

Article

Infiltration of Outdoor PM_{2.5} Pollution into Homes with Evaporative Coolers in Utah County

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Abstract: Global use of energy-inefficient mechanical vapor-compression air conditioning (AC) is increasing dramatically for home cooling. Direct evaporative coolers (EC) offer substantial energy savings, and may provide a sustainable alternative to AC for homes in hot, dry climates. One drawback of ECs is the potential for infiltration of outdoor air pollution into homes. Prior studies on this topic are limited by small sample sizes and a lack of comparison homes. In this study, we used aerosol photometers to sample indoor and outdoor fine particulate matter (PM_{2.5}) from 16 homes with AC and 14 homes with EC in Utah County, Utah (USA) between July 2022 and August 2023. We observed a significantly larger infiltration factor (F_{in}) of outdoor PM_{2.5} in EC vs. AC homes (0.39 vs. 0.12, $p = 0.026$) during summer. F_{in} significantly increased during a wildfire smoke event that occurred during the study. During the wildfire event, EC homes offered little to no protection from outdoor PM_{2.5} ($F_{in} = 0.96$, 95% confidence interval (CI) 0.85, 1.07), while AC homes offered significant protection ($F_{in} = 0.23$, 95% CI 0.15, 0.32). We recommend additional research focused on cooling pad design for the dual benefits of cooling efficiency and particle filtration.

Keywords: evaporative cooler; fine particulate matter; PM_{2.5}; indoor environmental quality; air conditioning; air pollution; air quality



Citation: Sonntag, D.B.; Jung, H.; Harline, R.P.; Peterson, T.C.; Willis, S.E.; Christensen, T.R.; Johnston, J.D. Infiltration of Outdoor PM_{2.5} Pollution into Homes with Evaporative Coolers in Utah County. *Sustainability* **2024**, *16*, 177. <https://doi.org/10.3390/su16010177>

Academic Editors: Weixin Yang, Guanghui Yuan and Yunpeng Yang

Received: 23 November 2023

Revised: 19 December 2023

Accepted: 20 December 2023

Published: 24 December 2023



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1. Introduction

Global increases in per capita income are fueling a surge in the residential use of mechanical vapor-compression air conditioners (AC) [1,2]. Typical AC units, which are not very energy efficient, currently dominate the global air conditioning market. This is particularly relevant in hot, arid climates such as in the Middle East where air conditioning accounts for up to 70% of building energy use [3,4]. Globally, housing accounts for approximately 30% of total energy consumption [5,6]. Due to increasing global temperatures, energy use for space heating is expected to decline by 34%, while energy use for space cooling is expected to grow by 72% by the end of the 21st century [7]. Davis et al. (2015) estimate that 70% of homes globally will have air conditioners by the year 2100, accompanied by an 83% increase in household energy use [8]. Thus, we are currently in an opportunity window to develop and promote sustainable, energy-saving alternatives to AC for residential space cooling.

One of the most promising alternatives to AC for arid and semi-arid regions are direct evaporative coolers (ECs). ECs cost less, require no chlorofluorocarbons (CFCs), and use only 20–50% of the energy required by AC units to achieve comparable cooling performance [9–11]. Globally, many regions with the largest AC adoption rates are in areas conducive to evaporative cooling. McNeil and Letschert (2008), for example, predict that by 2030, over 80% of homes in Mexico and over 50% of homes in Middle Eastern countries

will have AC, up from approximately 20% and 25%, respectively, in 2005 [12]. In hot, dry climates, ECs have the potential to significantly reduce energy consumption associated with residential space cooling.

Evaporative cooling methods have been used from ancient times to the present day in various forms and across multiple cultures to provide efficient, low-cost residential air conditioning in hot, dry climates [13–17]. Direct evaporative cooling is the simplest and most common type of residential evaporative cooling in use today. ECs, also known as swamp, drip, or desert coolers, work based on the heat transfer associated with water evaporation. ECs use a low-power electric fan to pull hot, dry outdoor air across wetted cooling pads, usually made from plant fibers (e.g., aspen wood shavings) or corrugated cellulose materials [9,18,19]. As hot air moves across the wet cooling pads, liquid water in the cooler pads absorbs thermal energy from the hot outdoor air as it changes phase to become water vapor [20]. This process lowers the temperature and simultaneously increases the relative humidity of air being blown into the home [9,21]. Because they work based on the evaporation of water, ECs are most effective in regions where there is a large wet bulb depression and where the wet bulb temperature is below 21 °C [10].

One concern with EC use is the potential for the infiltration of outdoor air pollution into homes. ECs pull large volumes of outdoor air into homes, generating < 10 to over 30 air changes per hour (ACH) in residential buildings, depending on home size and EC fan speed [22,23]. In contrast, AC units typically recirculate air in the home to conserve energy and have low ACH rates. For example, homes in Houston TX (USA), where AC is commonly used during summer months, have a median ACH rate of 0.37 [24]. Thus, AC homes may provide a protective barrier against outdoor air pollution because they draw very little outdoor air into the home. ECs may also significantly dilute indoor pollution originating from household sources, such as tobacco smoke and cooking aerosols [25]. Among outdoor pollutants that may infiltrate homes, fine particulate matter (PM_{2.5}) is a primary concern. PM_{2.5} exposure is associated with multiple poor health outcomes, including lung cancer, cardiopulmonary mortality, and infectious and non-infectious respiratory illnesses [26,27].

To date, there is little in the published literature on the infiltration of particulate air pollution into EC homes. Paschold et al. (2003) used a test chamber to evaluate indoor/outdoor (I/O) ratios of PM₁₀ and PM_{2.5} associated with EC use without interference from household activities, such as smoking and cooking [28]. Using tap water to wet the EC cooling pads, the PM₁₀ I/O ratios ranged from ~0.5 to 0.6, and the PM_{2.5} I/O ratios ranged from ~0.76 to 1.04 depending on pad type and fan speed. Li et al. (2003), in a study of 10 occupied homes in the El Paso, TX area, found I/O ratios of 0.57 and 0.63, for PM₁₀ and PM_{2.5}, respectively when the EC was running [23]. Both studies suggest that ECs provide some protection to residents from particle pollution, but they provide more protection from PM₁₀ than PM_{2.5}.

ECs offer substantial energy savings when compared to AC units in dry climates, and thus may provide a sustainable alternative to AC cooling in some regions. However, to be sustainable for human health, ECs should not put home occupants at higher risk of exposure to air pollution that infiltrates the home through the EC. Current evidence, albeit limited, suggests ECs may provide some protection from outdoor PM_{2.5} infiltration into homes. Data are especially limited on their effectiveness in protecting residents from wildfire smoke, with wildfires increasing in the Western U.S. over the last several decades [29–31]. The utility of ECs as a sustainable air conditioning option thus warrants further investigation into this topic. In this study, we aimed specifically to evaluate the I/O ratios of PM_{2.5} in occupied EC homes. This study builds upon prior research by increasing the sample size and using a comparison group of AC homes in the same area.

