maintaining adherence. This would require careful evaluation of participant burden and technological reliability, as well as consideration of whether frequent prompts could lead to message fatigue.

Another option for further exploration of the low-cost treatments presented in this study is to tailor a campaign to high-pollutant households, which may stand to see the most

improvement. These households are the highest need since they are living with the greatest levels of indoor air pollution, and the current study suggests these households may benefit the most from ventilation changes at key periods and other personalized recommendations.

Incorporating objective measures of behavior, such as range-hood use sensors or window/door open-state loggers, could reduce reliance on self-reported data and improve attribution of pollutant changes to specific actions. Implementing these measures, however, raises questions about cost, installation complexity, and privacy that are some of the positive aspects of the current study design. Larger sample sizes would allow for more robust statistical power and enable stratified analyses by housing type, ventilation system, and appliance mix. Analytical approaches such as difference-in-differences or mixed-effects models could help quantify heterogeneity of treatment effects. Achieving these larger samples would require broader recruitment strategies, potentially across multiple regions, and greater logistical capacity for deployment and retrieval of monitoring equipment. Linking pollutant reductions to health-relevant outcomes, such as symptoms, sleep quality, or cognitive performance, would provide critical evidence for the public health significance of this intervention, but would also require more intensive data collection and careful protection of participant confidentiality.

For policy and intervention implementation, future work should explore how an HHB/HHR-style approach could be integrated into existing public health and housing programs. This could include energy-subsidized households, asthma management initiatives, weatherization programs, and rental housing quality standards, with messaging adapted to the target audience and their most relevant pollutant sources. Messaging strategies could be tested at scale to compare the impact of universal versus pollutant-specific recommendations. Such efforts should be designed with adequate statistical power to detect differences in both behavior change and

health outcomes. At the same time, implementation studies would need to consider the cost-effectiveness of providing equipment, the training required for program staff, and the feasibility of maintaining data quality at larger scales.

Because this pilot represents a first-of-its-kind, multi-pollutant feedback study, a next step could be to conduct larger-scale trials that retain the tailored feedback model but test variations in messaging, delivery methods, and intervention intensity. These trials could be designed to provide more definitive evidence of causal effects on pollutant levels, document the persistence of changes over time, and evaluate downstream health impacts. The results would not only refine the intervention for research purposes but also inform policies and best practices for indoor air quality improvement programs.

## **Study Strengths and Limitations 5.2**

### *Strengths 5.2.1*

The study has notable strengths. It was conducted in occupied homes, enhancing external validity and demonstrating feasibility at community scale. Successful randomization allowed for participants to engage in the study without standardizing their everyday schedules or housing characteristics, so that real data could be delivered about their normal environment. The intervention combined measurement with tailored, actionable communication rather than assuming that data alone would change behavior. Monitoring encompassed multiple pollutants, enabling an integrated interpretation of ventilation, combustion sources, and VOC dynamics. Retention across sampling periods was high, suggesting sustained participant engagement. Partner responsiveness, including adding PM<sub>10</sub> feedback in Las Cruces, illustrates adaptability to local priorities without compromising core methods.

### *Limitations 5.2.2*

Limitations temper interpretation; the sample size limited statistical power for some outcomes and precluded robust subgroup analyses beyond the gas-stove comparison. The study was not designed to test demographic or income effects; the introduction and literature review appropriately motivate the work, but the results do not estimate those disparities with the current participants. Self-reported actions may be affected by recall or social desirability bias, and participants could not be blinded to treatment. Seasonal variability and external events (e.g., outdoor episodes) may have influenced concentrations despite the control group. NO<sub>2</sub> values below the instrument limit of detection were conservatively replaced with nearest outdoor monitor maxima to avoid false zeros; while sensible, this imputation adds uncertainty at the low end of the distribution. Sensor and sampling limitations that are common to field studies could contribute measurement error, although calibration and QA/QC procedures were used to minimize these traditional sources of bias. Alternative explanations—such as regression to the mean or Hawthorne effects—cannot be completely ruled out. However, the fact that within-household decreases in treated homes align with between-group differences at HHB2 supports the presence of a genuine intervention effect rather than a mere artifact.

## CONCLUSION

In sum, this pilot contributes novel evidence by (1) integrating feedback across multiple pollutants into one intervention, (2) using a randomized two-arm design with repeated household measurements, and (3) testing whether guidance for primary pollutants could indirectly reduce VOCs. Personalized IAQ feedback paired with simple, low-cost actions produced measurable reductions in CO<sub>2</sub> and NO<sub>2</sub> in real homes and suggested co-benefits for an episodic VOC, while highlighting that continuous VOC emitters require source removal and that outdoor-driven coarse particles often lie beyond the reach of household actions. Participants were less likely to employ the higher-effort or -cost recommendations such as installing filters, purchasing a portable air cleaner, or a HEPA-enabled vacuum. These findings offer a practical guide: combine multi-pollutant measurement with personalized and data informed recommendations, then target ventilation-responsive pollutants with simple, low-cost behavioral changes and remove continuous sources when present. This enables retaining structural or community strategies for pollutants dominated by outdoor or persistent sources. This approach is scalable, equity-relevant, and immediately actionable, and it provides insight into pathways for programs and policies seeking to reduce indoor exposures where people actually live.

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## APPENDIX A: HHB TECHNICAL DETAIL

# Home Health Box for Indoor Air Monitoring

## PM and gas sampling + sensors for PM, CO<sub>2</sub>, and more

The Home Health Box (HHB) is a compact indoor air monitor that is designed to plug into a wall outlet (with an optional backup battery for interruptions in line power). The HHB can be custom-configured to sample and sense a range of particulate and gaseous pollutants:

- Up to two particulate matter filter samplers (e.g., PM<sub>2.5</sub>, respirable, PM<sub>10</sub>)
- Up to two active gas-phase pollutant samplers (e.g., for thermal desorption tubes, glass sorbent tubes, or DNPH-Silica cartridges)
- One time-resolved particulate matter sensor (Sensirion SEN55)
- One NDIR CO<sub>2</sub> sensor (Sensirion SCD30)
- Up to five electrochemical sensors for other gaseous pollutants (e.g., NO<sub>2</sub>, CO)

The HHB uses the same virtually-silent pumping technology as our Ultrasonic Personal Air Sampler (UPAS).

For additional information, see: Tryner, J., Phillips, M., Quinn, C., Neymark, G., Wilson, A., Jathar, S.H., Carter, E., Volckens, J. Design and testing of a low-cost sensor and sampling platform for indoor air quality, *Building and Environment*, 2021, 206, 108398, <https://doi.org/10.1016/j.buildenv.2021.108398>.



Revision 1.5, June 2025

# Home Health Box for Indoor Air Monitoring

## Configuration Options and Specifications

### Particulate matter (PM) sampling channels

Quantity	The Home Health Box can be configured with 0, 1, or 2 PM sampling channels.
Flow rate	1 or 2 L min <sup>-1</sup> (depending on the size-selective inlet used)
Available inlets	PM <sub>2.5</sub> @ 1 L min <sup>-1</sup> PM <sub>2.5</sub> @ 2 L min <sup>-1</sup> Respirable PM @ 2 L min <sup>-1</sup> PM <sub>10</sub> @ 2 L min <sup>-1</sup>
Filter size	37 or 25 mm; we recommend using 37-mm-diameter PTFE membrane filters from Measurement Technologies Laboratories (PT37P-PF03), depending on analysis needs.

### Gas sampling channels

Quantity	The Home Health Box can be configured with 0, 1, or 2 gas sampling channels.
Flow rate	3 to 30 mL min <sup>-1</sup> ; user-programmable
Compatible media	6.35-mm-diameter × 89-mm long thermal desorption tubes Common glass thermal desorption tubes (e.g., 6 to 10 mm in diameter) Will accept a Waters Sep-Pak <sup>®</sup> DNPH-Silica cartridge (WAT037500) with a Sep-Pak <sup>®</sup> Ozone Scrubber cartridge (WAT54420) installed upstream

### Pollutant sensors

Baseline package	Particulate matter: Sensirion SEN55 (laser light scattering) Carbon dioxide: Sensirion SCD30 (non-dispersive infrared; NDIR) Qualitative relative tVOCs and NO <sub>x</sub> levels: Sensirion SGP41 (metal oxide; MOx)
Electrochemical sensors for additional pollutants (optional)	Up to four Alphasense B-series electrochemical sensors Carbon monoxide: CO-B4 Nitrogen dioxide: NO2-B43F Contact our engineering team if you'd like sensors for other pollutants (e.g., NO, O <sub>3</sub> ) added to your Home Health Box.  Formaldehyde: Sensirion SFA30 (This sensor is available as an experimental feature; the accuracy of data reported by this sensor has not been evaluated by AST.)

