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Journal

ACS ES&T Air, 3(2)

ISSN

2837-1402

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Publication Date

2026-02-13

DOI

10.1021/acsestair.5c00277

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Evaluation of Smoke Exposure Risk from January 2025 Los Angeles Wildfires Using Crowdsourced Data

Published as part of ACS ES&T Air *special issue* “The 2025 Los Angeles Fires”.

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Cite This: ACS EST Air 2026, 3, 373–384



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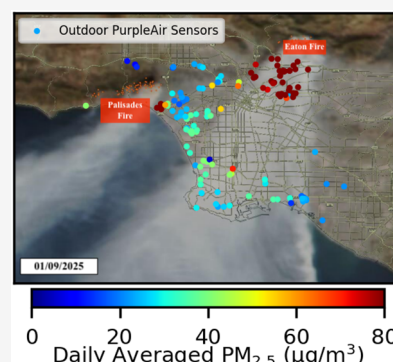
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ABSTRACT: Wildfire smoke is an increasingly significant contributor to air pollution in the western United States, posing serious health risks and complicating efforts to assess personal exposure, particularly indoors. The January 2025 Palisades and Eaton Fires in Los Angeles County caused elevated levels of $\text{PM}_{2.5}$ in the downwind cities. This study leverages a high-resolution network of crowdsourced PurpleAir sensors to evaluate indoor and outdoor $\text{PM}_{2.5}$ levels before, during, and after the wildfire smoke events. We matched indoor–outdoor sensors and analyzed disparities in smoke exposure across communities with different CalEnviroScreen (CES) vulnerability scores, ventilation types, and home values. Results indicate that outdoor $\text{PM}_{2.5}$ increased substantially during smoke days, with the highest CES-burdened communities experiencing the greatest ambient concentrations. Indoor $\text{PM}_{2.5}$ also increased across all neighborhoods but indoor/outdoor (I/O) ratios declined during the smoke period, indicating partial indoor protection and likely occupant behavior changes. Infiltrated $\text{PM}_{2.5}$ increased during the smoke period and varied across the CES groups. Building attributes showed limited predictive power. These findings highlight the interplay between behavioral actions and neighborhood factors in shaping wildfire smoke exposure and underscore the need for targeted interventions to improve indoor air quality in vulnerable communities.

KEYWORDS: wildfire, Los Angeles, smoke, particulate matter, sensors, exposure risk



1. INTRODUCTION

Wildfires have been a long-standing and frequent threat to California. As climate change progresses, wildfires are expected to increase in intensity and frequency in the future.^{1–3} It is reported that the fire season in the western United States starts earlier, lasts longer, and is more intense than in the last several decades.⁴ Wildfire occurrence statewide could increase several-fold by the end of the century, increasing fire suppression and emergency response costs and damage to property.⁵

Wildfires are significant sources of air pollution, emitting large quantities of fine particulate matter ($\text{PM}_{2.5}$), along with gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs).^{6,7} These emissions resulting from biomass combustion can vary depending on the fuel type, fire intensity, and weather conditions. Wildfire smoke can travel long distances, degrade the air quality, and pose serious health risks.^{2,8,9} Additionally, the emitted NO_x and VOCs contribute to secondary ozone and secondary organic aerosol formation downwind.^{10,11}

Despite long-term reduction efforts in anthropogenic emissions, wildfire smoke has emerged as a dominant and unpredictable pollution source, leading to spikes in pollutant levels that exceed U.S. National Ambient Air Quality Standards (NAAQS).^{12,13} These episodic events can counteract years of air

quality gains, especially in the western U.S., where wildfire seasons have grown longer and more intense due to climate change.¹⁴ As a result, regulatory agencies face growing challenges in maintaining healthy air quality and protecting public health.

Several recent studies have examined indoor–outdoor $\text{PM}_{2.5}$ relationships during wildfire smoke episodes, demonstrating that wildfire-derived $\text{PM}_{2.5}$ readily penetrates indoors and that the indoor concentration can remain elevated during smoke events. For example, Krebs et al. computed large-scale analyses using PurpleAir sensors and found an increase in indoor infiltration of wildfire smoke but disproportionately so in lower-income areas.¹⁵ Another work has further highlighted socioeconomic disparities in indoor exposure during wildfire events, showing that indoor $\text{PM}_{2.5}$ increases more rapidly with outdoor smoke in lower-income communities.¹⁶

Received: July 21, 2025

Revised: January 17, 2026

Accepted: January 20, 2026

Published: January 30, 2026



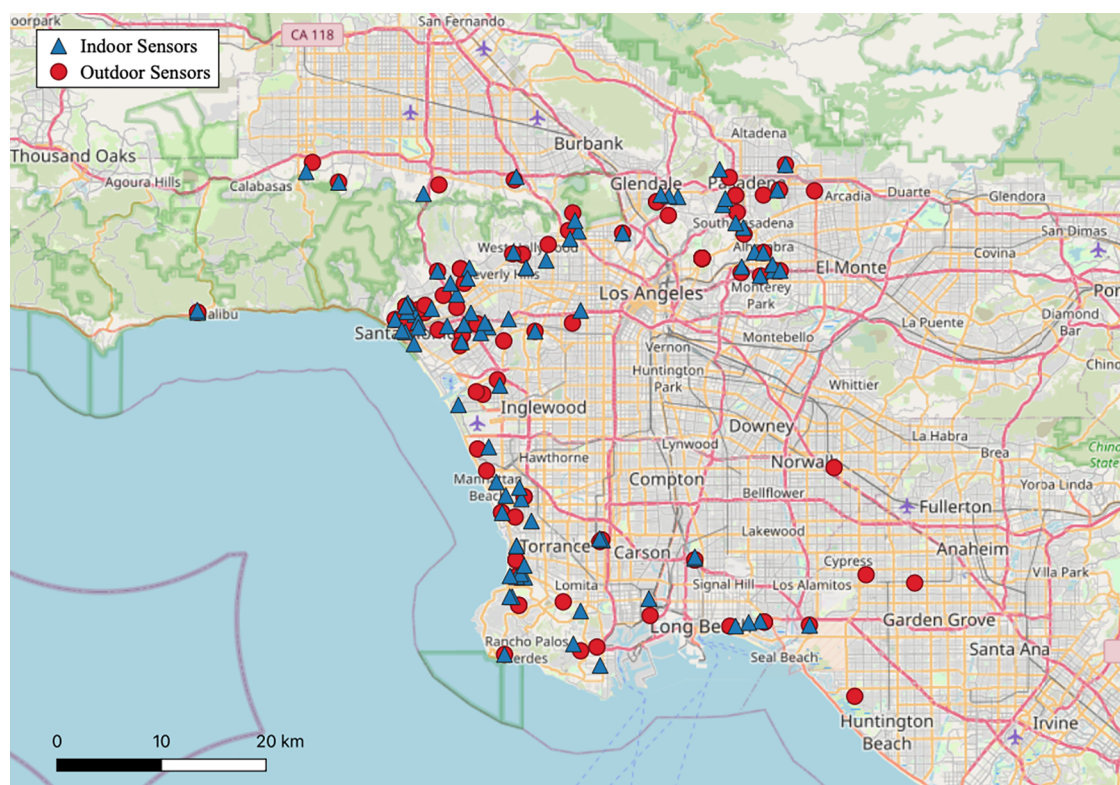


Figure 1. Spatial distribution of PurpleAir sensors used in the study across the Los Angeles region. Red circles represent outdoor sensors ($N = 114$) and blue triangles represent indoor sensors ($N = 95$).