2. Materials and Methods

2.1. Study Design

The primary objective of this study was to evaluate PM_{2.5} infiltration into EC and AC homes in Utah County, UT (USA) during summer and winter months without interference

from indoor aerosol sources. Utah County is located in the Western US, with a semiarid climate that is suited for ECs, but also susceptible to wildfire smoke events during the summer months. A secondary objective was to evaluate PM_{2.5} infiltration during wildfire smoke events in both EC and AC homes. Indoor and outdoor 24-h PM_{2.5} measurements were collected during each sampling event using aerosol photometers. We used convenience sampling to recruit homes from July 2022 to August 2023. Recruitment strategies included personal contacts, social media posts, and flyers mailed to university faculty and staff. Prospective participants completed a 13-item pre-screen questionnaire to determine eligibility. Inclusion criteria were: (1) must be a single-family home in Utah County, UT (USA); (2) must use either EC or AC air conditioning; (3) the primary home occupant must be at least 18 years old and the owner or renter of the property; (4) the primary home occupant must be able/willing to not cook, burn anything (candles/incense/fireplace, etc.), and not vacuum 3 h. prior and 24 h. during sampling; and (5) must plan to live in the home until at least 1 October 2024. Exclusion criteria were: (1) having a home occupant who smoked or vaped; (2) having guests who smoked or vaped in the home; and (3) using a humidifier, air purifier, or vaporizer.

We attempted to sample each home at least twice, once during the summer and once during the winter months. Additional effort was made to sample homes during a wildfire smoke event that occurred during the study. We used the Fire and Smoke Map on AirNow [32] to identify one wildfire smoke event, which occurred between 8 and 12 September 2022, with daily PM_{2.5} concentrations reaching over 25 µg/m³ at both of the Utah Division of Air Quality (UDAQ) monitors in Utah County (Figure S1). During this wildfire smoke event, we were able to conduct second visit measurements for three of the AC homes, and first visit measurements for four of the EC homes.

During each sampling visit, study personnel set up indoor and outdoor PM_{2.5} aerosol monitors and temperature/relative humidity meters. These instruments ran for approximately 24 h. Indoor monitors were placed in the main living area of the home away from windows and ventilation ducts. Laminated cards were hung on ovens and microwaves to remind occupants not to cook during the sampling period. Outdoor monitors were placed away from aerosol-generating sources such as clothes dryer vents. Study personnel administered a housing survey at each visit. The primary home occupant received a \$50 Visa gift card for each visit to compensate for their time, and to cover the cost of meals during the 24 h sampling period. A video/photo release form was used to document permission to photograph participants' air conditioning units. After the 24 h sampling period we confirmed with the study participant that no cooking, candle burning, or vacuuming was carried out during that 24 h sampling period. The Institutional Review Board at Brigham Young University (BYU) determined that the unit of study was the home, not the occupant(s), and thus did not require the human subjects' research approval.

2.2. Data Collection

2.2.1. Aerosol Photometer

We employed SidePak AM 510 Aerosol Monitor Dataloggers (TSI Inc., Shoreview, MN, USA) to quantify the PM_{2.5} mass concentration in mg/m³ during each data collection visit. Prior to data collection, all SidePak instruments underwent a four-point calibration using emery oil that was nominally adjusted to respirable mass aerosol concentrations by the manufacturer per ISO 12103-1, A1 test dust (Arizona dust) [33]. We prepared the SidePak monitors as per the manufacturer's guidelines, including downloading data from the previous visit, clearing the SidePak memory, and setting the logging interval to one minute. We cleaned and greased the impaction plate and applied grease to the impactor assembly O-ring. The flow rate was set to 1.7 lpm ± 1.0%, and the SidePak was zeroed using a HEPA filter. For both indoor and outdoor samples, the monitor was placed at the base of a tripod. Tygon[®] tubing was attached to the SidePak inlet and extended up to the top of the tripod 1 to 1.5 m above ground level (Figure 1a). A small loop was made with the tubing at the top of the tripod so the air inlet was facing downward. This was done to

prevent water or large particles from entering the tubing. For outdoor samples, the SidePak monitor was placed in the waterproof container (Figure 1b). Data were recorded over a continuous period of approximately 24 h. SidePak monitors were connected to AC power throughout the data collection phase to ensure uninterrupted operation.



Figure 1. Aerosol photometer tubing positioned approximately 1.0–1.5 m above the floor/ground for (a) indoor and (b) outdoor sampling. Outdoor aerosol photometers were placed in a plastic container with air holes to prevent water damage.

2.2.2. Temperature and Humidity

Extech SD500 temperature/relative humidity (TRH meters) dataloggers (Extech Instruments, Nashua, NH, USA) were used during each sample collection visit. Prior to each data collection event, previously recorded data were downloaded, the SD card was cleared, and the TRH meter batteries were replaced. The TRH meters were placed approximately 1–1.5 m off the ground on a tripod, one inside and one outside the home. The TRH meters were attached to the tripod with a piece of string. Data were logged every minute over the 24 h data collection period.

2.2.3. Demographic Data

Study personnel administered a housing survey during both the summer and winter data collection visits. The summer housing survey consisted of a 24-item questionnaire used to verify inclusion/exclusion criteria, and to collect data such as age and style of the home, number of occupants, and other housing characteristics. The questionnaire also included items regarding methods used by home occupants to ventilate the dwelling during summer months, and types of filters used in AC and EC cooling units. The winter housing survey was a 9-item questionnaire verifying inclusion/exclusion criteria and one item regarding methods used to heat the home during winter months.

2.3. Quality Assurance

We conducted quality assurance of our collected data, by reviewing and removing incomplete or suspicious data. Through our quality assurance steps, our data set was reduced from 31 homes and 67 unique home visits to 30 homes (16 AC, and 14 EC) and 50 unique home visits. Details of the data cleaning steps are included in the supplemental information.

As another data validation and quality assurance step, we compared the average $PM_{2.5}$ concentrations measured from the outdoor SidePak monitors and measurements made from two Utah Division of Air Quality (UDAQ) monitors located in Utah County. Across the entire study, the outdoor $PM_{2.5}$ concentrations were strongly linearly correlated between the SidePak and UDAQ monitors ($R^2 = 0.78$). The average outdoor SidePak $PM_{2.5}$ concentrations have a large systematic bias and can be more than $2\times$ larger than the corresponding UDAQ $PM_{2.5}$ concentrations (Figure S5). The light-scattering method used by the SidePak is sensitive to the particle size [34], morphology, and composition [35], as

well as the temperature and humidity [36]. Our data confirmed this dependence exists in the measures collected in our study from the SidePak instruments. The slope between the outdoor SidePak PM_{2.5} concentrations and the closest Utah UDAQ PM_{2.5} concentrations is markedly different in the summer than the winter (Figures S6 and S7). Thus, the SidePak concentrations should not be used to infer absolute PM_{2.5} concentrations, and we need to be cautious when comparing SidePak measurements conducted under substantially different sampling conditions.

For this study, we used the raw SidePak PM_{2.5} measurement to evaluate the relative differences in PM_{2.5} concentrations (rather than absolute differences) between location (indoor and outdoor), home cooling type (AC and EC), and season (summer and winter). Others have developed and used calibration factors to adjust PM_{2.5} concentrations from light-scattering instruments based on relative humidity [37–39]. The humidity adjustments are most important at RH values of >60% [38,40]. We have chosen not to adjust the SidePak PM_{2.5} in our study for two reasons. First, our measurements are generally below an RH of 60% in our study (Table S4). Second, we did not collect side-by-side PM_{2.5} data between reference monitors and the SidePak from which to develop our calibrations.

2.4. Data Analysis

All analyses were performed using R Statistical Software (v4.3.1. R Core Team 2023). We calculated statistics from the average indoor and outdoor SidePak concentrations measured from each visit between the AC and EC homes in summer and winter. These statistics included indoor concentrations, outdoor concentrations, and indoor/outdoor ratios. We then conducted two-sample *t*-tests to evaluate if there are significant differences in the average statistics between the AC and EC homes within each season.