### Power

Line power	The Home Health Box can run indefinitely when plugged into a wall outlet.
Optional backup battery	Li-ion; 24 W-h; battery life is configuration dependent; 8 h runtime when collecting two filter samples @ 2 L min <sup>-1</sup> and two gas samples @ 30 mL min <sup>-1</sup> with PM, CO <sub>2</sub> , NO <sub>2</sub> , and formaldehyde sensors on in a location with air density = 1.0 g L <sup>-1</sup> .

---

#### Access Sensor Technologies

[www.accsensensors.com](http://www.accsensensors.com) (970) 818-7520 [support@accsensensors.com](mailto:support@accsensensors.com)  
320 East Vine Drive, Suite 221, Fort Collins, CO 80524

APPENDIX B: PARTICIPANT SURVEYS

Confidential

Page 1

Home Health Box Initial Survey about Your Home and Household

Thank you for participating in the home health and air pollution study. Our records indicate you have received a Home Health Box. To complete your participation in the study, we kindly request that you respond fully to the survey below. The information you provide will help us understand the data we collect about the air in your home. If you have any concerns or questions at any time, please contact us by email at (ellison.carter@colostate.edu).

Thank you!

Thank you for participating in our Home Health Box study. In this study, we deploy a Home Health Box in your home to measure your indoor air pollutant levels. In total, we will conduct the measurements three times. Each time, the Home Health Box measurement will last one week. After the the three rounds of measurements are complete, you will receive a final report documenting the results from the three sets of measurements. This is your first measurement. We would like to invite you to complete this questionnaire to gather information that helps us interpret your indoor air quality data.

Your participation in this study is completely voluntary and you can stop your participation at any time. All responses to the questionnaire are confidential and will not be shared with anyone outside the study team. You will receive a total of \$100 upon completion of the first, second, and third Home Health Box installations and completion of the corresponding intake and four follow-up surveys as compensation for your participation in this study. We appreciate your participation in this study.

Where will you plug in and run the Home Health Box in your home?
Living room
Common area other than a living room
Other

If "other", where will you plug in the home health box in your home?

How many adults, including yourself, live in your home? Count anyone who spent at least 3 nights per week here for the last month or longer.

How many children (ages 0-18 years) live in your home? Count anyone who spent at least 3 nights per week here for the last month or longer.

What is your relationship with the people in your home? Check all that apply.
Spouse/partner
Child
Parent
Sibling
Other family
Friend
Other (please specify)

Other relationship:

**Work and Education**

What is your highest education level?

- No High school diploma or GED
- High school diploma or GED
- Some college but no degree
- Associate degree
- Bachelor's degree (i.e. BA, BS)
- Post graduate degree (i.e. Masters or Doctoral degree)

Are you currently working?

- Yes
- No

In general, how many hours per week do you work?

\_\_\_\_\_

Do you work from home?

- Yes
- No
- Hybrid

What category best describes the combined annual income, before taxes, of all members of your household for the last year?

- Less than \$25,000
- \$25,000-\$49,999
- \$50,000-\$99,999
- \$100,000 or more
- Decline to answer
- Don't know

11. What are the occupations of those adults living in your home (not including yourself). Check all that apply.
- Management
  - Office and administrative support
  - Sales and related
  - Educational instruction, and library
  - Healthcare practitioners and technical
  - Production
  - Food preparation and serving related
  - Business and financial operations
  - Construction and extraction
  - Computer and mathematical
  - Transportation
  - Building and grounds cleaning and maintenance
  - Material moving
  - Healthcare support
  - Installation, maintenance, and repair
  - Personal care and service
  - Arts, design, entertainment, sports, and media
  - Architecture and engineering
  - Protective service
  - Community and social service
  - Legal
  - Life, physical, and social science
  - Farming, fishing, and forestry
  - Other

If "other", what is(are) the occupation(s)?

\_\_\_\_\_

**Smoking Related Information**

Does anyone in your household smoke in the home?  Yes  
 No

---

Where does smoking occur?  Inside your home  
 Outside your home  
 Both

---

How frequently does smoking by person(s) in your household occur?  Less than once per month  
 More than once per month but less than weekly  
 Once per week  
 Multiple times per week but not daily  
 Daily

---

Does anyone in your household vape, use e-cigarettes or hookah in the home?  Yes  
 No

---

Where does vaping or hookah occur?  Inside your home  
 Outside your home  
 Both

---

How frequently is vaping or hookah used by the person(s) in your household?  Less than once per month  
 More than once per month but less than weekly  
 Once per week  
 Multiple times per week but not daily  
 Daily

---

Does anyone in your household smoke marijuana or cannabis products?  Yes  
 No

---

Where does marijuana or cannabis smoking occur?  Inside your home  
 Outside your home  
 Both

---

How does the person(s) use marijuana?  Inhaled (joint, bong, pipe, vape pen, dab)  
 Edible or tincture

---

How frequently is marijuana or cannabis used by person(s) in your household?  Less than once per month  
 More than once per month but less than weekly  
 Once per week  
 Multiple times per week but not daily  
 Daily

**How often do you smell the following types of smoking odor in your home coming from your neighbors or the hallway? (Select an option for each type of smoking odor)**

	Never	Less than once per week	Weekly	Daily
Tobacco smoke	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vaping or E-cigarettes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Marijuana smoke	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**Now, we would like to ask you questions about your residence.**

Which best describes your home?  Single family house  
 Duplex or Townhouse  
 Apartment or Condo  
 Mobile/Manufactured home  
 Other (specify)

If "Other", what type of home do you think your home is? \_\_\_\_\_

Do you rent or own your home?  Own  
 Rent

How long have you lived in your current home?  Less than 6 months  
 6 months or more, but less than 2 years  
 2 years or more, but less than 5 years  
 5 years or more, but less than 10 years  
 10 years or more

What year was your home built? Leave blank if you do not know. \_\_\_\_\_

What is the total number of bedrooms in your residence? \_\_\_\_\_

What is the total number of bathrooms in your residence? \_\_\_\_\_

How many rooms have carpet? \_\_\_\_\_

How many rooms have hard flooring (for example: wood or tile)? \_\_\_\_\_

How many rooms have area rugs larger than an entryway mat or bathmat? \_\_\_\_\_

How many doors of your home open to the outside? \_\_\_\_\_

How many windows of your home open to the outside? \_\_\_\_\_

Does your home have a garage?  Yes  
 No  
 Don't know

Is the garage attached to your home?  Yes  
 No  
 Don't know

**Now, we would like to ask you questions about how you cook, heat, and cool in your home.**

How do you or anyone in your family cook food at home?  
Check all that apply.

- Gas stove
- Electric or induction stove
- Microwave
- Toaster
- Air fryer
- Pressure cooker/slow cooker/crock pot
- Outdoor gas grill
- Outdoor charcoal grill
- Other

If "Other", how do you or anyone in your family cook food at home? \_\_\_\_\_

**Approximately how much time do you spend cooking food on each day of the week?**

	Less than 1 hour	More than 1 hour
Monday	<input type="radio"/>	<input type="radio"/>
Tuesday	<input type="radio"/>	<input type="radio"/>
Wednesday	<input type="radio"/>	<input type="radio"/>
Thursday	<input type="radio"/>	<input type="radio"/>
Friday	<input type="radio"/>	<input type="radio"/>
Saturday	<input type="radio"/>	<input type="radio"/>
Sunday	<input type="radio"/>	<input type="radio"/>

Does your kitchen have a vent that exhausts air to the outdoors?

- Yes
- No
- Don't know

How often do you use your kitchen exhaust vent when you and/or anyone in your family are cooking?

- Always
- Most of the time
- Sometimes
- Never

How often do you smell any type of cooking odor in your home coming from your neighbors or the hallway?

- Never
- Less than once a week
- Weekly
- Daily

How do you and your household stay cool in your home?  
Check all that apply.

- Central air conditioning
- Window air conditioning units
- Open windows
- Run fans (ceiling, stand-up, box, etc.)
- Run a whole house fan
- Swamp cooler
- Wear less clothing
- Other

If "Other", please state the way you and your household to stay cool in your home. \_\_\_\_\_

How do you and your household stay warming your home?  
Check all that apply.