In January 2025, Los Angeles (LA) County experienced a series of devastating wildfires, notably the Eaton Fire in Altadena and the Palisades Fire in Pacific Palisades.^{17,18} These fires, driven by severe Santa Ana winds and prolonged drought conditions, burned over 57,000 acres combined and resulted in substantial economic losses and widespread health impacts.^{19,20} The fires lasted from January 7 to January 31, making this one of the most destructive wildfire events in the region's history.²¹

The wildfires had a significant impact on air quality in the Los Angeles region. Smoke from the fires led to hazardous levels of $\text{PM}_{2.5}$, far above the U.S. Environmental Protection Agency's (EPA) health-safety threshold of $35 \mu\text{g}/\text{m}^3$.^{22–24} This deterioration in air quality poses serious health risks, particularly for individuals with respiratory ailments.²⁵

Assessing exposure to wildfire smoke presents several challenges. Traditional air quality monitoring networks may not capture localized variations in pollutant concentrations, especially in indoor environments where people spend most of their time.^{26–29} Additionally, the composition of wildfire smoke is chemically complex, and it can infiltrate homes and persist long after the fires are extinguished.³⁰ These factors complicate efforts to characterize individual exposure levels and assess the associated health risk.

Crowdsourced PurpleAir data offer a valuable opportunity to address the gaps in understanding personal exposure levels during wildfire events like the recent LA wildfires.^{31,32} Unlike traditional regulatory monitors, which are sparse and often miss localized pollution spikes, PurpleAir sensors are densely distributed and include both indoor and outdoor locations, allowing for higher-resolution spatial and temporal tracking of $\text{PM}_{2.5}$ concentrations.³³ This granularity is especially important during wildfire smoke events, when pollutant levels can vary dramatically over short distances and time scales.

In this analysis, we leverage crowdsourced PurpleAir data to examine personal exposure risks before (January 3–7), during (January 8–10), and after (January 11–31) the LA wildfire in neighborhoods with various socioeconomic levels. By analyzing this network of real-time measurements, we aim to better understand how wildfire smoke infiltrates indoor environments and affects individual exposure, ultimately informing more targeted public health responses and protective measures.

2. DATA AND METHODS

2.1. Study Location and Data Sources

The study area for this research encompasses the greater Los Angeles area, as shown in Figure 1, which includes a dense and diverse distribution of both indoor (blue triangles) and outdoor (red circles) PurpleAir sensors. This network of sensors provides higher spatial and temporal resolution $\text{PM}_{2.5}$ data, enabling a more localized assessment of air quality conditions across neighborhoods that may be differentially affected by wildfire smoke. The data used in this study are sourced from the publicly accessible PurpleAir network, focusing on the hourly and daily average $\text{PM}_{2.5}$ concentration. For this study, only sensors with complete monthly hourly averaged $\text{PM}_{2.5}$ measurements for January 2025 were included, resulting in a total of 95 indoor sensors and 114 outdoor sensors. This sensor network allows us to capture indoor–outdoor differences and temporal trends in $\text{PM}_{2.5}$ exposure before, during, and after the LA wildfires. In addition, this study supports a more refined understanding of personal exposure risk across the region.

2.2. Quality Assurance (QA) for PurpleAir Data

PurpleAir PA-II monitors contain two Plantower PMS5003 sensors (channels A and B). To ensure consistent performance between redundant channels, we applied QA criteria based on Plantower's recommended sensor agreement thresholds. For observation with “cf_1” $\text{PM}_{2.5} < 100 \mu\text{g}/\text{m}^3$, we removed records where the absolute difference between channels A and B exceeded $10 \mu\text{g}/\text{m}^3$. For observations with “cf_1” $\text{PM}_{2.5} \geq 100 \mu\text{g}/\text{m}^3$, we removed records

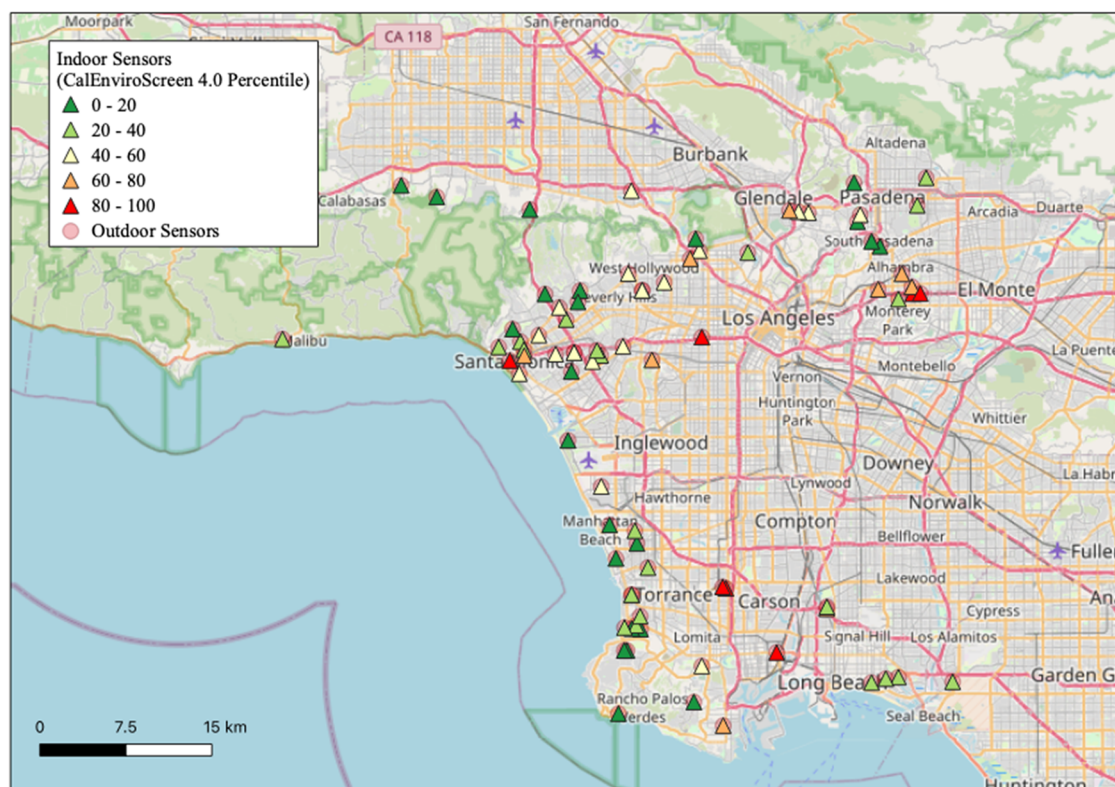


Figure 2. Spatial distribution of indoor and outdoor PurpleAir sensors that are less than 1.5 miles apart in the Los Angeles region categorized by CalEnviroScreen 4.0 percentile scores. Indoor sensors are indicated by triangles. Outdoor sensors are shown as light red circles.

where the percent difference between the two channels exceeded 10%. These QA steps were applied after filtering observations outside the Plantower-specified operating ranges for $\text{PM}_{2.5}$ (0–500 $\mu\text{g}/\text{m}^3$), temperature (14–140 $^{\circ}\text{F}$), and relative humidity (0–99%). This procedure ensured that only observations with stable agreement between the redundant channels were retained.

2.3. Correction of PurpleAir $\text{PM}_{2.5}$ Measurements

For outdoor sensors, PurpleAir $\text{PM}_{2.5}$ data were obtained from the EPA AirNow Fire & Smoke Map, which applies a standardized U.S.-wide correction prior to public release. This correction is based on the widely used method developed by Barkjohn et al.,³⁵ including quality-control filtering of A/B channels and a humidity-dependent adjustment to the PurpleAir cf_1 measurement. The EPA applies the Barkjohn et al. correction for concentrations $\leq 343 \mu\text{g}/\text{m}^3$ (eq 1). For concentrations $> 343 \mu\text{g}/\text{m}^3$, the EPA applies a quadratic fit extension (eq 2) to improve the performance under extreme wildfire smoke conditions.³⁴ Because the AirNow data set already includes this validated correction framework, no additional calibration was applied in this study.