Next, we used two different methods to estimate the infiltration factor (F_{in}). The infiltration fraction estimates the fraction of outdoor PM_{2.5} that infiltrates the indoor environment and should be between 0 and 1. Under ideal circumstances where there is no source of indoor PM_{2.5} pollution, the I/O and F_{in} should be equivalent. In cases where there are indoor sources of PM_{2.5}, F_{in} should be lower than the I/O ratio.

In Method 1, we estimated F_{in} using the correlation between the indoor and outdoor PM_{2.5} concentrations using the minute-by-minute SidePak measurements made at each home. We fitted a linear model to the average indoor SidePak PM_{2.5} concentrations for each minute, *j*, within each visit, *i*, using Equation (1), using the nomenclature consistent with Chen and Zhao (2011) [41]. We fitted the model using ordinary least squares.

$$C_{in\ i,j} = C_{s,i} + F_{in\ i} C_{out\ i,j} + e_{i,j}, \quad (1)$$

where:

$C_{in\ i,j}$ = Indoor SidePak PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) for visit, *i*, and minute, *j*
 C_s = Intercept, PM_{2.5} contribution ($\mu\text{g}/\text{m}^3$) from indoor sources for visit, *i*
 $C_{out\ i}$ = Outdoor SidePak PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) for visit, *i*, and minute, *j*
 $F_{in\ i}$ = Slope (infiltration factor) for visit, *i*
 $e_{i,j}$ = Error in the linear model fit for visit, *i*, and minute, *j*

In Method 2, we evaluated the correlation between the average indoor concentrations and outdoor concentrations across different visits. We estimated the infiltration factor using a linear model with the same form as in Method 1, but instead of fitting the model to the minute-by-minute data from each house visit, we fitted the model to the average indoor SidePak PM_{2.5} concentrations from visits grouped by air conditioning type and season, as shown in Equation (2).

$$C_{in\ i} = C_s + F_{in} C_{out\ i} + e_i, \quad (2)$$

where:

$C_{in\ i}$ = Average indoor SidePak PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) for visit, *i*
 C_s = Intercept, average PM_{2.5} contribution ($\mu\text{g}/\text{m}^3$) from indoor sources

$C_{out\ i}$ = Average outdoor SidePak $PM_{2.5}$ concentration ($\mu g/m^3$) for visit, i

F_{in} = Slope, infiltration factor

e_{in} = Error in the linear model fit for visit, i

3. Results

3.1. Home Demographics

Characteristics of the homes included in this study are included in Table 1. EC homes tended to be older and slightly smaller than AC homes. EC homes also tended to have fewer residents and lower occupant densities. AC homes were more likely to be owner-occupied compared to EC homes.

Table 1. Demographics of study homes by air conditioning type.

Home Characteristics	Central Air Conditioning ($n = 16$)					Evaporative Cooler ($n = 14$)				
	Mean	SD ^a	CV ^b	Min	Max	Mean	SD	CV	Min	Max
Age of home (yrs)	35.1	26.3	0.8	2	80	61	22.9	0.4	21	100
Area (m^2)	203	35	0.2	144	278	184	84	0.5	81	386
Number of residents	4.4	1.7	0.4	2	8	3.1	1.9	0.6	1	7
Occupant density ^c	2.2	0.9	0.4	1.0	3.6	2.0	1.8	0.9	0.5	7.4
Homeowner percentage	88%					57%				

^a SD = standard deviation, ^b CV = coefficient of variation; ^c Occupant density calculated as number of people living in the home per 100 square meters.

3.2. Average Concentrations and Indoor to Outdoor Ratios

The average indoor and outdoor concentrations for the visits are displayed in Figure 2. Large variability is observed in the average outdoor concentrations across the study. Larger outdoor concentrations are observed during the wildfire event occurring from 8 to 12 September 2022. Additionally, a few high outdoor concentrations are observed during the winter months, which are attributed to inversion conditions that frequently occur in Utah County in the winter. The indoor concentrations vary considerably in the summer, but are all relatively low during the winter.

In Figure 3, we summarized the average indoor and outdoor $PM_{2.5}$ concentrations measured for each home visit grouped by air conditioner type and season using box-plots. We also added the group average of the home visits by air conditioner and season. The average outdoor $PM_{2.5}$ concentrations measured by the closest reference UDAQ monitor and at the home by the SidePak monitors were consistently higher in AC homes, but the difference was not statistically significant. On the other hand, the mean indoor SidePak $PM_{2.5}$ concentrations were larger from the visits with EC homes for both summer and winter. For the t -tests, we treated each home visit as an independent and random variable, even though we conducted repeat visits at several of the homes during the summer season. This is a reasonable assumption, because the I/O ratios within repeated home visits have as much variability as those of visits between different homes (Figure S8).

Figure 3 also displays the mean and the distribution of I/O ratios across each home visit using the average SidePak $PM_{2.5}$ concentrations. The average I/O ratio across the summer visits was significantly higher in EC homes (0.83) than in AC homes (0.55; p -value = 0.006, See Table S11). These results are dependent on the seven home visits during the 8–12 September 2022 wildfire smoke event. When we remove the seven home visits in the summer that occurred during the wildfire smoke event, the difference in the average I/O by air conditioning type is no longer significant (p -value = 0.1, Figure S9). During the winter, the average I/O ratio across home visits is lower in EC homes, but the difference is not statistically significant.