- Run a furnace/centralized heating system
- Use a wood-burning fireplace
- Use a wood-burning stove
- Run a kerosene or gas space heater
- Run one or more electric space heaters
- Wear more clothing
- Run an oven with the door open
- In-floor radiant heating
- Radiator/baseboard heater
- Other

If "Other", please state the way you and your household to stay warming in your home. \_\_\_\_\_

Does your house use a humidifier?  Yes  
 No  
 Don't know

Does your house use a dehumidifier?  Yes  
 No  
 Don't know

**Now, we would like to ask you questions about your home activities that might impact indoor air quality.**

Do you have any warm-blooded pets at home (such as cats and dogs)?  Yes  
 No

How many pets total? \_\_\_\_\_

What kind of pets or animals are in your home? Check all that apply.

- Dog
- Cat
- Bird
- Rabbit, guinea pig, hamster, gerbil, or mouse
- Farm animals including chickens
- Other

If "Other", please state what kind of other pets or animals are in your home. \_\_\_\_\_

Do any of your pets sleep in your bed?  Yes  
 No

Where do you keep your pets?  Inside only  
 Outside only  
 Inside and outside

**Approximately, how much time do you spend doing cleaning activities (e.g., sweeping, vacuuming, cleaning surfaces, etc.) on each day of the week?**

	Less than 30 minutes	More than 30 minutes
Monday	<input type="radio"/>	<input type="radio"/>
Tuesday	<input type="radio"/>	<input type="radio"/>
Wednesday	<input type="radio"/>	<input type="radio"/>
Thursday	<input type="radio"/>	<input type="radio"/>
Friday	<input type="radio"/>	<input type="radio"/>
Saturday	<input type="radio"/>	<input type="radio"/>
Sunday	<input type="radio"/>	<input type="radio"/>

Does your vacuum cleaner have a HEPA filter?  Yes  
 No  
 I do not have a vacuum  
 Don't know

Does your family use air fresheners or other scented products (i.e., potpourri, spray fresheners, etc.) at home?  Yes  
 No

How often does your family use air fresheners or other scented products (i.e., potpourri, spray fresheners, etc.) at home?  Once a week or less  
 Every other day  
 Daily  
 Don't know

Do you burn candles or incense in your home?  Yes  
 No  
 Don't know

On average, how often do you burn candles or incense in your home?  Once a week or less  
 Every other day  
 Daily  
 Don't know

How often do you smell any type of incense odor in your home coming from your neighbors or the hallway?  Never  
 Less than once a week  
 Weekly  
 Daily

How often do you smell any type of garbage odor in your home coming from your community?  Never  
 Less than once a week  
 Weekly  
 Daily

Does your home have an indoor fireplace?  Yes  
 No  
 Don't know

What type of fireplace? Check all that apply.  Wood burning  
 Gas/propane  
 Fireplace insert

---

How often do you use your fireplace during the winter?

- Less than once per month
- More than once per month but less than weekly
- Once per week
- Multiple times per week but not daily
- Daily

---

Has there been water damage to your house, basement, or its contents during the past 12 months?

- Yes
- No
- Don't know

---

Has there been any mold or mildew on any surfaces inside your house in the past 12 months?

- Yes
- No
- Don't know

---

Which rooms have or have had mold or mildew? Check all that apply.

- Bathroom(s)
- Basement or attic
- Kitchen
- Bedroom(s)
- Living or family room
- Other

---

If "Other", please state what kind of other rooms have or have had mold or mildew. \_\_\_\_\_

---

Do you ever see cockroaches in your house?

- Yes
- No
- Don't know

---

In which room(s) have you seen cockroaches? Check all that apply.

- Bathroom(s)
- Basement or attic
- Kitchen
- Bedroom(s)
- Living or family room
- Other

---

If "Other", please state what kind of other rooms you have seen cockroaches. \_\_\_\_\_

---

Do you ever see rodents or rodent droppings in your house?

- Yes
- No
- Don't know

---

In which room(s) have you seen rodents or rodent droppings? Check all that apply.

- Bathroom(s)
- Basement or attic
- Kitchen
- Bedroom(s)
- Living or family room
- Other

---

If "Other", please state what kind of other rooms you have seen rodents or rodent droppings. \_\_\_\_\_

---

Do you have any concerns about your home environment?

- Yes
- No

---

Please describe your concerns about your home environment. \_\_\_\_\_

---

You have completed our initial survey! Good job! Thank you!

## First Home Health Box Follow-up

Please complete the survey below.

Thank you!

---

Thank you very much for completing the air quality measurements at your home! We appreciate your participation and dedication. To help us better understand and interpret the air quality at your home, please take a few minutes to complete this questionnaire about your household's activities during the week when your indoor air quality was measured. This is the first Home Health Box follow-up survey. Your answers are valuable to us.

---

**We would like to start by asking you questions about yourself and your most recent Home Health Box deployment.**

Please choose a survey date

\_\_\_\_\_

Participant's full name

\_\_\_\_\_

---

Did you, or your family member who is a patient of UHealth Asthma Clinic, collect your or their nasal epithelium lining fluid with the provided testing strips and store your samples in your freezer?

- Yes  
 No

---

Did you take our initial intake survey which included information about your home and household members?

- Yes  
 Maybe  
 No

---

Date of birth

\_\_\_\_\_

---

**Now, we would like to ask you some questions about residents in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).**

Including yourself, how many adults (18 years of age or older) lived in this residence during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

---

How many children (17 years of age or younger) lived in this residence while your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

---

Now, we would like to ask you some questions about activities in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).

**Choose the days of the week when you or anyone in your household cooked at your home while the most recent Home Health Box was running. For each day that cooking took place, please check the box for whether the amount of time spent cooking was less than one (1) hour or more than one (1) hour.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Less than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
More than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household hosted parties or guests at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Did you or anyone in your household use any appliance for space heating while the most recent Home Health Box was running? For each appliance, please indicate whether it was used Never, Sometimes, Most of the time, or Always.**

	Oil/gas furnace	Wood-burning fireplace	Wood-burning stove	Unvented kerosene or gas space heater	Electric space heater	Other
Never	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sometimes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Most of the time	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Always	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household used incense or candles at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Choose the days of the week when you or anyone in your household cleaned your home while the most recent Home Health Box was running. For each day that cleaning took place, please check the box for whether the amount of time spent cleaning was less than 30 minutes or more than 30 minutes.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
--	--------	---------	-----------	----------	--------	----------	--------

Less than 30 minutes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
More than 30 minutes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**Now, we would like to ask you some questions about possible air pollution sources at your home during the week when your indoor air quality was being measured.**

Were any of the following air pollution sources of concern to you or your households members while the most recent Home Health Box was running? (Select all that apply)

- Outdoor construction
- Outdoor traffic
- Outdoor wildfire smoke
- Outdoor smoking
- Indoor smoking
- Indoor cooking
- Other

---

Please list other pollutants of concern

---

How often did you or anyone in your household open windows while the most recent Home Health Box was running?

- Most of the time
- Sometimes
- Never

---

Did you or any member of your family add any of the following appliances to your home during the week while the most recent Home Health Box was running? (Select all that apply)

- Air filter for HVAC system
- Stove
- Stove vent
- Vacuum
- Portable air cleaner
- None
- Other

---

Is there any additional information that you would like to share that you think would help us understand your home's air quality while measurements were being conducted?

---

Thank you for taking our follow-up survey. We really appreciate your participation. Please remember to ship the Home Health Box back to us as soon as you are available.

## Control group Follow-Up for HHB2 and HHB3 (if applicable)

Confidential

Page 1

### Second and Third Home Health Box Follow-up

Please complete the survey below.

Thank you!

Thank you very much for completing the air quality measurements at your home! We really appreciate your participation and dedication. To help us better understand and interpret the air quality at your home, please take a few minutes to complete this questionnaire about your family activities during the week your indoor air quality was measured. This Home Health Box follow-up survey is the same for the second and third round Home Health Box deployments. Your answers are valuable to us.

**We would like to start by asking you questions about yourself and your most recent Home Health Box deployment.**

Please choose a survey date

\_\_\_\_\_

Participant's full name

\_\_\_\_\_

Did you, or your family member who is a patient of UHealth Asthma Clinic, collect your or their nasal epithelium lining fluid with the provided testing strips and store the samples in your freezer?

- Yes  
 No

Did you take our initial follow-up survey which included information about your home and household members?

- Yes  
 Maybe  
 No

Date of birth

\_\_\_\_\_

Was the most recent Home Health Box deployed in the same home as it was with the first deployment?

- Yes  
 Maybe  
 No

Physical address: where was the most recent Home Health Box deployed this time?

\_\_\_\_\_

Was the most recent Home Health Box placed in the same location in your home as the first deployment?