Indoor $\text{PM}_{2.5}$ concentrations were obtained directly from the indoor PurpleAir sensors. We applied a generalized correction equation developed by Barkjohn et al. (eq 1).³⁵ In this equation, $\text{PM}_{2.5}$ represents the corrected concentration, PA denotes the average raw $\text{PM}_{2.5}$ concentration from PurpleAir channels A and B, and RH refers to relative humidity. For this study, we used the $\text{PM}_{2.5\_cf\_1}$ data stream, as recommended by Barkjohn et al.³⁵

$$\text{PM}_{2.5} = 0.524 \times \text{PA}_{cf\_1} - 0.086 \times \text{RH} + 5.75 \quad (1)$$

$$\text{PM}_{2.5} = 0.46 \times \text{PA}_{cf\_1} + 3.93 \times 10^{-4} \times \text{PA}_{cf\_1}^2 + 2.97 \quad (2)$$

2.4. Sensor Grouping and Pollution Burden Distribution

To examine disparities in smoke exposure across communities, we categorized residential indoor PurpleAir sensors based on CalEnviroScreen 4.0 percentile scores, which represent cumulative environmental and socioeconomic burdens. For each indoor sensor, we identified its nearest outdoor PurpleAir sensor and paired the two as an

indoor–outdoor pair, provided that the nearest outdoor sensor was located within a 1.5-mile radius (Figure 2). This nearest-sensor approach ensures consistent and spatially representative matching across sensor locations.

We evaluated the sensitivity of this distance threshold by repeating the pairing procedure with a more restrictive 1000 m cutoff. From SI Figure A2 and A3, we found the regression results for the 1000 m and 1.5-mile sensor pairing approaches show highly comparable model performance, indicating that expanding the maximum indoor–outdoor matching radius does not degrade the accuracy of the infiltration factor estimation.

Under the 1000 m threshold, the number of valid indoor–outdoor pairs decreased substantially, from 81 pairs at 1.5 miles (Figure 2) to 42 pairs at 1000 m (SI Figure A1). This leads to a reduced representation of sensors located in more environmentally impacted areas. To maintain an adequate sample size and preserve spatial coverage across all CalEnviroScreen percentile groups, we retained the 1.5-mile radius for the final analysis.

We divided indoor and outdoor sensor groups into five percentile groups to examine the wildfire impact across various communities. In this study, a lower percentile (e.g., 0–20) indicates communities with relatively lower environmental and socioeconomic burdens, while a higher percentile (e.g., 80–100) represents communities facing the greatest combined risks from pollution exposure, health vulnerabilities, and socioeconomic disadvantages. We identified 23 indoor and outdoor sensor pairs in areas falling within the 0–20th percentile range. For areas at 20–40th percentiles, we identified 23 indoor and outdoor sensor pairs. For areas at 40–60th percentiles, we identified 19 indoor and outdoor sensor pairs. For areas at 60–80th percentiles, we identified 9 indoor and outdoor sensor pairs. For areas at 80–100th percentiles, we identified 7 indoor and outdoor sensor pairs.

2.5. Determining Fire Dates and Wildfire Impact

To determine the smoke-impacted days during the LA Fires event, we used satellite imagery and ground-based air quality data analyses. Visual inspection of NASA Worldview satellite images was conducted to

identify the presence and transport of wildfire smoke plumes over the Los Angeles region (SI Figure B).³⁶ In parallel, we analyzed daily average PM_{2.5} concentrations from the California Air Resources Board's Air Quality and Emissions Resources (AQMIS) database, focusing on the highest daily average values recorded across all monitoring sites in Los Angeles County during January 2025.³⁷ Days after January 7, when the PM_{2.5} concentrations exceeded the U.S. EPA 24-h standards of 35 $\mu\text{g}/\text{m}^3$, they were flagged as smoke-impacted (SI Figure C). Meteorological conditions such as temperature, wind speed, and precipitation are also considered to evaluate smoke and nonsmoke days (SI Figure D). Based on this combined approach, January 8–10 was identified as the smoke episode, with both visible smoke coverage and elevated PM_{2.5} levels, indicating significant wildfire smoke exposure in the region.

2.6. Building-Characteristics Identification

To evaluate how building-level features may influence indoor air quality during wildfire smoke events, we characterized ventilation systems and housing attributes for indoor sensor locations. Using the latitude and longitude of each indoor PurpleAir sensor, we performed reverse geocoding to obtain the corresponding street addresses. All identified addresses were manually reviewed to ensure that only residential properties were included in this study.

Because detailed building metadata (e.g., ventilation type, presence of central air, building age, and price per square foot) are consistently available only for single-family residences, we restricted the building-characteristics analysis to single-family homes (Section 3.3). For these properties, we queried publicly available real-estate platforms (Zillow and Redfin) to extract ventilation information and price per square foot (sqft), which served as a proxy for the building quality.

It is important to note that for CES analysis (Section 3.2), we retained all residential building types, including single-family homes, apartments, and other multifamily units. These analyses rely solely on measured indoor and outdoor PM_{2.5} concentrations and, therefore, do not require building-level metadata.

SI Figures E and F show the locations of indoor-outdoor sensor pairs categorized by the home ventilation type and price per square foot. In this study, we identified 27 homes with mechanical ventilation systems and 12 homes with only natural ventilation systems (SI Figure E). Based on the home price analysis, 28 homes had a price per square foot below \$1000, while 17 homes exceeded \$1000 per square foot (SI Figure F).

2.7. Indoor/Outdoor Ratio

The indoor/outdoor (I/O) ratio is used to assess the relative concentration of PM_{2.5} indoors compared to that outdoors and provides a broad indication of how indoor environments respond to both ambient pollution and indoor emission activities. It is calculated by dividing the average indoor PM_{2.5} concentration by the corresponding average outdoor PM_{2.5} concentration using matched hourly averaged data. In this study, the I/O ratio was calculated using full indoor time series, allowing the metric to capture the full range of indoor concentration dynamics, including periods influenced by indoor emission events. This method is used to evaluate overall indoor exposure conditions across communities during pre-smoke, smoke, and post-smoke conditions.

2.8. Infiltration Factors and Infiltration Ratios

To minimize the influence of indoor source emissions, we first compared indoor and outdoor concentrations and removed all indoor observations in which indoor PM_{2.5} exceeded the concurrent outdoor level. Because infiltration-driven indoor PM_{2.5} is expected to remain below outdoor concentrations, this screening step effectively excludes periods dominated by indoor activities (e.g., cooking or smoking) and retains observations most representative of infiltration processes.

Following this filtering, we estimated infiltration factors using a linear regression between indoor and outdoor PM_{2.5} concentrations, consistent with approaches recommended in the literature for separating indoor and outdoor contributions.³⁸ For each indoor–outdoor sensor pair, we fit the model

$$C_{\text{indoor}} = F_{\text{inf}}C_{\text{outdoor}} + \beta$$

where F_{inf} represents the infiltration factor and β captures the contribution from indoor sources or baseline indoor PM_{2.5} not directly explained by outdoor concentrations. This regression-based approach provides two key advantages for this study: (1) the slope F_{inf} quantifies the proportion of outdoor smoke that penetrates indoors under different conditions and (2) the intercept β provides an estimate of indoor emissions that may not be fully removed through peak-screening alone.

To ensure reliable estimation, regressions were conducted only for sensor pairs with sufficient overlap in valid indoor and outdoor observations after data cleaning. The resulting infiltration factor F_{inf} was used in all subsequent analyses. This method enhances the interpretability of infiltration estimates and improves the consistency with established PM_{2.5} infiltration modeling approaches.

In contrast, the infiltration ratio, described in section 3.3, refers to the ratio of indoor PM_{2.5} of outdoor origin to outdoor PM_{2.5}. This metric provides a straightforward comparison of indoor and outdoor concentrations but does not separate the infiltration processes from indoor removal or residual sources. The infiltration ratio is interpreted as a descriptive indicator of indoor exposure conditions rather than a direct mechanistic measure of building infiltration.

3. RESULTS AND DISCUSSION

3.1. Indoor and Outdoor PM_{2.5} on Nonsmoke and Smoke Days

Figure 3a,b shows the spatial distribution of daily averaged outdoor PM_{2.5} concentrations across the Los Angeles region from PurpleAir sensors on two dates: January 5, 2025 (before wildfire impact) and January 9, 2025 (during the wildfire event). On January 5, PM_{2.5} levels across the region were relatively low, with most sensors reporting values below 20 $\mu\text{g}/\text{m}^3$, indicating normal urban background air quality conditions in this region.

