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Layne Willis

Julie Hart

Raja Nagisetty

Clay Comstock

David P. Gilkey

See next page for additional authors

Authors
Layne Willis, Julie Hart, Raja Nagisetty, Clay Comstock, David P. Gilkey, and Daniel Autenrieth

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The application of portable air cleaners in spaces occupied by vulnerable people during wildfire events

Layne Willis, MS[1], Julie Hart, Ph.D., CIH[1], Raja Nagisetty[2], Clay Comstock, Ph.D. [3], David Gilkey, D.C., Ph.D., CSP[1], Daniel Autenrieth, Ph.D., CIH, CSP[1*]

[1] *Department of Safety, Health and Industrial Hygiene, Montana Technological University, Butte, MT 59701*

[2] *Environmental Engineering Department, Montana Technological University, Butte, MT 59701*

[3] *Life Sciences Department, Salish Kootenai College, Pablo, MT 59855*

KEYWORDS

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PurpleAir
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ABSTRACT

In this study, PM2.5 concentrations were collected and documented during wildfire smoke impacted days using PurpleAir PA-II sensors at three different locations in a community located in the northwestern United States. Each location was comprised of three co-located sensors with one sensor positioned outdoors, one sensor indoors, and one sensor indoors with an air cleaner in the room. The relationship between both indoor and outdoor PM2.5 concentrations provided evidence on the effectiveness of sheltering indoors from wildfire smoke events with and without an air purification system.

1. INTRODUCTION

Increased wildfire frequency and severity throughout the western United States have led to increased human exposure to wildfire-induced fine particulate matter ≤ 2.5µm (PM2.5) (Lydersen, 2017). The mixture of pollutants in wildfire smoke can depend on the geographic location of the burn area (Liang, 2021). Wildfire smoke plumes can travel great distances and settle into surrounding communities (Preisler, 2015).

The Environmental Protection Agency (EPA) has established both a 24-hour and an annual standard for PM2.5 as a component of the National Ambient Air Quality Standards (NAAQS) under the Clean Air Act. These guidelines are designed to protect the general population from increased risk of negative health effects from long/short-term exposure (U.S. EPA, 2020). Most recently, the 24-hour and annual standards have been reviewed by the EPA at 35 $\mu g/m^3$ and 12 $\mu g/m^3$ respectively (U.S. EPA, 2020).

Air monitoring for wildfire smoke is formally conducted through each state, using criteria set forth by the Office of Air Quality Planning and Standards (OAQPS) (U.S. EPA, 2016). Air quality stations are strategically located to represent a large geographic area. Size-selective sampling for PM2.5 is conducted through various EPA reference and equivalent methods in accordance with 40 CFR Part 53 (U.S. EPA, 2016). Low-cost sensors (< $1000) use advancing technology to understand and

* ***Corresponding author***: dautenrieth@mtech.edu

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communicate air quality on a consumer level, when compared to reference instruments (EPA, 2021). Consumer monitoring products can be used on an individual level to measure particulate matter concentrations in a variety of locations (EPA, 2021). These consumer devices are widely used across rural areas where formal monitoring does not occur (EPA, 2021).

The health effects of wildfire-induced PM2.5 exposure include coughing, trouble breathing, scratchy throat, headache, and much more (U.S. EPA, 2019). The most vulnerable populations in terms of harmful effects from PM2.5 exposure are the youth, older adults, and the transitory population (U.S. EPA, 2019). As PM2.5 concentrations rise, the common guidance from healthcare officials is to take shelter by staying indoors, keeping windows closed, and using a portable air cleaner (PAC) (Xing, 2016).

Portable Air Cleaners (PACs) aid in the filtration and removal of particulate matter inside buildings. Each PAC is rated for a given room volume, where it can effectively eliminate contaminants with the appropriate filter. The use of HEPA filters can provide the added benefit of reducing airborne particles like dust, mold, viruses, and bacteria. PACs have been demonstrated to significantly reduce indoor PM2.5 concentrations associated with wildfire smoke (Stauffer, 2020).

2. OBJECTIVE

The primary objective of this study was to evaluate the effectiveness of staying indoors during a wildfire event and staying indoors with a PAC operating during wildfire events in settings occupied by traditionally vulnerable groups. Indoor and outdoor air quality measurements were taken at three different sites in a community located in the northwestern United States. Previous research has shown the effectiveness of commercial and “do it yourself” (DIY) PACs at controlling PM2.5 concentrations for office workers exposed to wildfire smoke in this same community (Stauffer, 2020). Each site in this study was selected based on occupant designation (youth, older adult, transient), room size, and proximity to a DEQ county air monitoring station. Ideally, this study was intended to evaluate the effectiveness of each sheltering method, depending on wildfire-induced PM2.5 concentrations. Furthermore, a secondary objective of this study was to compare PM2.5 exposure at each location based on the time of day, and the time spent in each PM2.5 concentration level.