- Yes  
 Maybe  
 No

Where was the Home Health Box placed in your home during the most recent deployment?			
	Living Room	Bedroom	Common Area
A table under knees (ex. coffee table)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
A table between knees and torso (ex. desk)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
A table above torso (ex. standing desk)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**Now, we would like to ask you some questions about residents in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).**

Including yourself, how many adults (18 years of age or older) lived in this residence during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

How many children (17 years of age or younger) lived in this residence while your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

Now, we would like to ask you some questions about activities in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).

**Choose the days of the week when you or anyone in your household cooked at your home while the most recent Home Health Box was running. For each day that cooking took place, please check the box for whether the amount of time spent cooking was less than one (1) hour or more than one (1) hour.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Less than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
More than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household hosted parties or guests at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Did you or anyone in your household use any appliance for space heating while the most recent Home Health Box was running? For each appliance, please indicate whether it was used Not at all, Sometimes, Most of the time, or Always.**

	Oil/gas furnace	Wood-burning fireplace	Wood-burning stove	Unvented kerosene or gas space heater	Electric space heater	Other
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sometimes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Most of the time	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Always	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household used incense or candles at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Choose the days of the week when you or anyone in your household cleaned your home while the most recent Home Health Box was running. For each day that cleaning took place, please check the box for whether the amount of time spent cleaning was less than 30 minutes or more than 30 minutes.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Less than 30 minutes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
More than 30 minutes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Were any of the following air pollution sources of concern to you or your households members while the most recent Home Health Box was running? (Select all that apply)

- Outdoor construction
- Outdoor Traffic
- Outdoor wildfire smoke
- Outdoor smoking
- Indoor smoking
- Indoor cooking
- Other

Please list other pollutants of concern

---

How often did you or anyone in your household open windows while the most recent Home Health Box was running?

- Most of the time
- Sometimes
- Never
- Don't know

---

Did you or any member of your family add any of the following appliances to your home during the week while the most recent Home Health Box was running? (Select all that apply)

- Air filter
- Stove
- Stove vent
- Vacuum
- None of these

---

Is there any additional information that you would like to share that you think would help us understand your home's air quality while measurements were being conducted?

---

Thank you for taking our follow-up survey. We really appreciate your participation. Please remember to ship the Home Health Box back to us as soon as you are available.

# Treated group Follow-Up for HHB2 and HHB3 (if applicable)

Confidential

Page 1

## Second and Third Home Health Box Follow-up

Please complete the survey below.

Thank you!

Thank you very much for completing the air quality measurements at your home! We really appreciate your participation and dedication. To help us better understand and interpret the air quality at your home, please take a few minutes to complete this questionnaire about your family activities during the week your indoor air quality was measured. This Home Health Box follow-up survey is the same for the second and third round Home Health Box deployments. Your answers are valuable to us.

**We would like to start by asking you questions about yourself and your most recent Home Health Box deployment.**

Please choose a survey date

\_\_\_\_\_

Participant's full name

\_\_\_\_\_

Did you, or your family member who is a patient of UHealth Asthma Clinic, collect your or their nasal epithelium lining fluid with the provided testing strips and store the samples in your freezer?

- Yes
- No

Did you take our initial intake survey which included information about your home and household members?

- Yes
- Maybe
- No

Date of birth

\_\_\_\_\_

Was the most recent Home Health Box deployed in the same home as it was with the first deployment?

- Yes
- Maybe
- No

Physical address: where was the most recent Home Health Box deployed this time?

\_\_\_\_\_

Was the most recent Home Health Box placed in the same location in your home as the first deployment?

- Yes
- Maybe
- No

**Where was the Home Health Box placed in your home during the most recent deployment?**

	Living room	Bedroom	Common area
A table under knees (ex. coffee table)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
A table between knees and torso (ex. desk)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
A table above torso (ex. standing desk)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**Now, we would like to ask you some questions about residents in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).**

Including yourself, how many adults (18 years of age or older) lived in this residence during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

How many children (17 years of age or younger) lived in this residence while your indoor air quality was being measured (i.e., while the most recent Home Health Box was running)? Count anyone who spent at least three (3) nights here.

\_\_\_\_\_

**Now, we would like to ask you some questions about activities in your home during the week when your indoor air quality was being measured (i.e., while the most recent Home Health Box was running).**

**Choose the days of the week when you or anyone in your household cooked at your home while the most recent Home Health Box was running. For each day that cooking took place, please check the box for whether the amount of time spent cooking was less than one (1) hour or more than one (1) hour.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Less than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
More than 1 hour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household hosted parties or guests at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Did you or anyone in your household use any appliance for space heating while the most recent Home Health Box was running? For each appliance, please indicate whether it was used Never, Sometimes, Most of the time, or Always.**

	Oil/gas furnace	Wood-burning fireplace	Wood-burning stove	Unvented kerosene or gas space heater	Electric space heater	Other
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sometimes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Most of the time	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Always	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Choose the days of the week when you or anyone in your household used incense or candles at your home while the most recent Home Health Box was running. (Select all that apply)

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

**Choose the days of the week when you or anyone in your household cleaned your home while the most recent Home Health Box was running. For each day that cleaning took place, please check the box for whether the amount of time spent cleaning was less than 30 minutes or more than 30 minutes.**

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Less than 30 minutes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
More than 30 minutes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**Now, we would like to ask you some questions about possible air pollution sources at your home during the week when your indoor air quality was being measured.**

Were any of the following air pollution sources of concern to you or your households members while the most recent Home Health Box was running? (Select all that apply)

- Outdoor construction
- Outdoor Traffic
- Outdoor wildfire smoke
- Outdoor smoking
- Indoor smoking
- Indoor cooking
- Other

Others (list, if more than one)

How often did you or anyone in your household open windows while the most recent Home Health Box was running?

- Most of the time
- Sometimes
- Never
- Don't know

Did you or any member of your family add any of the following appliances to your home during the week while the most recent Home Health Box was running? (Select all that apply)

- Air filter
- Stove
- Stove vent
- Vacuum
- None of these

Is there any additional information that you would like to share that you think would help us understand your home's air quality while measurements were being conducted?

**Now, we want to ask you a few questions related to the most recent Home Health Report you received.**

**The following is a list of words that describe feelings you may have about your Home Health Report. For each one, please tell us whether or not this word describes how you feel, rating the intensity of the feeling on a scale from 0 to 5 where 0 is not at all, 1 is very mild, 2 is mild, 3 is moderate, 4 is strong and 5 is very strong. Please answer for yourself only.**

**Examples: If receiving your Home Health Report made you feel informed, and the intensity of that feeling was strong, you would then rate the intensity for "informed" as 4, for strong. As another example, if receiving your Home Health Report did not make you feel empowered, you would enter 0 for not at all.**

	0	1	2	3	4	5
Interested	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Helpless	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Respected	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Worried	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Empowered	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Curious	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Scared	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Informed	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Have you or anyone in your household taken any actions to influence your home's air quality based on your Home Health Report?

- Yes
- No
- Don't know

---

What actions have you or anyone in your household taken based on your Home Health Report? (Select all that apply)

- Install portable air cleaners
- Minimize the use of products emitting air pollutants (ex. indoor smoking, incense)
- Install stove ventilation
- Minimize the use of appliances emitting air pollutants (ex. gas or wood-burning fireplace)
- Replace air filters in air handling system (ex. HVAC)
- Increase window opening
- Decrease window opening
- Use stove ventilation more
- Use stove ventilation less
- Consult with an HVAC inspector
- Increase ventilation (ex. run HVAC system more, use fans)
- Decrease ventilation (ex. close windows and doors, turn off HVAC system)
- Idle cars less in the garage
- Others

---

Others actions taken based on Home Health Report (list, if more than one)

---

Do you or anyone in your household plan to take any actions?

- Yes
- Maybe
- No

---

What actions will you or anyone in your household take based on your Home Health Report? (Select all that apply)

- Install portable air cleaners
- Minimize the use of products emitting air pollutants (ex. indoor smoking, incense)
- Install stove ventilation
- Minimize the use of appliances emitting air pollutants (ex. gas or wood-burning fireplace)
- Replace air filters in air handling system (ex. HVAC)
- Increase window opening
- Decrease window opening
- Use stove ventilation more
- Use stove ventilation less
- Consult with an HVAC inspector
- Increase ventilation (ex. run HVAC system more, use fans)
- Decrease ventilation (ex. close windows and doors, turn off HVAC system)
- Idle cars less in the garage
- Others

---

Thank you for taking our follow-up survey. We really appreciate your participation. Please remember to ship the Home Health Box back to us as soon as you are available.