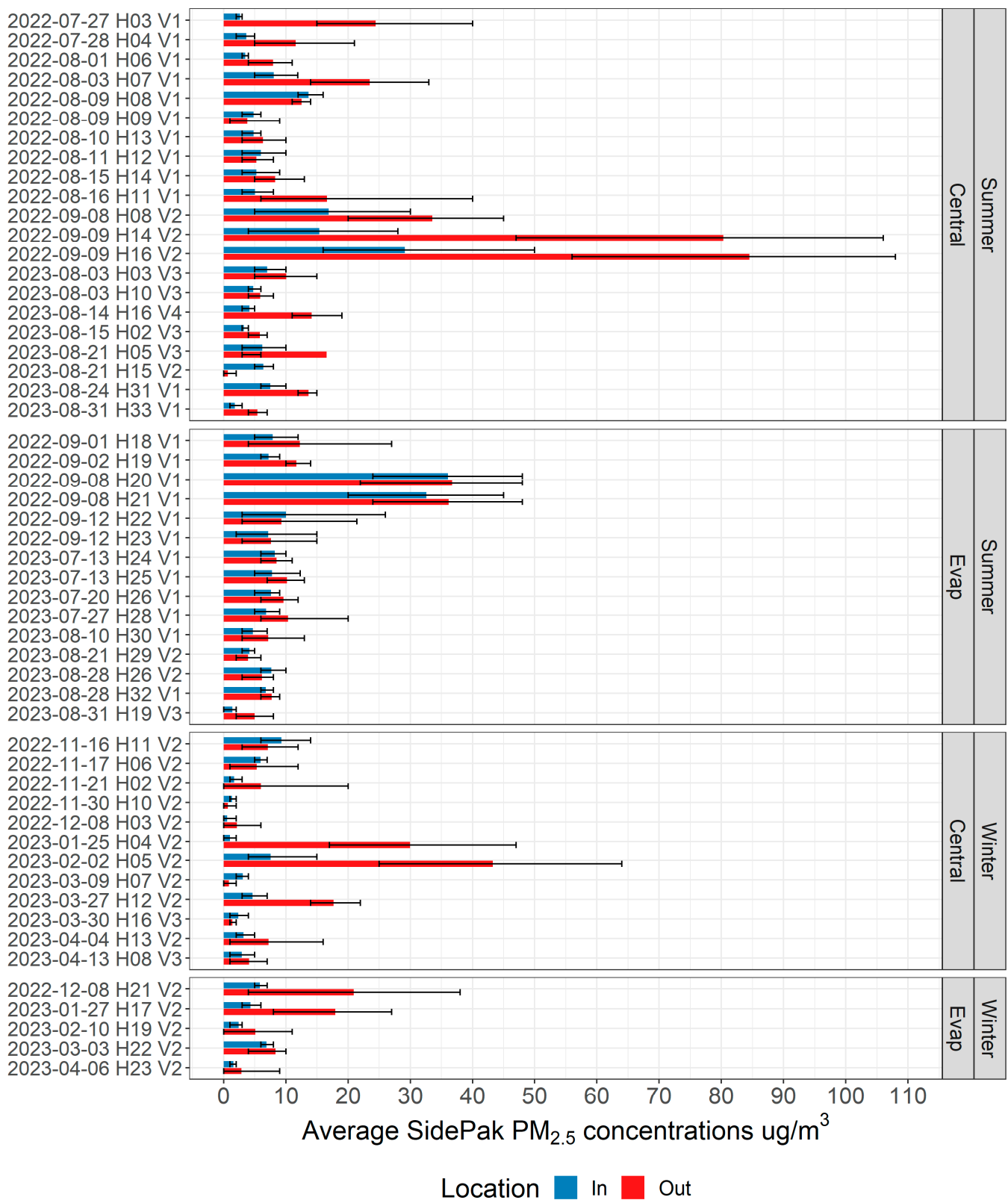


Figure 2. Average indoor and outdoor SidePak PM_{2.5} concentrations for each date, home (H), and visit (V) grouped by season and air conditioner type from the final dataset. The error bars are the 10th and 90th percentile minute-by-minute concentrations for each home visit.

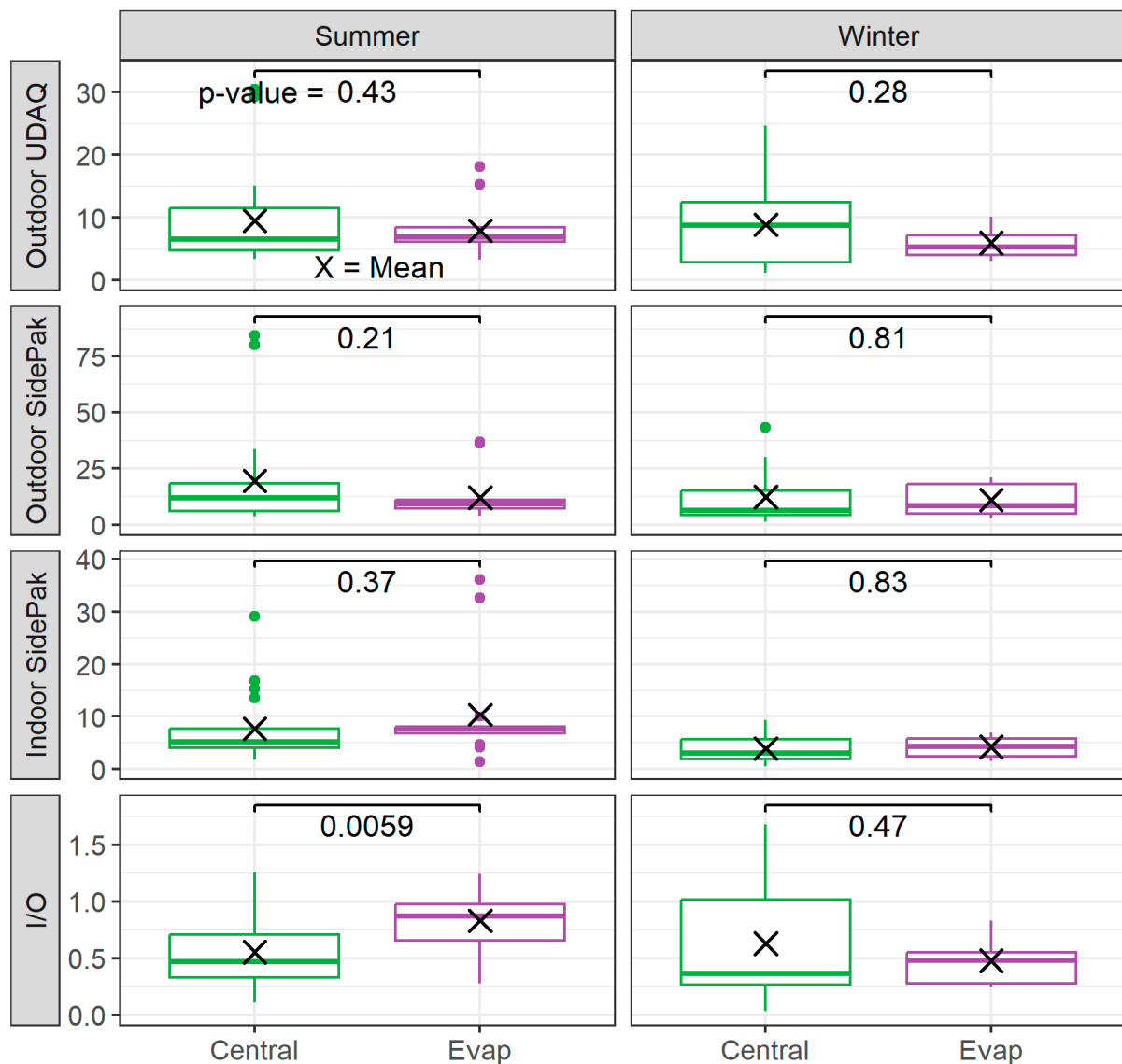


Figure 3. Box plots of average concentration statistics from the home visits organized by air conditioner type and season; “Outdoor UDAQ” = The average outdoor $\text{PM}_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) from the UDAQ reference monitors; “Outdoor SidePak” = the outdoor $\text{PM}_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) from the SidePak monitors; “Indoor SidePak” = the average indoor $\text{PM}_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) from the SidePak monitors; “I/O” = I/O ratio calculated from the average indoor and outdoor SidePak $\text{PM}_{2.5}$ concentrations. The box plots are in the style of Tukey; middle line is the median, the bottom and upper lines are the 25th and 75th percentiles, respectively; whiskers extend to the largest value within 1.5 times the interquartile range; observations beyond the whiskers are labeled individually [42]. The X symbols represent the mean group value, and horizon lines and numbers are the p -values comparing the averages from a two-sample t -test.

Because we attempted to minimize indoor air pollution sources, and removed home visits that appeared to have strong indoor sources, we attribute the higher I/O ratios to a higher infiltration of outdoor air pollution in homes with evaporative coolers. In the next two sections, we empirically estimated the infiltration fraction of outdoor $\text{PM}_{2.5}$, which is the fraction of the outdoor $\text{PM}_{2.5}$ concentration that infiltrates the indoor environment.

3.3. Infiltration Factor Using Method 1

Figure 4 shows minute-by-minute SidePak $PM_{2.5}$ concentrations for both indoor and outdoor locations for two example visits that occurred during the wildfire smoke event: Home 16 on 9–10 September 2022, and Home 23 on 12–13 September 2022. The time-series for all visits are shown in Figures S2–S4.