In contrast, by January 9, there was a dramatic increase in PM_{2.5} concentrations, particularly in areas downwind of the Palisades Fire and Eaton Fire, where many sensors recorded values exceeding 60 $\mu\text{g}/\text{m}^3$ (red shades), far above the EPA 24-hour standard of 35 $\mu\text{g}/\text{m}^3$. The satellite background shows a visible smoke plume over the coastal and central LA, confirming widespread smoke transport. This comparison clearly illustrates the severe impact of wildfire smoke on air quality, with elevated PM_{2.5} levels concentrated near the fire locations and expanding across densely populated areas.

To complement the outdoor PM_{2.5} analysis, we also examined indoor air quality patterns during the same period to assess the extent of smoke infiltration into indoor environments. Figure 4a,b displays daily averaged indoor PM_{2.5} concentrations measured by PurpleAir sensors in the Los Angeles region on January 5, 2025 and January 9, 2025, which are before and during the LA Fires event. On January 5, indoor PM_{2.5} levels were generally low across the region, indicating typical indoor air quality conditions.^{28,39}

By January 9, despite widespread outdoor smoke transport visible in the satellite imagery, indoor PM_{2.5} levels remained relatively low across most sensor locations. While outdoor air quality was likely severely degraded in plume-impacted areas, a majority of indoor sensors still reported PM_{2.5} concentrations below 30 $\mu\text{g}/\text{m}^3$. This suggests that many buildings provided effective barriers against immediate smoke infiltration, potentially due to closed windows, air filtration use, or limited air exchange.

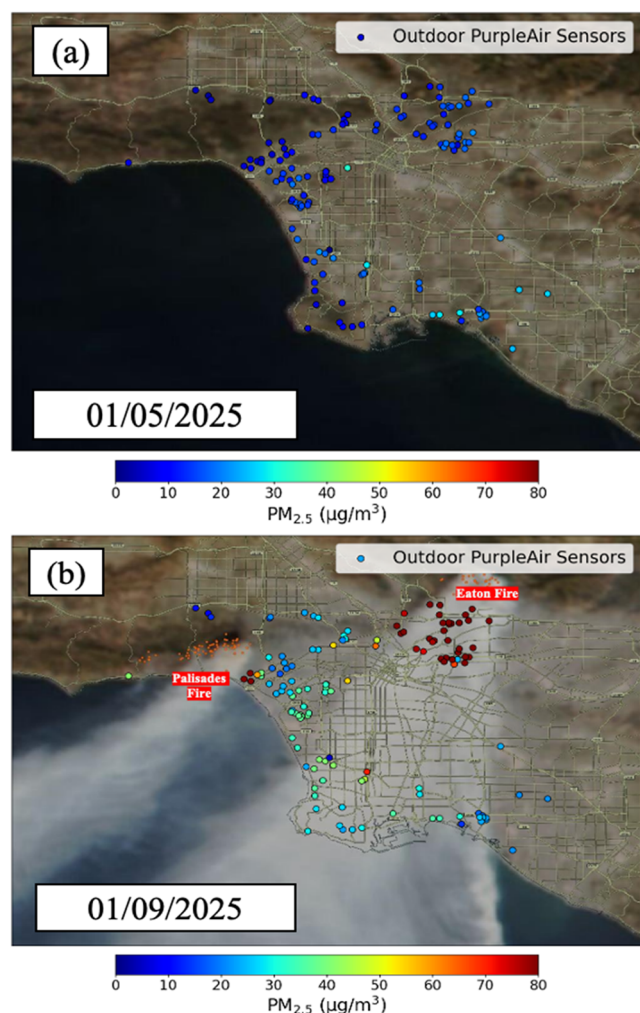


Figure 3. Outdoor $\text{PM}_{2.5}$ concentrations across the Los Angeles region before and during the 2025 wildfire event. (a) Relatively low $\text{PM}_{2.5}$ levels on January 5, 2025, prior to the wildfire impact. (b) Significant increase in $\text{PM}_{2.5}$ concentrations across the region, particularly downwind of the Palisades and Eaton fires.

3.2. Neighborhood Variability of $\text{PM}_{2.5}$, Indoor/Outdoor Ratio, and Infiltration during Pre-smoke, Smoke, and Post-smoke Conditions

Indoor and outdoor $\text{PM}_{2.5}$ concentrations, as well as I/O ratios, varied substantially across CalEnviroScreen (CES) percentile categories and smoke periods (Figures 5, 6, 7). Across all CES groups, wildfire smoke led to significant increases in both indoor and outdoor $\text{PM}_{2.5}$, with disproportionate impacts observed in more environmentally burdened communities.

During the smoke period, indoor $\text{PM}_{2.5}$ concentrations increased by approximately 2–3 times relative to pre-smoke levels across all CES categories (Figure 5). The highest CES burden group (80–100th percentile) experienced the greatest indoor concentrations, with medians nearly double those in the lowest CES group. In contrast, indoor $\text{PM}_{2.5}$ levels before and after the smoke event remained relatively low and stable across CES categories, returning to pre-smoke conditions shortly after the event subsided.

Outdoor $\text{PM}_{2.5}$ levels displayed even stronger gradients across the CES groups (Figure 6). During smoke days, outdoor concentrations reached substantially higher values than indoors, with medians often exceeding $40 \mu\text{g}/\text{m}^3$ in the upper CES

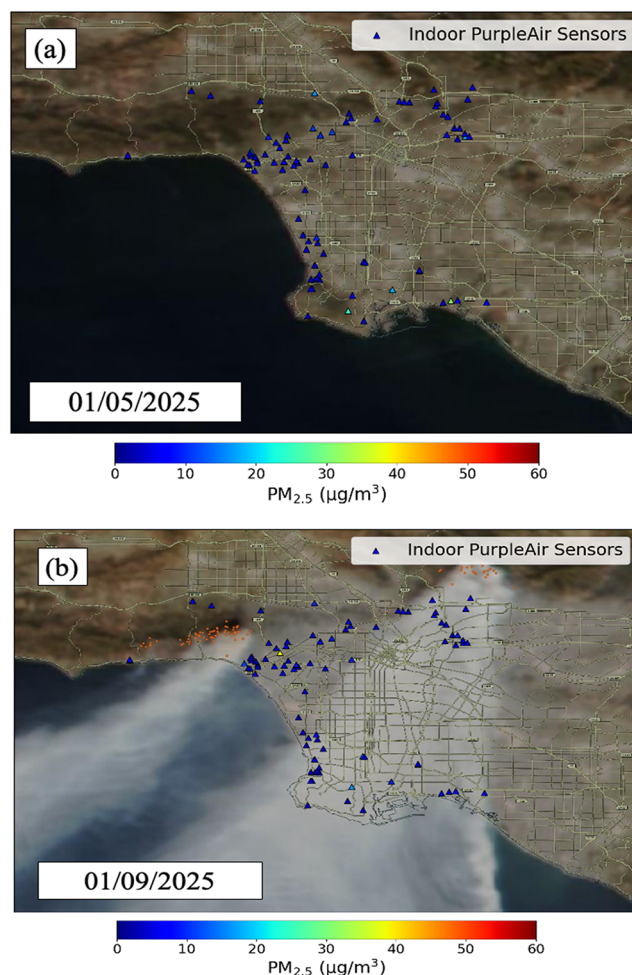


Figure 4. Indoor $\text{PM}_{2.5}$ concentrations across the Los Angeles region before and during the January 2025 LA Fires event. (a) Indoor air quality on January 5, 2025, with low $\text{PM}_{2.5}$ across most locations. (b) Increased indoor $\text{PM}_{2.5}$ concentrations in some of the indoor environments on January 9, 2025, during active wildfire smoke transport from the fires.

percentile categories and maxima surpassing $120 \mu\text{g}/\text{m}^3$. These outdoor concentrations increased systematically with an increasing CES percentile, indicating that more environmentally burdened communities were subjected to more intense ambient smoke exposure. Pre-smoke and post-smoke outdoor levels remained comparatively low and consistent across all CES groups.