# Final Follow-up Survey about Home Health Report and Home Health Box Experience

Please complete the survey below.

Thank you!

**Thank you very much for completing the air quality measurements at your home! We appreciate your participation and dedication. By this point, you should have received all the Home Health Reports that are associated with the Home Health and Air Pollution Study. We would like to request your feedback on your experience receiving the Home Health Reports and using the Home Health Box. Your participation in this survey is entirely voluntary, and your responses are valuable.**

**The following is a list of words that describe feelings you may have about your Home Health Report(s). For each one, please tell us whether or not this word describes how you feel, rating the intensity of the feeling on a scale from 0 to 5 where 0 is not at all, 1 is very mild, 2 is mild, 3 is moderate, 4 is strong and 5 is very strong. Please answer for yourself only.**

**Examples: If receiving your Home Health Report(s) made you feel informed, and the intensity of that feeling was strong, you would then rate the intensity for "informed" as 4, for strong. As another example, if receiving your Home Health Report(s) did not make you feel empowered, you would enter 0 for not at all.**

	0	1	2	3	4	5
Interested	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Helpless	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Respected	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Worried	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Empowered	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Curious	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Scared	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Informed	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Up to this point in time, have you or anyone in your household taken any actions to influence your home's air quality based on your Home Health Report(s)?

- Yes
- No
- Don't know

---

What actions have you or anyone in your household taken based on your Home Health Report(s)? (Select all that apply)

- Install portable air cleaners
- Minimize the use of products emitting air pollutants (ex. indoor smoking, incense)
- Install stove ventilation
- Minimize the use of appliances emitting air pollutants (ex. gas or wood-burning fireplace)
- Replace air filters in air handling system (ex. HVAC)
- Increase window opening
- Decrease window opening
- Use stove ventilation more
- Use stove ventilation less
- Consult with an HVAC inspector
- Increase ventilation (ex. run HVAC system more, use fans)
- Decrease ventilation (ex. close windows and doors, turn off HVAC system)
- Idle cars less in the garage
- Others

---

Others (please list if more than one)

---

Do you or anyone in your household plan to take any actions moving forward into the future?

- Yes
- No
- Maybe

---

What actions will you or anyone in your household take moving forward into the future based on your Home Health Report? (Select all that apply)

- Install portable air cleaners
- Minimize the use of products emitting air pollutants (ex. indoor smoking, incense)
- Install stove ventilation
- Minimize the use of appliances emitting air pollutants (ex. gas or wood-burning fireplace)
- Replace air filters in air handling system (ex. HVAC)
- Increase window opening
- Decrease window opening
- Use stove ventilation more
- Use stove ventilation less
- Consult with an HVAC inspector
- Increase ventilation (ex. run HVAC system more, use fans)
- Decrease ventilation (ex. close windows and doors, turn off HVAC system)
- Idle cars less in the garage
- Others

---

Others (list if more than one)

---

Agree Disagree

- The HHB easy to use \_\_\_\_\_
- The HHB was a burden on me \_\_\_\_\_
- The HHB was complicated \_\_\_\_\_
- The HHB was convenient for my home \_\_\_\_\_
- The information in the HHR was useful \_\_\_\_\_
- The HHR results surprised me \_\_\_\_\_
- The HHR gave results I expected \_\_\_\_\_
- I learned about the air quality in my home from this project \_\_\_\_\_

---

How could we improve the Home Health Box to better meet your needs?

**Now we are going to ask you about participation in the Home Health Box study.**

**If we need your help again in our future study, how likely would you be to do each of the following? Let us know on a scale from 1 to 5 where 1 is very unlikely and 5 is very likely, how likely you would be to do each of these things.**

	1	2	3	4	5
Participate in a 20-minute phone survey	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Participate in a 30-minute phone survey	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reply to an invitation letter to learn more about a new study	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

---

Thank you very much for participating in our Home Health Box project and taking this survey! Your participation and information you provided is valuable to us.

APPENDIX C: HHR EXAMPLES

High Pollutant Level HHR



This report will tell you about air quality in your home.

This report also has recommendations about how to improve indoor air quality in your home.



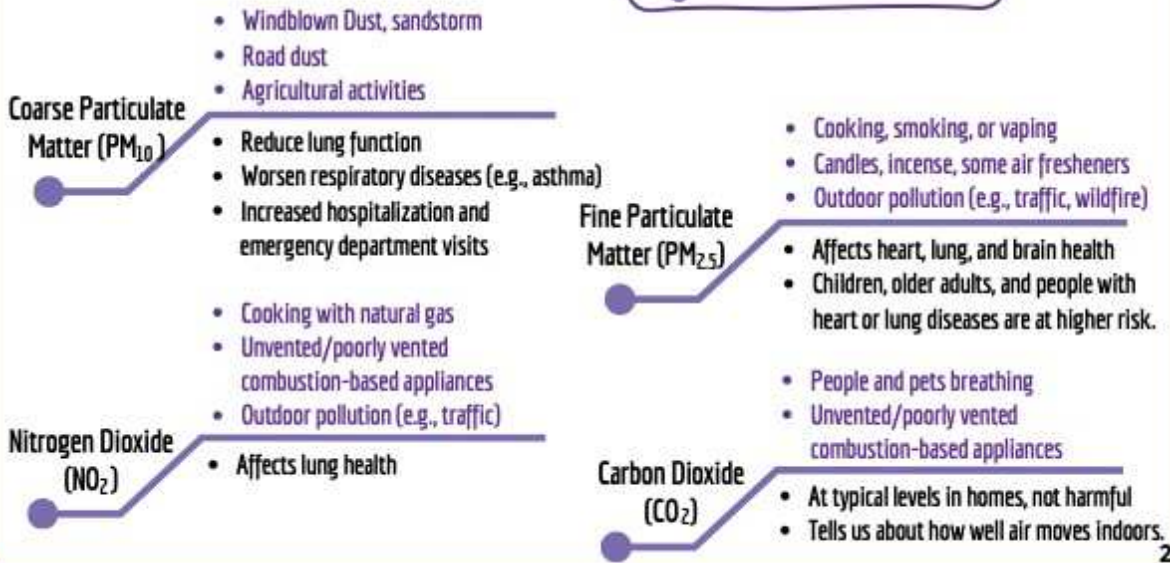
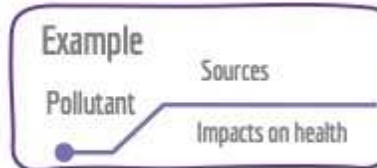
# HOW TO READ MY REPORT

## KEY: Understanding risk

Air pollution in your home may pose different health risks depending on how high the levels are and how your body responds. We use the best information available - for example, standards for outdoor air - to suggest guidelines for low, medium, and high levels of concern.



### Indoor Pollutant Sources and Health



# MY INDOOR AIR QUALITY

## How do I read this diagram?

### Average indoor air pollution levels

The three colors on the dial plot (shaped like a rainbow) correspond to low (green), medium (yellow), and high (red) levels of concern for the pollutant level.

The needle and number on each dial indicate one of the following: the weekly average  $PM_{2.5}$ , the highest 1-h average  $NO_2$ , or the highest 8-h average  $CO_2$  concentration in your home.



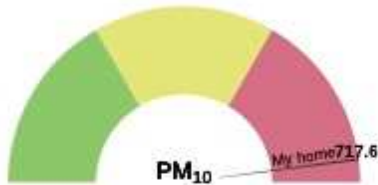
### Daily variation in indoor air pollution levels

The solid black line represents the levels of air pollutants in your home measured every 15 minutes.

- ☀ Daytime
- 🌙 Nighttime

### Coarse Particulate Matter

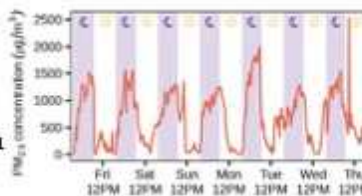
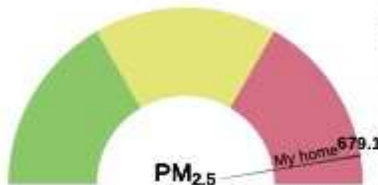
Measured in units of mass per volume,  $\mu g/m^3$ .



- Indoor coarse particulate matter exceeds the EPA 24-h outdoor air standard ( $150 \mu g/m^3$ ).
- Actions to mitigate indoor  $PM_{10}$  are strongly encouraged.
- The HHB does not provide real-time  $PM_{10}$  concentration data.