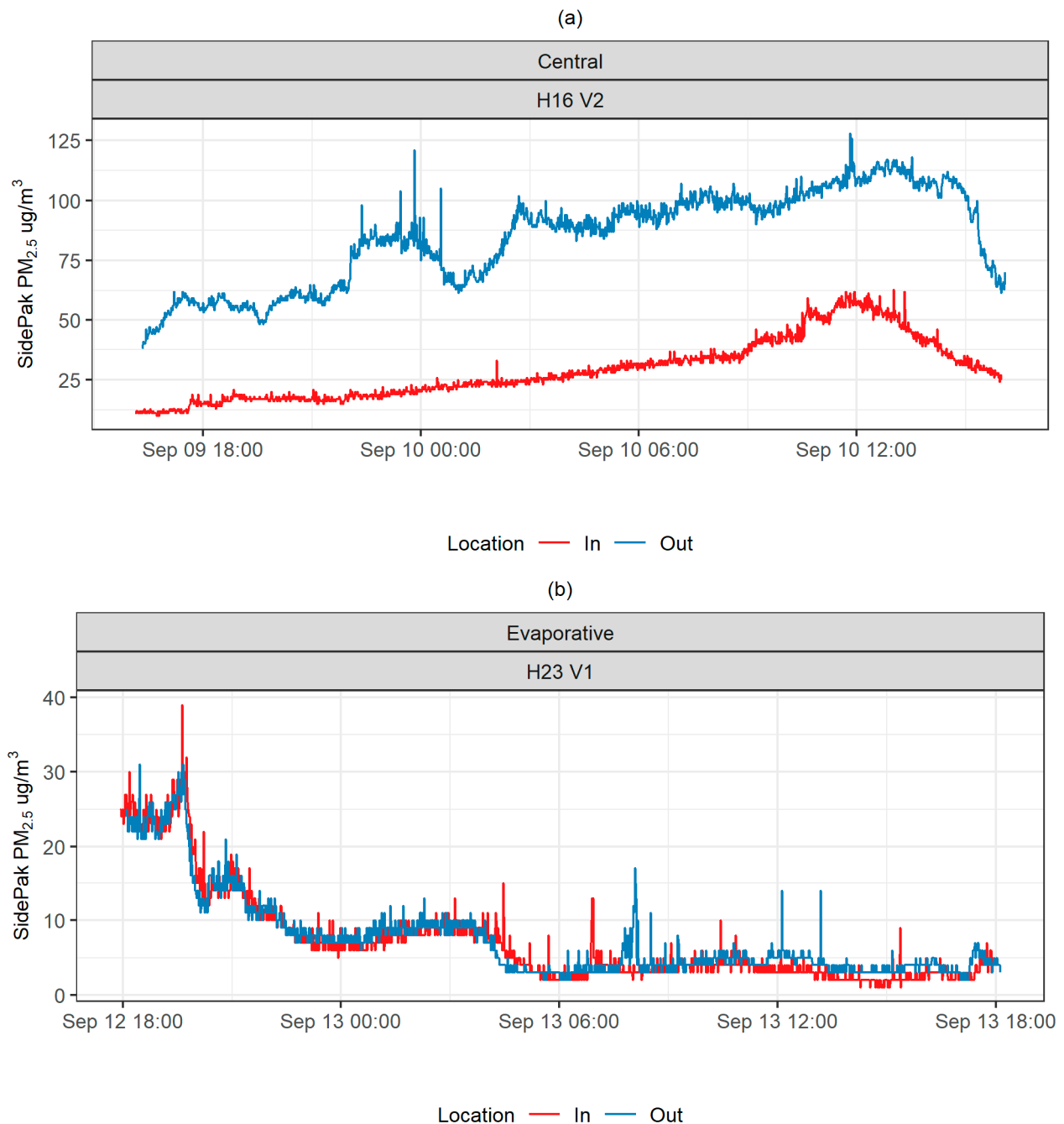


Figure 4. Indoor and outdoor SidePak $PM_{2.5}$ concentrations for (a) Home 16 on 9–10 September 2022 (Visit 2) and (b) Home 23 on 12–13 September 2022 (Visit 1).

Figure 5 shows the correlation between the indoor and outdoor SidePak correlations for the two example visits. The coefficient estimates for C_s and F_{in} and the coefficient of determination (R^2) measure of the goodness of fit of the model are also displayed. We have used R^2 to quantify correlation because it explains the percent of variation in the indoor concentrations that is explained by the outdoor concentrations using the model form.

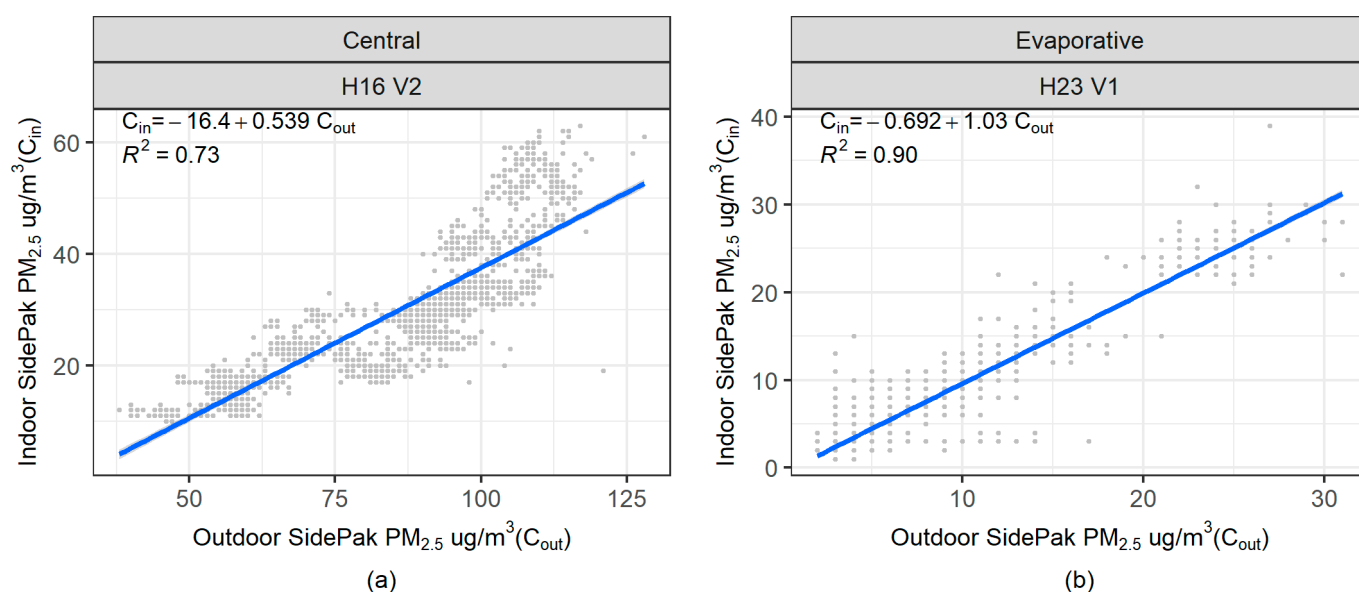


Figure 5. Correlation of indoor and outdoor SidePak PM_{2.5} concentrations for two visits (a) Home 16 on 9–10 September 2022 (Visit 2) and (b) Home 23 on 12–13 September 2022 (Visit 1) with the Equation (1) coefficients, R^2 goodness of fit, and model fit (displayed in blue).