I/O ratios revealed additional insights into indoor protection and pollutant dynamics (Figure 7). Pre-smoke ratios typically ranged from 0.6 to 0.8. During the smoke period, ratios decreased across all CES categories (median ~ 0.3 – 0.5), reflecting the disproportionately larger rise in outdoor concentrations relative to indoor levels, indicating that indoor environments provided partial protection during peak smoke conditions. Post-smoke ratios increased above both pre-smoke and smoke-period values, frequently exceeding 0.8–1.0, suggesting slower indoor clearance of particles or increased indoor emission events compared with the rapid decline in outdoor $\text{PM}_{2.5}$ after the event.

Indoor–outdoor $\text{PM}_{2.5}$ infiltration relationships were evaluated across five CalEnviroScreen (CES) categories for the periods before, during, and after the LA Fires event (Figure 8A–

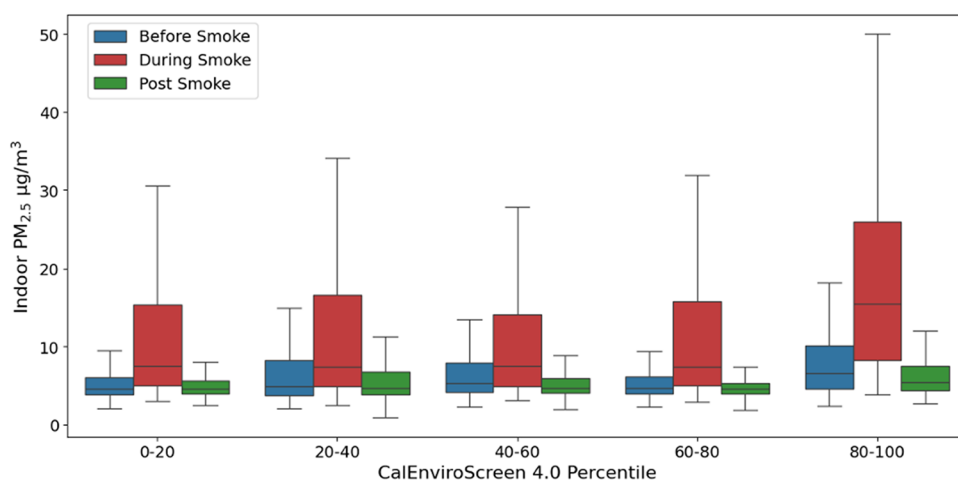


Figure 5. Indoor $\text{PM}_{2.5}$ concentrations by CalEnviroScreen percentile category and smoke period. Boxes show the interquartile range with median values, and whiskers represent the 5th–95th percentiles.

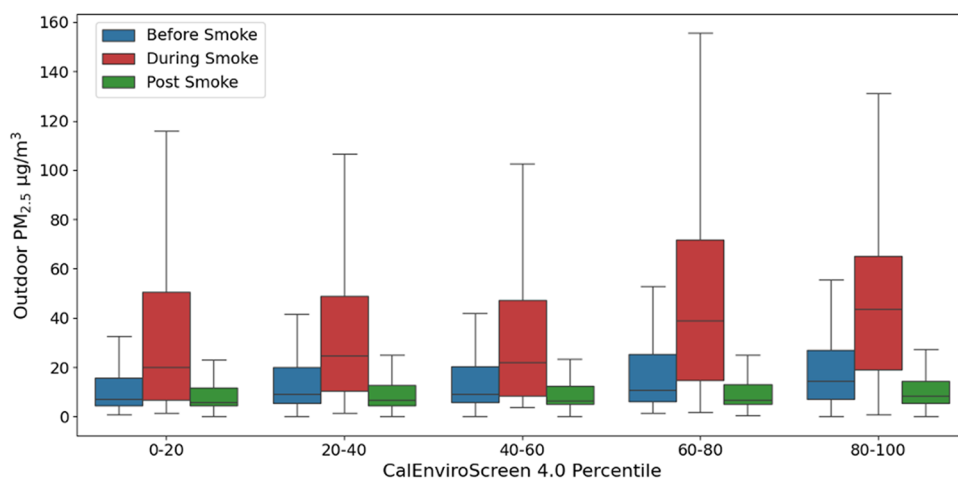


Figure 6. Outdoor $\text{PM}_{2.5}$ concentrations by CalEnviroScreen percentile category and smoke period. Boxes show the interquartile range with median values, and whiskers represent the 5th–95th percentiles.

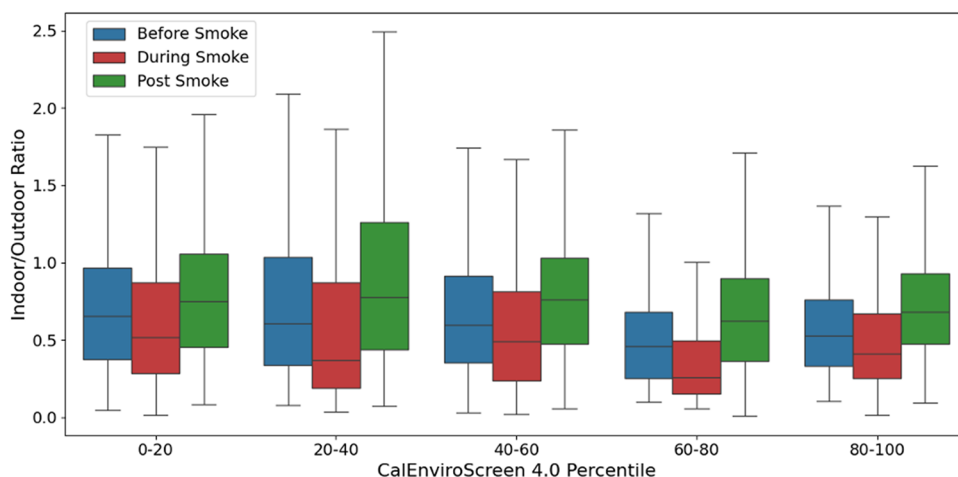


Figure 7. Indoor/outdoor (I/O) ratios by CalEnviroScreen percentile category and smoke period. Boxes show the interquartile range with median values, and whiskers represent the 5th–95th percentiles.

C). Indoor emission peaks were removed prior to analysis; thus, the resulting indoor $\text{PM}_{2.5}$ measurements primarily represent infiltration-driven concentrations. Prior to the fire, indoor $\text{PM}_{2.5}$ showed a modest positive association with outdoor $\text{PM}_{2.5}$ across

all CES percentile categories (Figure 8A). Infiltration slopes fell within a narrow range (0.11–0.20), suggesting relatively consistent particle penetration efficiency under non-smoke winter conditions. Regression intercepts were low (2.7–4.3 $\mu\text{g}/$