3. BACKGROUND

3.1 Background of PM2.5

The increase in frequency and severity of wildfires throughout the western United States has resulted in an increased average amount of wildfire-induced smoke exposure (Lydersen, 2017). Components of wildfire smoke include gaseous pollutants, water vapor, and particulate matter. PM represents the main component that poses a public health threat. PM2.5, commonly referred to as fine particulate matter, refers to particulates with an aerodynamic diameter $\leq$2.5µm. Particles of this size will tend to deposit throughout the respiratory tract. A smaller fraction can deposit into the alveolar region of the lungs, which may cause respiratory illness (Li, 2019). Common health effects associated with wildfire-induced PM2.5 can range from coughing and eye irritation to much more severe such as cardiovascular effects. The resultant smoke PM2.5 concentrations are measured by ambient air monitors and samplers located worldwide. The U.S. EPA must regularly update and revise national air quality standards for PM2.5, under the Clean Air Act.

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3.2 Wildfire Smoke Infiltration

The infiltration of wildfire smoke from outside to inside is a major factor that leads to human exposure to PM2.5 indoors during wildfire events (Pantelic, 2019). The infiltration of wildfire smoke has been studied in residential homes, as well as industrial buildings. Infiltration into larger industrial buildings largely depends on the type of ventilation system being used, and the building construction. Pantelic et al. (2019) compared two industrial buildings, one used a mechanical ventilation system with two-stage particle filtration, and one relied on natural ventilation during wildfire events. The particle filtration consisted of a first stage minimum efficiency reporting value (MERV) 8 pleated filter, and the final stage MERV 13 filter (Pantelic, 2019). The building with two-stage particle filtration had a mean indoor PM2.5 concentration of 21 $\mu g/m^3$, and an indoor/outdoor ratio of 0.27 (Pantelic, 2019). The building with natural ventilation had a mean indoor PM2.5 concentration of 36 $\mu g/m^3$, and an indoor/outdoor ratio of 0.67 (Pantelic, 2019). Wildfire smoke infiltration into residential homes is largely due to natural ventilation, and the opening of windows and doors (Barn, 2007). Barn et al. (2007) found that the infiltration factor for 17 homes in British Columbia, Canada during the wildfire season was 0.61 (Nguyen, 2021). Newly constructed homes built with central air conditioning systems were more effective at keeping wildfire smoke out, when compared to older homes in areas of lower socio-economic status (Liang, 2021). Compared to older homes, residences-built post 2000 had lower infiltration ratios during “fire days” (Liang, 2021).

Shrestha (2019) compared the impact of outdoor air pollution from wildfires to the air quality inside low-income housing to determine if indoor areas can be effectively used for PM2.5 protection. Twenty-eight homes were evaluated over two to seven days with air pollutants, including PM2.5, measured to characterize the relationship between indoor and outdoor concentrations. All the homes utilized natural ventilation, which was demonstrated to have a negative effect on indoor air pollutant concentrations due to infiltration of PM2.5 (Shrestha, 2019). The study also evaluated indoor factors such as exhaust stove hoods compared to recirculating hoods (Shrestha, 2019). Homes with exhaust stove hoods demonstrated an indoor/outdoor ratio of 49% less than homes using recirculating hoods and 55% less than homes using no stove hoods (Shrestha, 2019). This study revealed that low-income homes are significantly affected by environmental conditions, road proximity, and indoor behaviors (Shrestha, 2019).

3.3 Health Effects of PM2.5

Health effects of PM2.5 exposure from wildfire sources can range from relatively minor (respiratory irritation), to serious (asthma, heart failure, premature death) effects depending on the concentration, duration of exposure, and individual at risk (U.S. EPA, 2019). The youth (<18 years) are more sensitive to air pollution, and thus wildfire smoke (U.S. EPA, 2019). They spend more time outdoors, are typically more active, and consequently inhale more air during wildfire smoke season (Sacks et al. 2011). Older adults are more susceptible to short-term exposures to wildfire smoke due to an increased number of pre-existing conditions associated with age (U.S. EPA, 2009). Certain defense mechanisms decline with age, resulting in increased hospital admissions for older adults (U.S. EPA, 2009). The transitory population are those of lower socio-economic status at the community level. Transitory populations may not have consistent access to shelter within indoor environments.