Figures S10–S12 show the correlation of indoor and outdoor minute-by-minute SidePak PM_{2.5} concentrations for each visit, along with the linear fit of Equation (1). Tables S9 and S10 contain the C_s , F_{in} , and R^2 estimated for each home visit. Figure 6 summarizes the C_s , F_{in} , and R^2 for each visit by air conditioning type and by season. We also calculated the mean C_s , F_{in} , and R^2 value by air conditioning type (AC and EC) and season (summer and winter) using a simple average by treating each visit equally using Equations (S1)–(S3). The mean C_s , F_{in} , and R^2 are also plotted in Figure 6, as are the p -values from a t -test evaluating differences in the mean C_s , F_{in} , and R^2 data by type of air conditioner.

The average C_s (the estimated contribution from indoor sources) ranges between 3.3 and 4.1 $\mu\text{g}/\text{m}^3$ in the summer and winter (Table S11), and no significant differences are detected between the AC and EC visits. Although we asked participants to minimize indoor sources of air pollution in the homes, such as from cooking or candles, we still expect sources of indoor PM_{2.5}, such as re-suspended dust from movement and air flow within the home [43]. We estimated negative C_s for just four of the fifty visits, all occurring during the wildfire smoke event (Tables S9 and S10 and Figure S14). In the winter, there is no discernable trend of C_s with outdoor PM_{2.5} concentrations (Figure S14). We believe that the C_s should be independent of the outdoor PM_{2.5} concentrations, and the negative C_s estimates in the summer are limitations of our correlation method to estimate indoor and outdoor contributions to the indoor PM_{2.5} concentrations.

In the summer, the average F_{in} for AC visits is 0.12 and more than two times higher (0.39) for visits in EC homes, and the difference is statistically significant (p -value = 0.026). However, if we remove the seven wildfire smoke days, the difference is no longer statistically significant (Figure S13). The goodness of fit R^2 is also higher for the EC visits than the AC visits.

In the winter, F_{in} is lower for both types of homes (0.07 for AC, and −0.01 for EC), but the difference is not statistically significant between AC and EC visits. The R^2 for the winter visits is quite low for both types of air conditioners (0.06 for AC, and 0.04 for EC).

F_{in} varies considerably for the same homes between summer and winter visits. In addition, the infiltration factors from repeat measurements from the same home and same season also vary substantially, especially for AC visits in the summer (Figure S15). This suggests that ambient conditions influence F_{in} as much as, or more than, the properties of the home. In Figure S16, we plotted the F_{in} for each visit chronologically within season and

home type. In general, the largest F_{in} occurred during the 8–12 September 2022 wildfire event for both AC and EC homes.

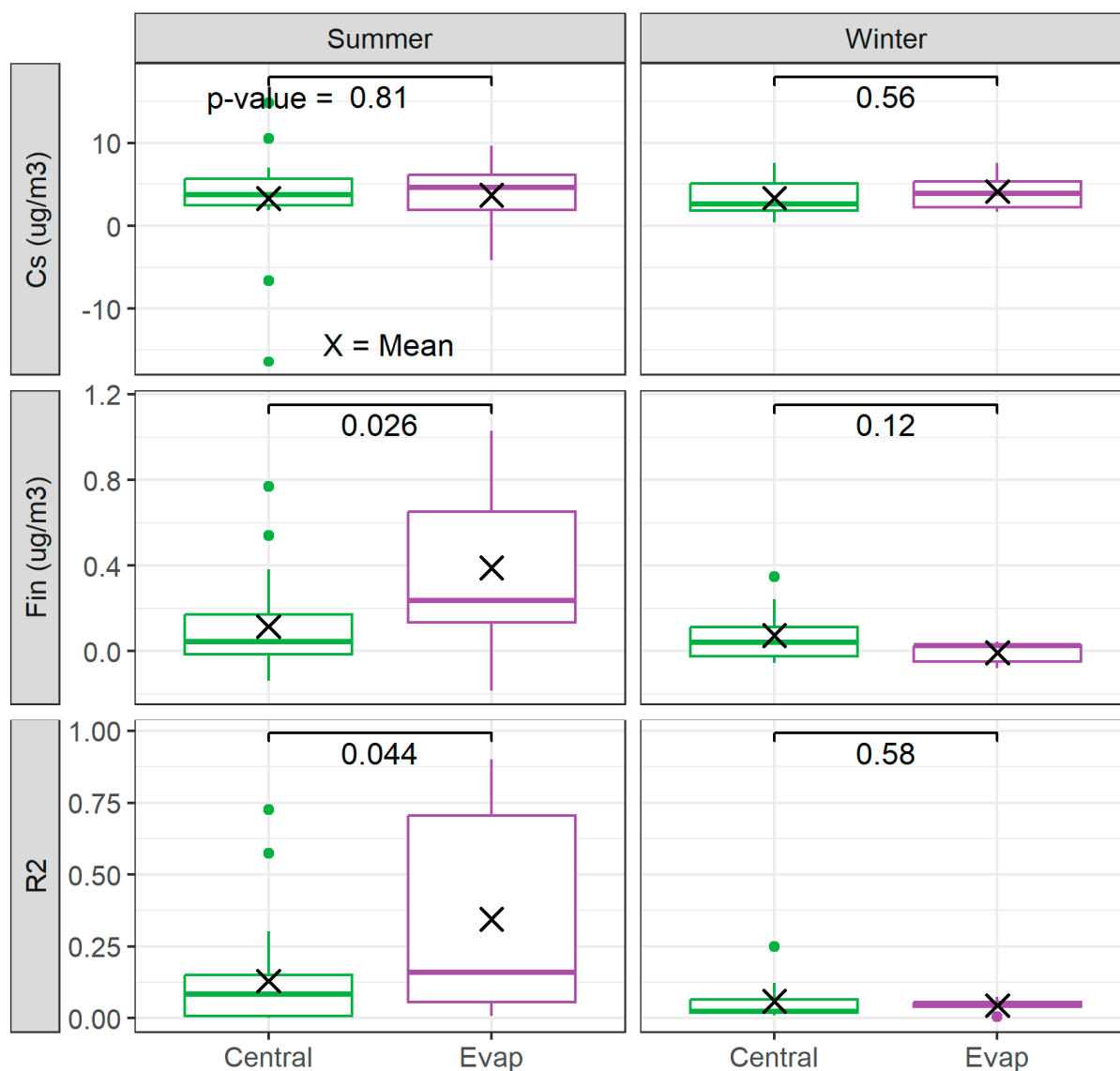


Figure 6. Box plots of the C_s , F_{in} , and R^2 estimated for each home visit organized by air conditioner type and season. The X symbols represent the mean value, and horizontal black lines and numbers are the p -values comparing the averages from two-sample t -tests.

We evaluated if F_{in} in the summer was related to outdoor temperature, assuming that EC usage could increase with outdoor temperatures, which could increase the infiltration of outdoor particles. However, no clear trend is evident. If anything, F_{in} appeared to decrease with temperature for summer visits in homes with evaporative coolers (Figure S17). The lack of a clear trend in F_{in} with respect to temperature may be, in part, because we selected hot days for summer visits where the residents needed to use their AC or EC (Tables S5 and S7).

In the summer, F_{in} tends to increase with outdoor $PM_{2.5}$ concentrations, which is consistent with the wildfire event observations. However, there is no trend in F_{in} with respect to outdoor $PM_{2.5}$ concentrations during our winter observations (Figure S18).