### Fine Particulate Matter

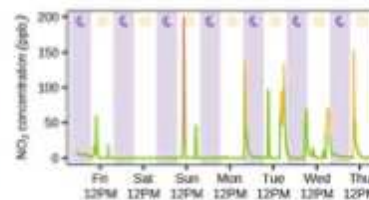
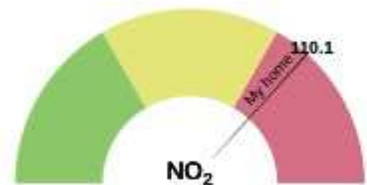
Measured in units of mass per volume,  $\mu g/m^3$ .



- Your indoor fine particulate matter exceeds the EPA 24-h outdoor air standard ( $35 \mu g/m^3$ ).
- Actions to mitigate indoor  $PM_{2.5}$  are strongly encouraged.

### Nitrogen Dioxide

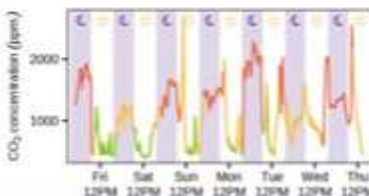
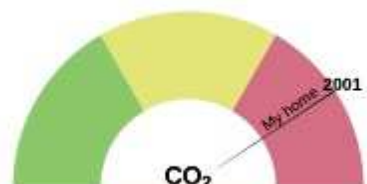
Measured in parts per billion, ppb.



- Indoor nitrogen dioxide exceeds the EPA 1-h outdoor air standard (100 ppb).
- Actions to mitigate indoor  $NO_2$  are strongly encouraged.

### Carbon Dioxide

Measured in parts per million, ppm.



- Indoor carbon dioxide exceeds the ASHRAE recommended range for acceptable indoor air.
- Actions to control indoor  $CO_2$  are strongly encouraged (see page 4).

3



# HOW TO IMPROVE THE HEALTH OF MY HOME

1



Turn on your stove hood while cooking.

2



Only smoke or vape outdoors.

3



To address elevated CO<sub>2</sub>, continue increasing ventilation when hosting guests or with a crowd at home.

For example,

- open windows or turn on exhaust fans;
- install a standalone or window fan.



4



Replace old vented appliances. Fix any leaks promptly.

5



Close windows if you notice ambient air pollution levels are high or traffic is heavy.

## Principles to improve indoor air quality

-- "KEEP IT PRINCIPLE"



Keep it Dry



Keep it Well-Ventilated



Keep it Clean



Keep it Contaminant-Free



Keep it Safe



Keep it Maintained



Keep it Pest-Free



Keep it Thermally Controlled

This work is funded by National Institutes of Health and conducted by Colorado State University.



National Institutes of Health  
*Turning Discovery Into Health*



WALTER SCOTT, JR.  
COLLEGE OF ENGINEERING  
COLORADO STATE UNIVERSITY

4

Low Pollutant Level HHR

# MY HOME HEALTH REPORT

FIRST REPORT

Questions?  
Contact [ellison.carter@colostate.edu]

This report will tell you about air quality in your home.

This report also has recommendations about how to improve indoor air quality in your home.



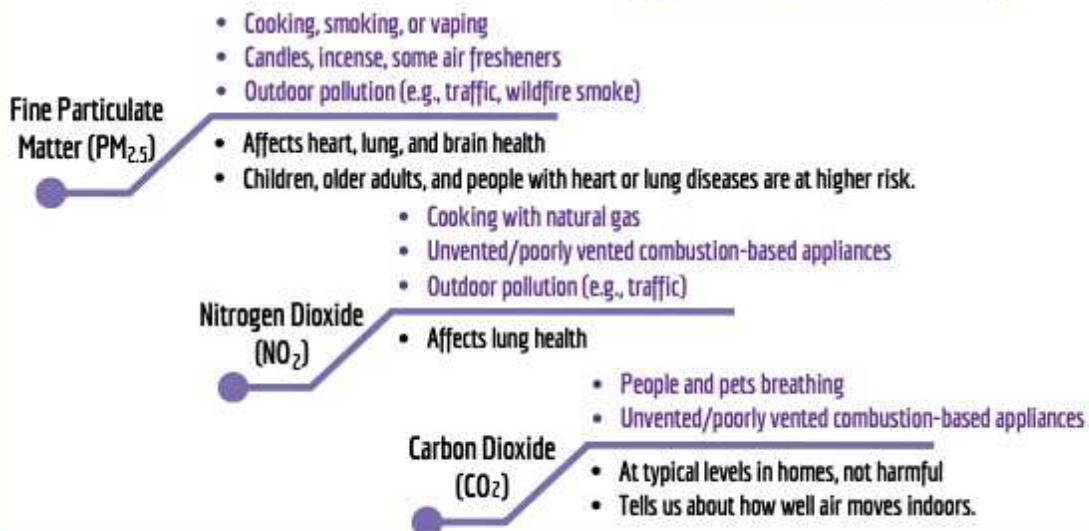
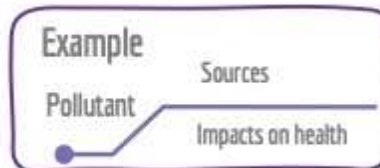
# HOW TO READ MY REPORT

## KEY: Understanding risk

Air pollution in your home may pose different health risks depending on how high the levels are and how your body responds. We use the best information available - for example, standards for outdoor air - to suggest guidelines for low, medium, and high levels of concern.



## Indoor Pollutant Sources and Health



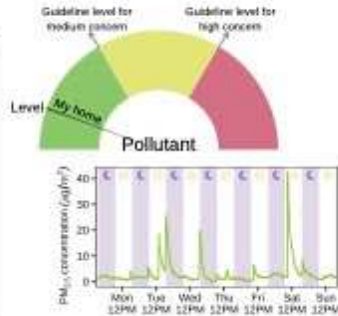
# MY INDOOR AIR QUALITY

## How do I read this diagram?

### Average indoor air pollution levels

The three colors on the dial plot (shaped like a rainbow) correspond to low (green), medium (yellow), and high (red) levels of concern for the pollutant level.

The needle and number on each dial indicate one of the following: the weekly average  $PM_{2.5}$ , the highest 1-h average  $NO_2$ , or the highest 8-h average  $CO_2$  concentration in your home.



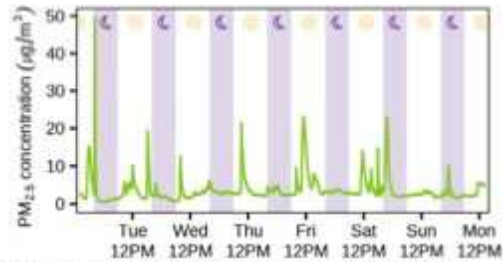
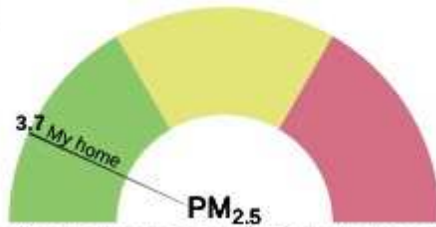
### Daily variation in indoor air pollution levels

The solid black line represents the levels of air pollutants in your home measured every 15 minutes.

- Daytime
- Nighttime

## Fine Particulate Matter

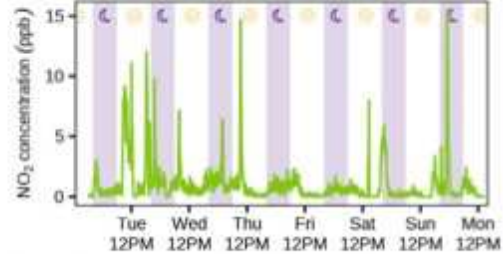
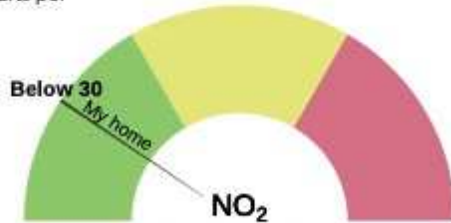
Measured in units of mass per volume,  $\mu g/m^3$ .



- Your indoor fine particulate matter is lower than the EPA annual outdoor air standard ( $9 \mu g/m^3$ ).

## Nitrogen Dioxide

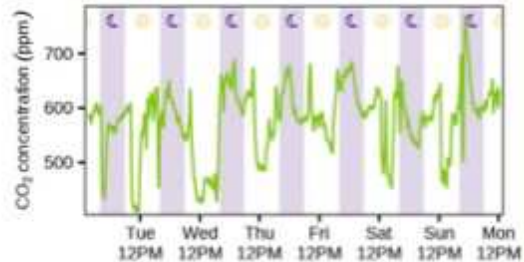
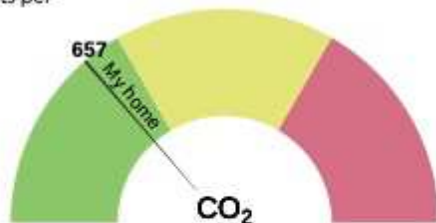
Measured in parts per billion, ppb.