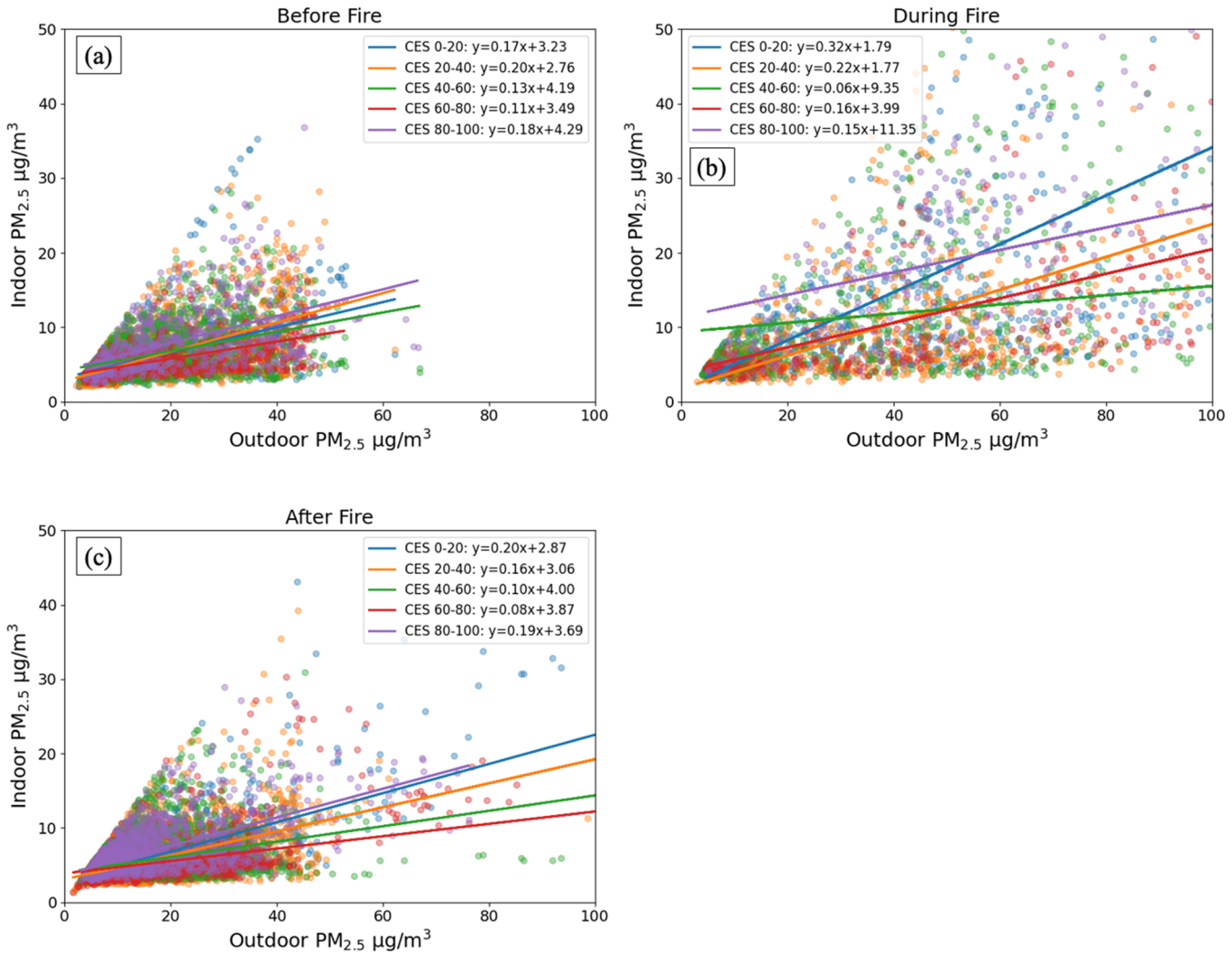


Figure 8. (A–C) Indoor vs outdoor $\text{PM}_{2.5}$ concentrations for five CalEnviroScreen percentile categories before, during, and after the wildfire smoke event. Indoor emission peaks were removed prior to analysis. Linear regression lines illustrate infiltration behavior across CES groups.

Table 1. Mean and Standard Deviation (Mean $\pm$ SD) of Outdoor and Indoor $\text{PM}_{2.5}$ Concentrations, Indoor/Outdoor (I/O) Ratios, and Infiltration Concentrations across CalEnviroScreen (CES) Categories before, during, and after the Wildfire Smoke Event

CES	mean outdoor concentration ($\mu\text{g}/\text{m}^3$)			mean indoor concentration ($\mu\text{g}/\text{m}^3$)			indoor/outdoor ratio			mean infiltrated concentration ($\mu\text{g}/\text{m}^3$)		
	mean $\pm$ SD			mean $\pm$ SD			mean $\pm$ SD			mean $\pm$ SD		
	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke
0–20	12 $\pm$ 15	42 $\pm$ 58	9 $\pm$ 9	6 $\pm$ 4	17 $\pm$ 27	5 $\pm$ 4	0.8 $\pm$ 0.7	0.7 $\pm$ 0.9	1.2 $\pm$ 3.3	6 $\pm$ 3	20 $\pm$ 32	5 $\pm$ 3
20–40	14 $\pm$ 12	42 $\pm$ 59	10 $\pm$ 11	9 $\pm$ 16	17 $\pm$ 28	9 $\pm$ 14	1.2 $\pm$ 3.7	1.3 $\pm$ 7.3	2.0 $\pm$ 41.6	6 $\pm$ 4	14 $\pm$ 22	5 $\pm$ 3
40–60	14 $\pm$ 14	37 $\pm$ 51	10 $\pm$ 8	7 $\pm$ 5	12 $\pm$ 11	6 $\pm$ 4	0.8 $\pm$ 1.1	0.6 $\pm$ 0.4	1.1 $\pm$ 7.3	7 $\pm$ 3	12 $\pm$ 13	5 $\pm$ 2
60–80	17 $\pm$ 17	57 $\pm$ 64	11 $\pm$ 12	6 $\pm$ 8	13 $\pm$ 15	5 $\pm$ 5	0.6 $\pm$ 0.6	0.4 $\pm$ 0.4	0.8 $\pm$ 0.8	6 $\pm$ 3	15 $\pm$ 18	5 $\pm$ 2
80–100	18 $\pm$ 13	55 $\pm$ 56	12 $\pm$ 10	8 $\pm$ 7	20 $\pm$ 17	8 $\pm$ 12	1.2 $\pm$ 11.8	0.7 $\pm$ 1.4	1.2 $\pm$ 7.6	8 $\pm$ 4	22 $\pm$ 18	6 $\pm$ 3

m^3) and likely reflected baseline indoor pollutant levels, sensor noise, or residual variability rather than indoor source activity. During the wildfire smoke period, outdoor $\text{PM}_{2.5}$ increased substantially and the indoor–outdoor relationships exhibited clear shifts. Infiltration slopes diverged across CES groups, demonstrating that the smoke infiltration behavior was more heterogeneous under extreme pollution conditions (Figure 8B). The lowest CES groups (0–20) showed the steepest slope (0.32), indicating greater transmission of wildfire smoke into

indoor environments. In contrast, the CES 40–60 group exhibited a lower slope (0.06), suggesting reduced infiltration. Regression intercepts increased for several CES groups, particularly CES 40–60 and CES 80–100, but because indoor emission periods were removed, these elevated intercepts are interpreted as residual indoor background or systematic offset during high-smoke conditions. After the fire, indoor $\text{PM}_{2.5}$ behavior returned to patterns similar to the pre-fire period (Figure 8C). Infiltration slopes

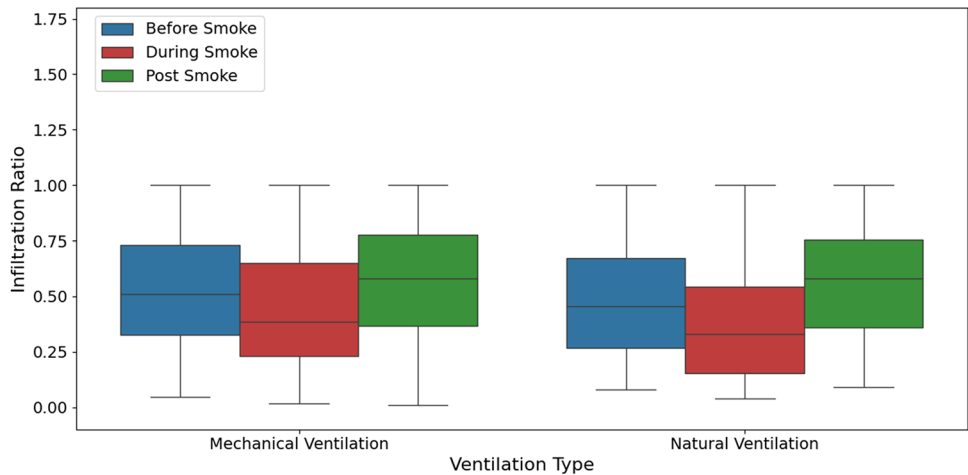


Figure 9. Infiltration ratios by ventilation type (mechanical vs natural) across presmoke, smoke, and postsmoke periods. Boxes show the interquartile range with median values, and whiskers represent the 5th–95th percentiles.