3.4. Infiltration Factor Using Method 2

Figure 7 shows the average SidePak PM_{2.5} concentration data for each visit, with separate panels for air conditioner type (AC and EC) and season (summer and winter). The estimates of the infiltration factor (F_{in}) from Method 2 are displayed in Figure 7 with the fits of Equation (2) to each group of data. We observe a positive correlation in the indoor and outdoor PM_{2.5} concentrations across both types of homes and seasons. The slope, F_{in} , is consistently larger for the visits during the summer compared to winter, and for EC visits compared to AC visits. Additionally, the F_{in} estimated for EC visits (0.96) is more than four times the F_{in} for homes with AC (0.24). The difference in F_{in} between AC and EC visits in summer is highly significant (Table S13). In the winter, F_{in} is slightly positive, but is not significantly different than zero for either EC or AC visits (Table S12).

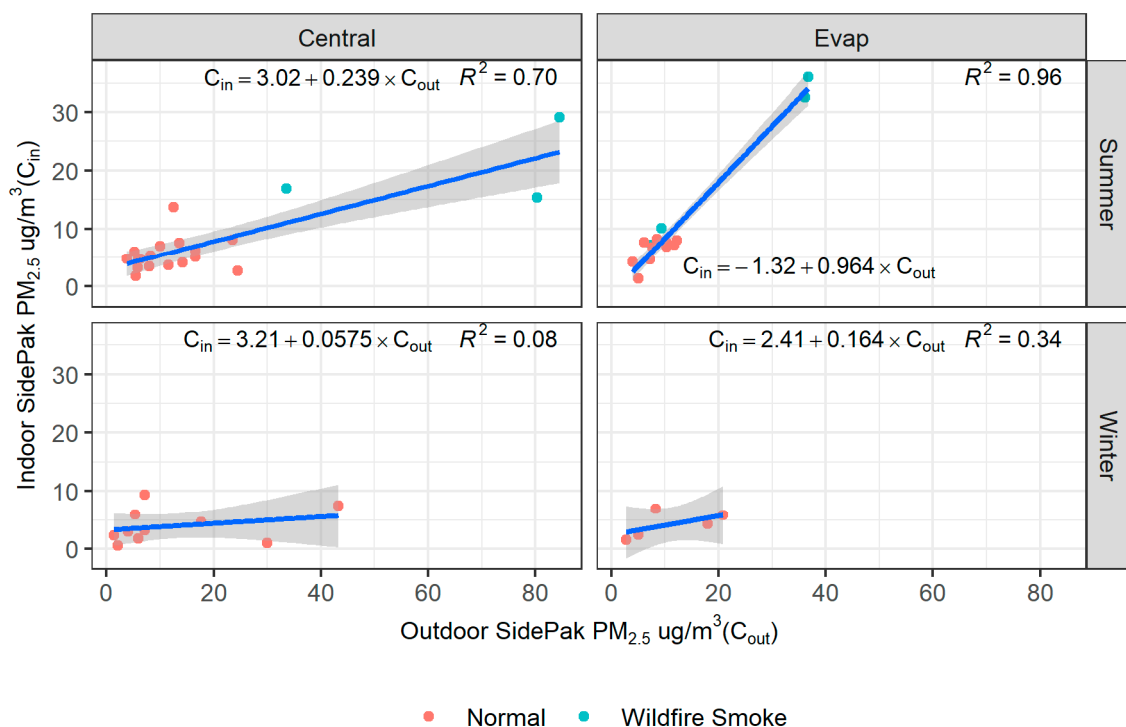


Figure 7. Correlation of the average indoor and outdoor SidePak PM_{2.5} concentrations by season and air conditioner type. The Equation (2) coefficients, R^2 goodness of fit, and model fit (displayed in blue). The grey shadow shows the observations that are within the standard error of the model prediction [42].

The estimates of linear regression coefficients (C_s and F_{in}) using Equation (2) are highly influenced by the home visits with large outdoor PM_{2.5} concentrations measured during the 8–12 September 2022 wildfire smoke event. When these seven days are removed, F_{in} is much smaller for both the visits in homes with AC and EC (Figure S19). The F_{in} for AC visits is moderately positive but is no longer significantly different than zero (Table S12). The F_{in} for EC visits is still strongly positive (0.54) and significantly different than zero. However, F_{in} is no longer significantly different (p -value = 0.14) between AC and EC visits (Table S15).

3.5. Comparison of Infiltration Factors between Method 1 and Method 2

In Table 2, we compared the mean F_{in} estimated using Method 1 with the F_{in} estimated using Method 2 for the AC and EC visits conducted in the summer.

Table 2. Infiltration factor (F_{in}) estimated from Method 1 and Method 2 for summer visits.

	Central Air (AC)			Evaporative (EC)		
	Estimate	95% Confidence Interval		Estimate	95% Confidence Interval	
		Lower Bound	Upper Bound		Lower Bound	Upper Bound
Mean F_{in} from Method 1	0.12	0.01	0.22	0.39	0.17	0.61
F_{in} from Method 2	0.23	0.15	0.32	0.96	0.85	1.07

The F_{in} obtained using Method 2 is substantially larger for both types of homes. Despite the differences, both methods estimate that F_{in} is larger in EC homes. We believe there are two factors that lead to higher F_{in} estimates using Method 2.

- (1) As noted in Section 3.3, the F_{in} from Method 1 increases with outdoor $PM_{2.5}$ concentrations. However, the wildfire smoke visits only account for seven of the thirty home visits conducted in the summer. Because we calculated the mean F_{in} treating each visit equally (Equation (S2)), the average F_{in} from Method 1 is substantially lower than the individual days with wildfire smoke.
- (2) The infiltration factors estimated for the summer from Method 2 are highly influenced by the seven visits that occurred on the wildfire smoke days. As shown in Figure 7, the wildfire smoke visits are outside the cloud of visits on other days, making the wildfire visits very influential on the estimate of F_{in} . The estimate of F_{in} including the days with wildfire smoke was 0.96 for EC visits, but only 0.57 when removing the wildfire smoke days.

We believe the estimates from Method 2 are most appropriate for estimating the F_{in} for days with wildfire smoke and Method 1 is appropriate for estimating the F_{in} for an average summer day. The individual F_{in} estimated from Method 1 from the wildfire smoke days ranged from 0.27 to 0.54 for AC visits (three visits), and 0.81 to 1.03 for EC visits (four visits) (Tables S9 and S10). The individual F_{in} from the wildfire smoke days correspond better to the F_{in} estimated from Method 2, particularly for EC homes. In winter, the two methods yielded more comparable estimates for F_{in} (Table S16).

The infiltration factors estimated from our study for AC homes in wildfire events are near the bottom range reported from previous indoor air quality studies in the US, which range between 0.2 and 0.8 [41,44,45]. However, individual study homes (presumably AC) have been observed across a much broader range between 0.01 and 0.87 during wildfire smoke events [46]. The F_{in} estimates for EC homes on average summer days fall within the range of the literature values. However, the F_{in} from EC homes measured during the wildfire smoke event in our study were close to 1, which extends beyond the range of previously reported values.