Recently published studies on health outcomes in the northwest region of the United States associated with wildfire-sourced PM2.5 provide insight into the potential severity of wildfire exposure on public health. It is known that wildfire smoke can lead to increased hospital admissions for those with pre-existing respiratory health issues (Youssouf, 2014). Orr (2020) studied the long-term effects of wildfire smoke on the most susceptible population, the elderly. The study took place in Seeley Lake, MT, from July 31 to September 18, 2017, during heavy wildfire activity with a daily average PM2.5 concentration of 220.9 $\mu g/m^3$ (Orr, 2020). Health assessments were conducted in the community on 95 participants with an average age of 63 years (Orr, 2020). Follow-up assessments took place in 2018 and 2019 as well (Orr, 2020). The study revealed a significant decrease ($p < .05$) in lung function in 45.9% of the study population one year after the wildfire event, declining to 33.9% of the study participants two years after the wildfire event. (Orr, 2020). The study demonstrated that wildfire smoke has long-lasting effects on human health, and mitigation strategies are needed to reduce exposure (Orr, 2020).

Gan (2018) monitored the air quality from Washington wildfires to evaluate a potential association between adverse health outcomes and increased wildfire smoke exposure. The study was evaluated using a time-stratified case-crossover design and considered one wildfire season from July 1 to October 31, 2012 (Gan, 2018). Geographically weighted ridge regression, a spatial analysis technique that considers non-stationary variables (e.g., physical environmental factors, climate, etc.) and models the relationship between the non-stationary variables and an outcome of interest was used(Gan, 2018). The results showed that a 10 $\mu g/m^3$ increase in geographically weighted ridge regression smoke PM2.5 resulted in an 8% increased risk of asthma-related hospitalizations; however, chronic obstructive pulmonary disease (COPD) was not significantly associated with an increase in PM2.5 (Gan, 2018).

3.4 Low-Cost Air Quality Sensors

Low-cost sensors are used for monitoring atmospheric concentrations of particulate matter at relatively low costs when compared to NAAQS compliance EPA-approved monitors. Most of the low-cost sensors use optical particle counters or photoelectric sensors to detect particulate matter. Photoelectric sensors use infrared light and a photoelectric receiver to detect the presence of an object and to identify its size (AtGrating, 2022). The sensor is aligned with the light emitter, and a change in electrical signal will occur with any obstruction to the light (AtGrating, 2022). This is achieved with the photoelectric effect, where electrons of the passing particle absorb the photon energy (AtGrating, 2022). Optical sensors detect the state of the object and convert that into a light signal (AtGrating, 2022). When a particle passes through a beam of light, the light is scattered and can be measured to determine particle size (AtGrating, 2022). Low-cost sensors have become increasingly popular over recent years, with over 9,000 active PurpleAir aerosol monitors throughout the United States in 2020 (Tsai et al., 2020).

Correction factors for air quality monitoring equipment are essential for eliminating bias and improving the accuracy of the measurement. Barkjohn (2021) evaluated almost 12,000 24-hour averaged PM2.5 measurements collected from PurpleAir sensors, and Federal Reference Method (FRM) measurements from governmental stations across 16 states. This study revealed that PurpleAir sensors overestimate PM2.5 concentrations by an average of 40% (Barkjohn, 2021). A correction factor based on a simple linear regression and the addition of a factor to account for relative humidity reduced bias (Barkjohn, 2021). Overall, the root mean square error was reduced from 8 to 3 $\mu g/m^3$ (Barkjohn, 2021). The results show that the application of a correction factor may improve the accuracy of low cost sensors in air quality applications.

3.5 Portable Air Cleaner Effectiveness

Portable air cleaners (PACs) are designed to filter air in a room at a certain rate, as described by the clean air delivery rate (CADR). The CADR is the product of flow rate and filter efficiency. For example, a high-efficiency particulate air (HEPA) filter with 99.97% efficiency cleaning at 500 cubic

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feet per minute (cfm) would have a CADR of very close to 500 cfm. A HEPA filter in the portable air cleaner traps PM2.5 by drawing air through a high-efficiency filter.