- Indoor nitrogen dioxide is lower than the EPA annual outdoor air standard (53 ppb).
- Your indoor  $NO_2$  is at a very low level where the HHB might not always distinguish the true concentration from zero.

## Carbon Dioxide

Measured in parts per million, ppm.



- Indoor carbon dioxide is within the ASHRAE recommended range for acceptable indoor air.

3



# HOW TO IMPROVE THE HEALTH OF MY HOME

-  Overall, the indoor air quality is good. Keep up the habits for healthy indoor air.
-  Increase ventilation when cooking.
-  Reduce or eliminate the use of air fresheners or strongly scented products indoors.
-  Use a HEPA-enabled vacuum cleaner.
-  Close windows if you notice ambient air pollution levels are high or traffic is heavy.
-  Installing a portable air cleaner that is properly sized for the space could further improve indoor air quality.

## Principles to improve indoor air quality -- "KEEP IT PRINCIPLE"

-  Keep it Dry
-  Keep it Well-Ventilated
-  Keep it Clean
-  Keep it Contaminant-Free
-  Keep it Safe
-  Keep it Maintained
-  Keep it Pest-Free
-  Keep it Thermally Controlled

This work is funded by National Institutes of Health and conducted by Colorado State University.




APPENDIX D: ALL RECOMMENDATIONS DATABASE

Recommendations for PM<sub>2.5</sub>


# PM<sub>2.5</sub>


- Indoor fine particulate matter is lower than the EPA annual outdoor air standard (9 µg/m<sup>3</sup>).
- Your indoor fine particulate matter is lower than the EPA 24-h outdoor air standard (35 µg/m<sup>3</sup>).
- Actions to control indoor fine particulate matter are encouraged.
- Indoor fine particulate matter exceeds the EPA 24-h outdoor air standard (35 µg/m<sup>3</sup>).
- Actions to mitigate indoor fine particulate matter levels are strongly encouraged.

 Turn on your stove hood while cooking.


 Only smoke or vape outdoors.


 Limit use of candles or incense indoors.


 Installing a portable air cleaner that is properly sized for the space could further improve indoor air quality.


 Install a filter in your home furnace/AC system with a rating of MERV-13 or higher.


 Hire a professional (like an HVAC contractor) to clean your vents.

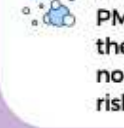
 Use a HEPA-enabled vacuum cleaner.

 Reduce or eliminate the use of candles, incense, or strongly scented products indoors.

 Increase ventilation when cooking, for example, add an exhaust fan that vents to the outside.

 Your home's PM<sub>2.5</sub> measurements appear higher partly due to tiny water droplets from your humidifier.

 Reduce or eliminate the use of air fresheners or strongly scented products indoors.

 These water-based particles are anticipated to be less harmful than PM<sub>2.5</sub> from other sources, so while the reading may be elevated, it may not indicate the same level of health risk.

## Recommendations for NO<sub>2</sub>








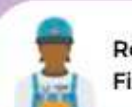


# NO<sub>2</sub>

- Indoor nitrogen dioxide is lower than the EPA annual outdoor air standard (53 ppb).
- Indoor nitrogen dioxide is lower than the EPA 1-h outdoor air standard (100 ppb).
- Actions to control indoor nitrogen dioxide are encouraged.
- Indoor nitrogen dioxide exceeds the EPA 1-h outdoor air standard (100 ppb).
- Actions to mitigate indoor nitrogen dioxide levels are strongly encouraged.

**Comments**

**Comments**

**Comments**

-  Do not idle cars in the garage.
-  Only smoke or vape outdoors.
-  Increase ventilation when cooking.
-  Improve ventilation near gas stoves with an exhaust fan that vents to the outside.
-  You may consider yearly inspections and maintenance for central heating (furnaces, flues, chimneys).
-  Open flues when using gas fireplaces.
-  Use proper fuel in your kerosene space heater.
-  Replace old vented appliances. Fix any leaks promptly.
-  Select appropriately sized and EPA-certified stoves. Ensure tight-fitting stove doors.
-  Increase ventilation when using a gas heater.

## Recommendations for CO<sub>2</sub>

# CO<sub>2</sub>

- Indoor carbon dioxide is within the ASHRAE recommended range for acceptable indoor air.

- Indoor carbon dioxide is within the ASHRAE recommended range for acceptable indoor air, but elevated.
- Actions to control indoor carbon dioxide are encouraged.

- Indoor carbon dioxide exceeds the ASHRAE recommended range for acceptable indoor air.
- Actions to control indoor carbon dioxide are strongly encouraged.

Comments

Comments

Comments



Improve ventilation when hosting guests or with a crowd at home.



Install a standalone or window fan to increase ventilation in crowded rooms.



Close windows if you notice ambient air pollution levels are high or traffic is heavy.



Increasing ventilation when cooking, for example, with an exhaust fan that vents to the outside, can further improve indoor air quality.



Overall, the indoor air quality is good. Keep up the habits for healthy indoor air.



Based on your response to the follow-up survey, not using candles or incense may have supported healthy indoor air.

Continue to reduce or eliminate the use of candles, incense, or strongly scented products indoors.



To address elevated CO<sub>2</sub>, continue increasing ventilation when hosting guests or with a crowd at home.

For example,

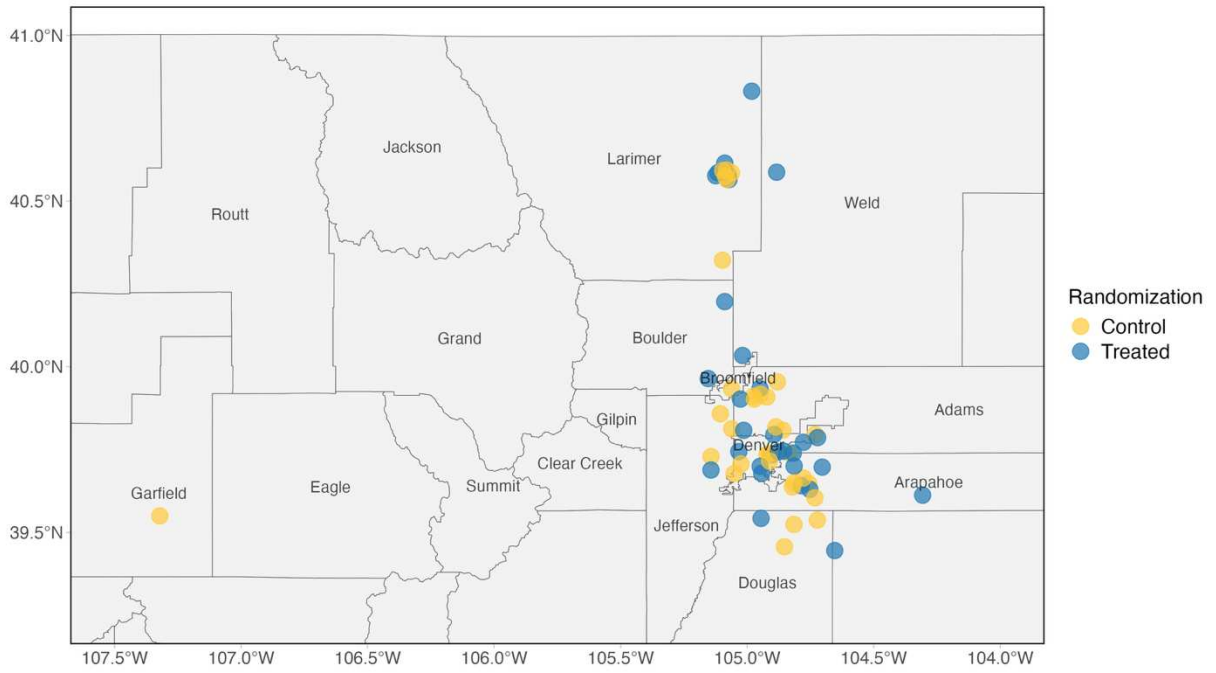
- open windows or turn on exhaust fans;
- install a standalone or window fan.