4. Discussion

Evaporative cooling offers a low-energy alternative to AC, and wider acceptance and use of ECs in arid and semi-arid regions globally may partially offset projected increases in energy use associated with residential space cooling. To be considered as a sustainable alternative to AC, however, ECs should not put home occupants at higher risk of exposure to outdoor air pollution that infiltrates the home through the cooler. For average summer days in our study, EC homes provided a modest amount of protection (F_{in} of 0.39), but AC homes provided a greater amount of protection (F_{in} of 0.12). No difference in infiltration factor by air conditioning type was observed during the winter when air conditioning is not in use. Thus, we believe the differences we observe in summer can be attributed to the use of air conditioning and not to other factors related to the homes.

Our findings agree with the existing literature regarding infiltration of $PM_{2.5}$ into EC homes. The I/O ratio (0.83) for EC homes in our study falls within the range of 0.63–1.04 reported in prior studies [23,28]. One strength of our study was the addition of a comparison group of AC homes, which previous studies lacked. AC homes in our study

offered significantly greater protection (I/O ratio = 0.55; p -value = 0.006) from infiltration of outdoor air pollution, and this was most noticeable during a wildfire smoke event that occurred during the study period. Our analysis suggests that EC homes provide little to no protection from outdoor $PM_{2.5}$ during wildfire events in the summer (F_{in} of 0.96), when the $PM_{2.5}$ concentrations are highest, and protection is most desired. Similar homes in Utah County equipped with AC benefited from a substantial amount of protection from outdoor $PM_{2.5}$ pollution during the same wildfire event (F_{in} of 0.23).

Higher infiltration factors have been observed during wildfire smoke days in nursing homes compared to normal days (0.59 vs. 0.43) [44], whereas a large study using crowd-sourced home monitor data in California estimated lower infiltration of outdoor $PM_{2.5}$ during wildfire events, which is attributed to residents changing their behavior in response to poor air quality, such as closing windows and using air purifiers on poor air quality days [45].

We believe that changes in particle size, morphology, and composition is a driving factor for the larger infiltration of particles during summer, including wildfire smoke events. During winter inversions, the $PM_{2.5}$ composition in Utah County is dominated by ammonium nitrate [47], which evaporates indoors at warm temperatures and low humidity [48]. Other studies have also demonstrated lower F_{in} values during winter compared to summer [49]. On the other hand, carbonaceous wood smoke particles have been shown to effectively infiltrate and remain airborne in particle phase inside homes [46,50] and other buildings [44].

By conducting 24 h samples, the results from each home in our study were limited to the types of conditions measured. Thus, our study results were highly influenced by the seven home visits we conducted during one single wildfire smoke event. For future studies, we recommend using many continuous monitors, so that each home is sampled over the same conditions, especially during any high $PM_{2.5}$ pollution events. We also recommend conducting sampling over longer periods of time inside homes without restrictions on aerosol-producing activities, as were in place in this study. This will allow for evaluation of how ECs can mitigate indoor air pollution sources through their large ACH rates, which we intentionally avoided in our study. This study was limited to single-family homes in one county in Utah. Thus, our findings may not be generalizable to multi-unit dwellings. In addition, housing envelopes vary widely across regions based on cost and available building materials, which may influence $PM_{2.5}$ infiltration differently than homes in our study. Thus, our findings may not be generalizable to homes in other regions.

In our study, our instruments only measured $PM_{2.5}$ particles. We acknowledge that we are missing the potential effectiveness of ECs in removing PM_{10} particles. PM_{10} is an important measure of dust that can occur in high levels during dust storms in Utah and other arid regions that can also utilize ECs, and should be considered in future studies [47,51].

Several of the study participants living in homes with ECs reported that they limit the use of their ECs during days with poor air quality. Our study confirms that this can be an effective strategy to improve indoor air quality, but may not be possible or desirable for the residents if the EC is their only way to effectively cool their home.

Although not a randomized study, the average age of EC homes (61 years) was much older than for AC homes (35 years). Additionally, the residents who participated in the study who lived in EC homes were more likely to rent their home than the participants who lived in AC homes (Table 1). Thus, our study suggests that the use of ECs in older homes may contribute to disparities in air pollution exposure by social and economic factors among residents living in Utah County. Because of their low cost and energy-efficiency, we recommend additional research to evaluate EC interventions that can reduce the infiltration of outdoor $PM_{2.5}$.

5. Conclusions

In arid and semi-arid regions, evaporative cooling has strong potential to help offset energy use associated with the rapidly growing demand for residential air conditioning.

One barrier to their success as a sustainable alternative to AC, however, is the possibility of infiltration of outdoor PM_{2.5} and its associated health effects. Prior research on ECs primarily focuses on system efficiencies such as air flow rate and pressure drop, water consumption, heat and mass transfer, and degradation of pad materials [52–54]. Our findings suggest a need for studies focused on EC design specifically to decrease infiltration of particle-phase pollutants. Improved EC cooling pads, for instance, may have utility in serving a dual purpose of providing an efficient wetting medium while also serving as an effective filter for fine particulates. Optimal pad configurations for efficiency and particle removal, tailored to local air pollution conditions, may then be recommended to EC users.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16010177/s1>, S.1 Classification of Wildfire Smoke Events, S.2 Removal of Incomplete Data, S.3 Inspection of minute-by-minute Sidepak PM_{2.5} Data, S.4 Comparison of PM_{2.5} Measurements from the SidePak to the Utah Division of Air Quality (UDAQ) Monitors, S.5 Indoor/Outdoor PM_{2.5} Ratios S.6 Temperature and Relative Humidity Data, S.7 Infiltration Factor Estimates using Method 1, S.8 Summary Statistics from Method 1, S.9 Infiltration Factor Estimates using Method 2. S.10 Comparison of Infiltration Factor Estimates using Method 1 and Method 2. S.11 References [55–58].

Author Contributions: Conceptualization, D.B.S. and J.D.J.; methodology, D.B.S., H.J., R.P.H., T.C.P., S.E.W., T.R.C. and J.D.J.; validation, D.B.S., H.J. and R.P.H.; formal analysis, D.B.S., H.J. and R.P.H.; investigation, D.B.S., H.J., R.P.H., T.C.P., S.E.W., T.R.C. and J.D.J.; resources, D.B.S. and J.D.J.; data curation, D.B.S., H.J. and R.P.H.; writing—original draft preparation, D.B.S., H.J., R.P.H., T.C.P., T.R.C. and J.D.J.; writing—review and editing, D.B.S., H.J., R.P.H., T.C.P., S.E.W., T.R.C. and J.D.J.; visualization, D.B.S., H.J., R.P.H., T.C.P., T.R.C. and J.D.J.; supervision, D.B.S. and J.D.J.; project administration, D.B.S. and J.D.J.; funding acquisition, D.B.S., S.E.W. and J.D.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by a College Undergraduate Research Award from Brigham Young University’s College of Life Sciences and an Experiential Learning Grant from the Ira A. Fulton College of Engineering.

Institutional Review Board Statement: The Institutional Review Board at Brigham Young University (BYU) determined that the unit of study was the home, not the occupant(s), and thus did not require the human subjects’ research approval.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data and analysis scripts are publically available at <https://github.com/darrell-sonntag/EvapCoolerUtahCounty>, accessed 21 December 2023. The information from the participant survey is also made available, except for any information which could be used to identify the homes in the study (address and home area).

Acknowledgments: We acknowledge the full team of BYU students who worked on this project, including: Paula Chanthakhoun, Alisandra Olivares, Seth Van Roosendaal, Julianna Stock, Jaxson Tadge, Braedon Tarone, Joseph West, and Dallin Widowski. We are especially grateful to the participants who allowed us access to their homes to conduct this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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