Table 2. Mean and Standard Deviation (Mean $\pm$ SD) of Outdoor and Indoor PM_{2.5} Concentrations and Infiltration Ratios for Mechanical and Natural Ventilation across Pre-smoke, Smoke, and Post-Smoke Periods^a

ventilation type	mean outdoor concentration ($\mu\text{g}/\text{m}^3$)			mean indoor concentration ($\mu\text{g}/\text{m}^3$)			infiltration ratio		
	mean $\pm$ SD			mean $\pm$ SD			mean $\pm$ SD		
	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke
mechanical ventilation	16 $\pm$ 16	52 $\pm$ 65	12 $\pm$ 12	7 $\pm$ 4	18 $\pm$ 28	5 $\pm$ 3	0.53 $\pm$ 0.24	0.45 $\pm$ 0.23	0.57 $\pm$ 0.24
natural ventilation	16 $\pm$ 15	54 $\pm$ 64	12 $\pm$ 11	6 $\pm$ 3	12 $\pm$ 10	5 $\pm$ 2	0.48 $\pm$ 0.24	0.38 $\pm$ 0.25	0.56 $\pm$ 0.23
<i>p</i> -value	7.7 $\times 10^{-01}$	5.7 $\times 10^{-01}$	8.2 $\times 10^{-01}$	7.0 $\times 10^{-12}$	2.3 $\times 10^{-14}$	1.0 $\times 10^{-02}$	2.6 $\times 10^{-09}$	7.0 $\times 10^{-10}$	3.7 $\times 10^{-02}$

^aThe *p*-values represent the statistical significance of the difference between mechanical and natural ventilation homes for each metric (outdoor PM_{2.5}, indoor PM_{2.5}, and infiltration ratio) within each of the three periods (before, during, and after smoke).

across CES categories stabilized between 0.08 and 0.2, indicating a normalization of the infiltration efficiency once ambient smoke levels decreased. Intercepts also returned to presmoke values consistent with baseline indoor conditions.

Table 1 shows the variability of outdoor and indoor PM_{2.5} concentration, I/O ratio, and infiltrated indoor PM_{2.5} concentration across all CalEnviroScreen (CES) categories at different wildfire smoke periods. We found that as outdoor PM_{2.5} concentrations rose during the wildfire smoke period, indoor concentrations also increased in response. However, despite this rise in indoor PM_{2.5}, most I/O ratios decreased during the smoke period, indicating that indoor environments became relatively less polluted compared to the outdoors. In addition, since indoor emissions were not removed for the indoor concentration or I/O ratio analysis, the declining I/O ratios during the smoke period imply that most occupants likely engaged in protective behaviors, such as keeping windows closed, limiting indoor activities that generate particles, or using air filters.

The infiltration results, which exclude indoor emission periods, reinforce this interpretation. Infiltration concentrations were low before the smoke event, increased during smoke events, and dropped back to near-background levels afterward. This consistent pattern across CES groups indicates that outdoor smoke intrusion was the dominant driver of indoor PM_{2.5} during the event. After smoke days, however, the I/O ratio rose for all CES groups, suggesting a rebound in occupant activity once the immediate smoke threat diminished, such as reopening windows or resuming cooking and cleaning. The

divergence between infiltration and unfiltered indoor metrics underscores that occupant behavior plays a major role in shaping indoor PM_{2.5} patterns, especially before and after smoke events, while wildfire periods are dominated primarily by infiltration-driven exposure.

3.3. Infiltration Ratio by Ventilation Type and Home Value

Infiltration behavior differed between mechanical and natural ventilation systems across the three study periods (pre-smoke, smoke, and post-smoke). As shown in Figure 9, both ventilation types exhibited the lowest infiltration ratios during the smoke period, with infiltration increasing again after smoke conditions subsided. Despite this overall pattern, natural ventilation consistently showed a slightly lower indoor PM_{2.5} concentration and median infiltration ratio during smoke days compared with those of mechanical systems, suggesting enhanced occupant-initiated behaviors or inherent structure characteristics that reduced smoke penetration.

Table 2 shows that outdoor PM_{2.5} concentrations increased during smoke days for both ventilation categories, rising from $\sim 16 \mu\text{g}/\text{m}^3$ pre-smoke to $\sim 52 \mu\text{g}/\text{m}^3$ during the smoke period. Mechanical ventilation homes experienced larger indoor concentration increases compared to naturally ventilated homes, reflecting greater transmission of outdoor PM_{2.5} into mechanically ventilated buildings during wildfire conditions.

Correspondingly, the mean infiltration ratio declined in both groups during the smoke event. The reported *p*-values in Table 2 quantify whether the differences in mean outdoor PM_{2.5}, indoor PM_{2.5}, and infiltration ratios between the two ventilation categories are statistically significant within each study period.

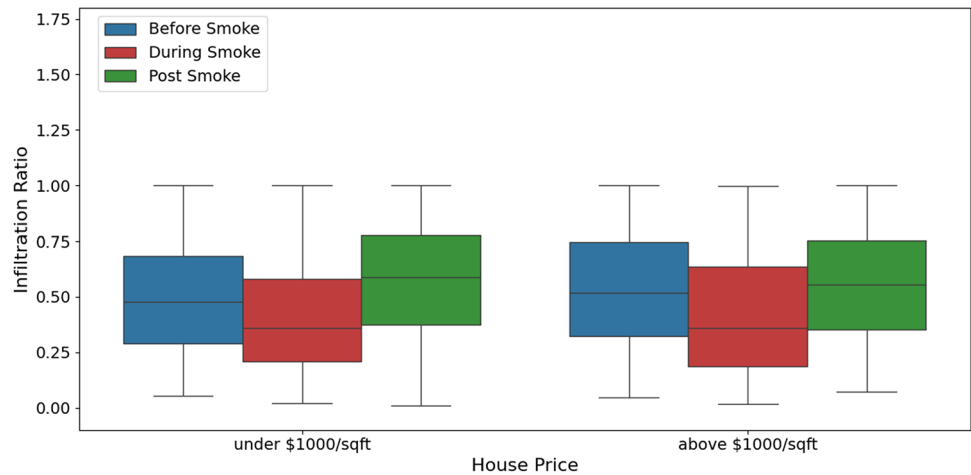


Figure 10. Infiltration ratios by house price (under \$1000/sqft vs above \$1000/sqft) across presmoke, smoke, and postsmoke periods. Boxes show the interquartile range with median values, and whiskers represent the 5th–95th percentiles.

Table 3. Mean and Standard Deviation (Mean $\pm$ SD) of Outdoor and Indoor PM_{2.5} Concentrations and Infiltration Ratios for Mechanical and Natural Ventilation across Pre-Smoke, Smoke, and Post-Smoke Periods^a

housing price	mean outdoor concentration ($\mu\text{g}/\text{m}^3$)			mean indoor concentration ($\mu\text{g}/\text{m}^3$)			infiltration ratio		
	mean $\pm$ SD			mean $\pm$ SD			mean $\pm$ SD		
	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke	before smoke	during smoke	after smoke
under \$1000/sqft	17 $\pm$ 15	53 $\pm$ 66	12 $\pm$ 12	6 $\pm$ 4	16 $\pm$ 22	5 $\pm$ 3	0.50 $\pm$ 0.24	0.41 $\pm$ 0.24	0.58 $\pm$ 0.23
above \$1000/sqft	15 $\pm$ 14	45 $\pm$ 53	12 $\pm$ 9	6 $\pm$ 4	15 $\pm$ 24	5 $\pm$ 3	0.54 $\pm$ 0.25	0.43 $\pm$ 0.27	0.56 $\pm$ 0.24
<i>p</i> -value	3.9 $\times$ 10 ^{−03}	3.9 $\times$ 10 ^{−04}	5.4 $\times$ 10 ^{−04}	3.2 $\times$ 10 ^{−02}	5.3 $\times$ 10 ^{−01}	3.2 $\times$ 10 ^{−12}	5.5 $\times$ 10 ^{−07}	1.2 $\times$ 10 ^{−01}	1.4 $\times$ 10 ^{−05}

^aThe *p*-values represent the statistical significance of the difference between the house group with a house price under \$1000/sqft and the house group with a house price above \$1000/sqft for each metric (outdoor PM_{2.5}, indoor PM_{2.5}, and infiltration ratio) within each of the three periods (before smoke, during smoke, and after smoke).