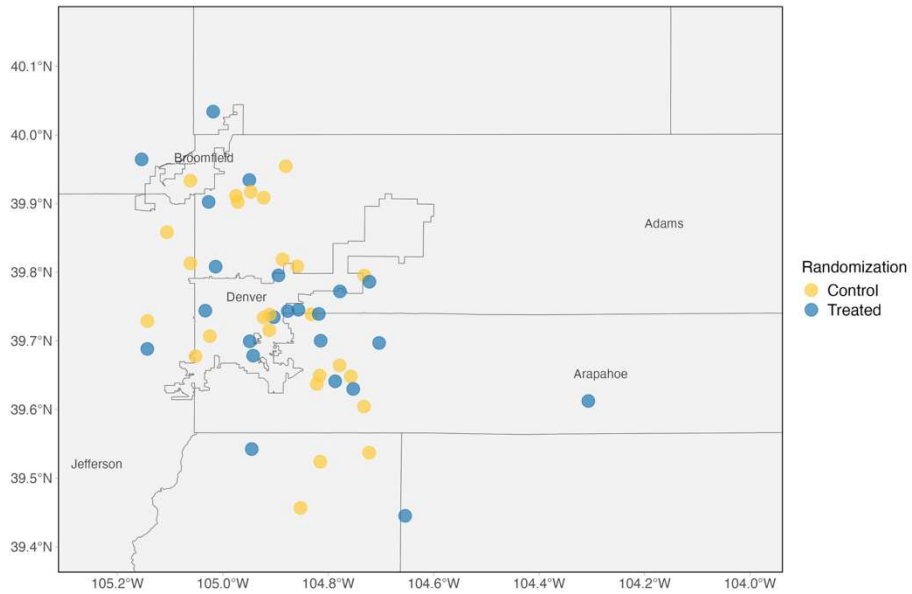
# APPENDIX E: PARTICIPANT MAPS

## Colorado Participant Maps

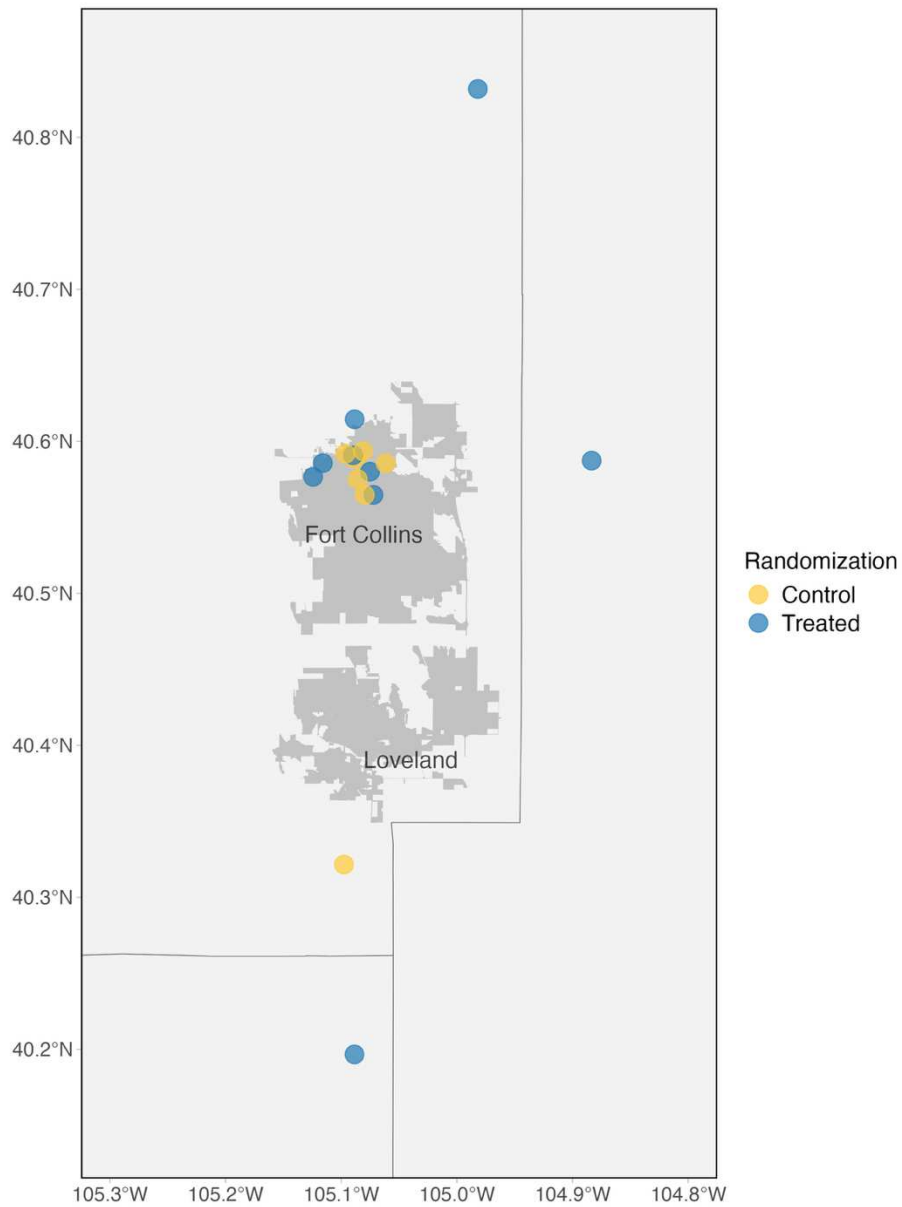
### Colorado Households



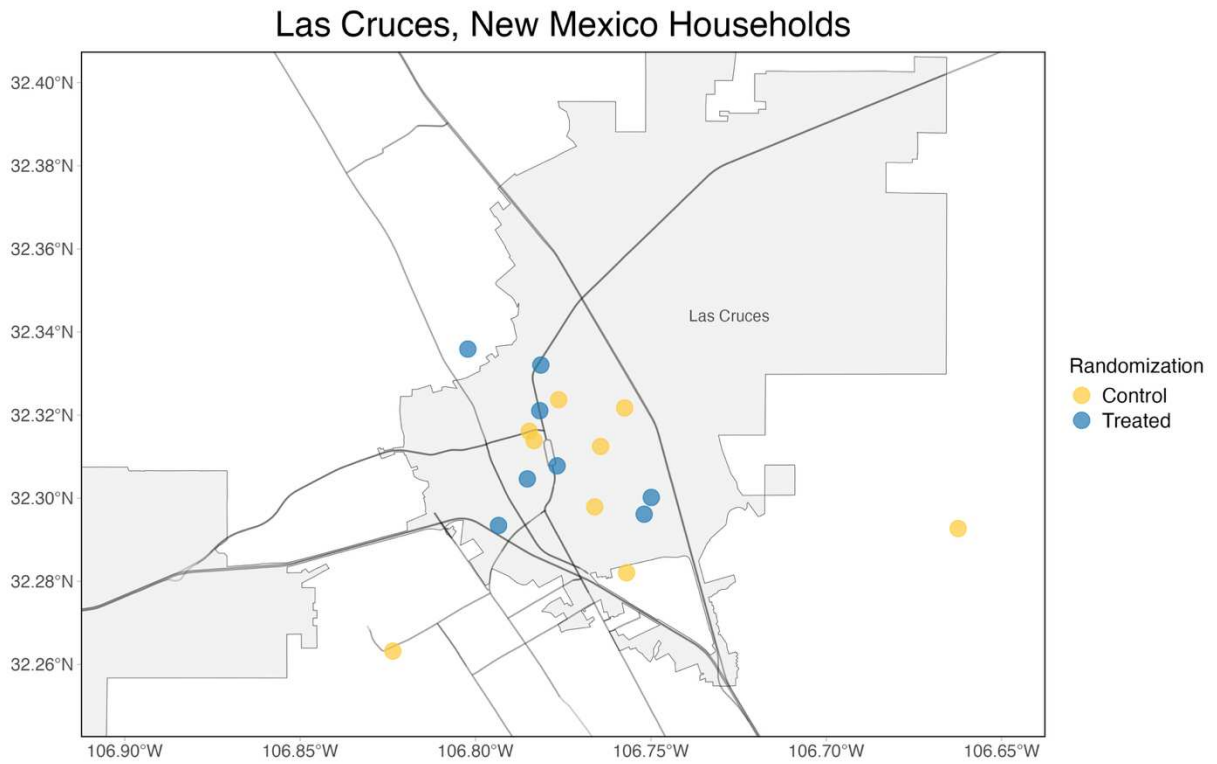
### Denver-Area Households



# Northern Colorado Households



## Las Cruces, New Mexico Participant Maps



## APPENDIX F: VOLATILE ORGANIC COMPOUND DATASET