To compute these *p*-values, we used a two-sample Welch's *t*-test. Statistical comparison indicates significant differences between mechanical and natural ventilation during the smoke period, implying that natural ventilation provided slightly better protection during wildfire smoke days despite typically being more permeable under non-smoke conditions. After the smoke event, infiltration ratios rebounded to levels similar to those observed during the pre-smoke period for both building types.

Overall, these results indicate that wildfire smoke events alter infiltration dynamics across all homes, but naturally ventilated homes experienced comparatively lower smoke infiltration during the peak smoke period. Mechanical ventilation systems, although generally stable under normal conditions, showed greater indoor PM_{2.5} increases during smoke days, suggesting that the ventilation setting, filter types, and occupant behavior likely play a critical role in modifying smoke penetration.

Infiltration patterns also varied by housing price category, with homes valued below \$1000/sqft exhibiting slightly lower infiltration during smoke days compared with those of higher-priced homes (Figure 10). Across all periods, both groups showed a decrease in infiltration ratio during the wildfire smoke event and a rise during the post-smoke period. However, infiltration ratios during smoke days remained higher for the group of houses valued above \$1000/sqft relative to the group of houses valued below \$1000/sqft. This suggests that higher-priced homes did not necessarily provide better protection from wildfire smoke penetration.

Outdoor PM_{2.5} concentrations increased substantially during the smoke period for the two housing categories. Indoor concentrations showed a corresponding but dampened increase.

Since indoor concentrations were not filtered to remove indoor source emissions, these patterns likely reflect differences in occupant behavior. Notably, indoor concentrations during smoke days were nearly identical between lower- and higher-priced homes, indicating that differences in home value did not translate into substantial reductions in indoor PM_{2.5} levels during wildfire smoke conditions.

The reported *p*-values in Table 3 quantify whether the differences in mean outdoor PM_{2.5}, indoor PM_{2.5}, and infiltration ratios between the two house price categories are statistically significant within each study period. To compute these *p*-values, we used a two-sample Welch's *t*-test. *p*-Value indicates that some of these contrasts are statistically significant. Outdoor concentrations differed between price groups before, during, and after smoke days. Indoor concentrations also showed no significant differences during smoke days. Infiltration ratios differed significantly before smoke and after smoke but not during the smoke period, indicating that elevated outdoor smoke levels tended to minimize housing price differences in infiltration during the wildfire event.

Overall, these findings suggest that the home value alone was not a strong determinant of indoor PM_{2.5} protection during wildfire smoke. Instead, indoor concentrations during smoke likely reflect a combination of building characteristics and occupant behaviors.

4. DISCUSSION

This study demonstrates the value of crowdsourced PurpleAir data in evaluating residential exposure risk during a major wildfire event in Los Angeles. The dense spatial coverage of

indoor and outdoor sensors enabled a detailed examination of $PM_{2.5}$ infiltration dynamics across different communities and home environments during, before, and after the January 2025 LA Fires. Results reveal that wildfire smoke significantly elevated $PM_{2.5}$ concentrations both outdoors and indoors.

Communities in the highest CalEnviroScreen percentile (80–100) experienced higher infiltrated indoor $PM_{2.5}$ concentrations and in I/O ratios consistently relative to those of other groups. These findings suggest that structurally disadvantaged populations face elevated residential exposure risk, not only due to higher background ambient $PM_{2.5}$ levels but also because of limited building resilience to outdoor air pollution.

The observed reduction in I/O ratios and infiltration ratios during the smoke period is consistent with patterns documented in prior large-scale studies of indoor $PM_{2.5}$ during wildfire events. Liang et al. analyzed more than 1400 California homes and found that the I/O $PM_{2.5}$ ratio and infiltration ratio decreased substantially on wildfire days compared with non-fire days. This result aligns with our study, reinforcing that lower I/O ratios and infiltration ratios during wildfire events are an expected outcome of smoke-driven behavioral changes and building operation patterns.³¹

Infiltrated $PM_{2.5}$ derived from cleaned indoor data showed substantial differences in smoke penetration across the CES categories. During the smoke event, both the least burdened (0–20) and most burdened (80–100) communities exhibited elevated infiltrated $PM_{2.5}$ concentration, whereas mid-percentile groups showed lower infiltrated $PM_{2.5}$. This pattern indicates that exposure dynamics cannot be explained by socioeconomic indicators or building quality alone; instead, they likely reflect a mix of structural features, smoke intensity gradients, and occupant behaviors. After the smoke event, the infiltrated $PM_{2.5}$ level returned to pre-smoke values, suggesting that wildfire events temporarily override normal building performance characteristics.

Our findings are broadly consistent with prior wildfire studies showing substantial indoor penetration of outdoor smoke $PM_{2.5}$ but also provide important nuance. Similar to Krebs et al.,¹⁵ we observe clear differences in indoor exposure across communities with differing vulnerability. However, whereas previous work emphasized income-driven differences in average indoor concentrations or regression-based infiltration estimates, our results show that the infiltration ratio often decreases during wildfire smoke periods despite absolute indoor $PM_{2.5}$ concentrations increasing. This pattern suggests that residents actively modify their indoor environment through behaviors such as closing windows, reducing ventilation, or using filtration.

Ventilation analyses revealed that naturally ventilated homes experienced slightly lower infiltration ratios during smoke days compared with mechanically ventilated homes, despite conventional assumptions that mechanical ventilation systems provide better filtration. Similarly, the home value did not reliably predict indoor protection. Higher-priced homes exhibited slightly higher infiltration during smoke days, and indoor concentrations were nearly identical across price categories. These findings indicate that building operation and occupant decision-making during wildfire events play critical roles in determining exposure, often outweighing structural or economic characteristics.

While this study provides a detailed, real-world evaluation of wildfire smoke exposure disparities, several methodological considerations must be incorporated into the interpretation of results. PurpleAir sensors, although widely used and corrected

using established EPA and Barkjohn approaches, still carry uncertainty under extreme smoke or high-humidity conditions. Indoor emissions were removed for infiltration calculations but cannot be fully disaggregated from background indoor concentrations, meaning that some regression intercepts may still reflect residual indoor sources. Building metadata (ventilation type and home value) was available only for single-family homes, limiting the representativeness of analyses involving structural characteristics. Moreover, critical behavioral factors such as window opening, HVAC operation, and indoor activities were not observed but can shape the I/O relationships reported here. Finally, indoor and outdoor sensor matching within a 1.5-mile radius, although validated through a sensitivity analysis, may introduce spatial mismatch in areas with steep pollution gradients, and hourly averaging may obscure short-lived exposure spikes relevant to acute health impacts.

Despite these challenges, the study highlights that communities with greater environmental and socioeconomic burdens are disproportionately affected by outdoor wildfire smoke and show elevated indoor exposure during smoke events. Mechanical ventilation does not guarantee lower infiltration, and higher-value homes are not inherently more protective during extreme pollution episodes. These findings reinforce the need for targeted public health interventions.

■ ASSOCIATED CONTENT

■ Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsestair.5c00277>.

Additional methodological details and supplementary analyses that support the results presented in the main text; spatial distribution of paired indoor and outdoor PurpleAir sensors across the Los Angeles region and comparison of indoor/outdoor linear regression results using different pairing distance thresholds (1000 m vs 1.5 miles) (Figures A1–A3); MODIS true-color satellite imagery illustrating the temporal evolution of the wildfire smoke plume affecting the study region from January 7 to January 11, 2025 (Figures B1–B5); county-wide $PM_{2.5}$ conditions and identification of the smoke episode relative to the U.S. EPA 24-h $PM_{2.5}$ standard (Figure C); meteorological context, including temperature, wind speed, and precipitation before, during, and after the smoke period (Figures D1–D3); and spatial distribution of indoor/outdoor sensor pairs stratified by home ventilation type and housing value, respectively (Figures E1–E2 and F1–F2) (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This publication was developed under Assistance Agreement No. 84032501 awarded by the U.S. Environmental Protection Agency to the University of California Berkeley. It has not been formally reviewed by the EPA. The views expressed in this document are solely those of the publication authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

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