The number of air changes per hour (ACH) represents how often the air is circulated in a specified room volume every hour. The greater the number of ACH, the greater the opportunity for particulate matter and other pollutants to be removed (AHM, 2021). The size of the room where the PAC is placed is an important variable and will influence the number of air exchanges made through the air cleaner. The Association of Home Appliance Manufacturers recommends the following equation for the largest room size that the PAC can be placed in during a wildfire event, depending on the number of air changes desired (AHAM, 2021):

$$Room\ Size\ (ft^2) = \frac{CADR\ (cfm)\ \times 60}{ACH\ \times Ceiling\ Height\ (ft)} \quad (1)$$

There have been several recent studies that evaluated the effectiveness of PACs in reducing indoor PM2.5 concentrations associated with wildfire events. Xiang (2021) studied the effectiveness of a PAC in apartment rooms, and a single-family home, by comparing the particulate matter concentration before and after the intervention of a PAC. The HEPA-PAC was left off for the first day of the study and then turned on in five out of the seven residences for the second day of the study (Xiang, 2021). A CADR of 116 cfm for dust, and 105 cfm for smoke was supplied by the manufacturer. Room sizes in the apartments and one house ranged from 581 ft^2 to 1905 ft^2, and year-built ranged from 1906 to 2019 (Xiang, 2021). The PAC was set to auto-mode, where it was able to switch speed settings (sleep, 1, 2, 3, turbo) based on measured concentrations (Xiang, 2021). Participants in this study were required to report indoor activities such as cooking, smoking, cleaning, candle burning, and window opening, along with the associated timeframe (Xiang, 2021). The study results revealed a 48%-78% decrease in the indoor PM2.5 concentration from using the PAC (Xiang, 2021). This study also suggests and gives relevant data to support the use of auto-mode PACs in the household (Xiang, 2021).

PACs have also been shown to control wildfire-sourced PM2.5 concentrations in the office setting (Stauffer, 2020). The effectiveness of a 3M Filtrete Ultra Clean PAC (FAP02-RS), with a MERV 13 rating, was evaluated by monitoring PM2.5 concentrations with two light scattering TSI Sidepack AM520 instruments each positioned in co-located offices; one with a PAC and one without (Stauffer, 2020). The indoor PM2.5 concentrations were compared with ambient PM2.5 mass concentrations obtained from a National Ambient Air Quality monitoring station located a few miles away (Stauffer, 2020). The results from this study revealed a 73% reduction in PM2.5 concentrations during working hours and a 92% reduction in PM2.5 concentrations during non-working hours (Stauffer, 2020). An office without a PAC was used as a matched control (Stauffer, 2020). The TSI Sidepacks overestimated the PM2.5 concentrations associated with wildfire smoke (Stauffer, 2020). A second outcome of this study was the publication of a ratio correction factor (Stauffer, 2020).

A summary of studies by Barn (2016) suggests that the application PACs should be considered a primary response mechanism to mitigate public exposures to wildfire smoke. The study evaluated health outcomes, such as endothelial function and inflammatory biomarker concentrations, in relation to the efficiency of particulate air filters to remove fine particulate matter from the indoor environment. Allen et al. found that indoor PM2.5 concentrations were reduced by 59% when using a HEPA-equipped PAC during landscape fire events. The 59% decrease in concentration, on average, was associated with improved endothelial function and decreased concentrations of inflammatory biomarkers (Allen, 2011). Correspondingly, research on residential air cleaner guidance shows that the best-documented health benefits come from reducing the amount of PM2.5 in homes (Harriman, 2019).

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Indoor exposures to PM2.5 particles of both indoor and outdoor origin account for about 70%, on average, of the total PM2.5 exposure throughout the United States (Fann, 2016). The study also supports the idea that portable air cleaners are the best way to reduce large amounts of PM2.5 if the central system does not use a MERV of 13 or higher filter efficiency (Harriman, 2019).

4. METHODS

4.1 Data Collection

4.1.1 Equipment

4.1.1.1 PurpleAir Sensors

Multiple PurpleAir-II-SD outdoor air quality sensors were used to measure real-time PM2.5 concentrations in this study. Although labeled as an outdoor sensor, the PurpleAir-II-SD is intended for outdoor and indoor use with an IP68 weather resistance rating. Built-in Wi-Fi allows for all data to be linked to an air quality map for easy data visualization across any smart device. An SD card is available in the instance of loss of connection or logging issues. The sensor utilizes two Plantower laser particle counters that are classified as class 1. Each particle counter stores particle sizes in five different bins: 0.3, 0.5, 2.5, 5.0, & 10µm (PurpleAir, 2022). For this study, we focused on the PM2.5 bin that includes particle sizes ~0.3µm to ~2.5µm. The counting efficiency of each particle counter is 50% at 0.3µm & 98% at 0.5µm (PurpleAir, 2022). The effective range of each particle counter is 0 to 500 $\mu g/m^3$, with a maximum range of 1000 $\mu g/m^3$ (PurpleAir, 2022). Each particle counter is independent of the other, with Channel A and Channel B. Each of the channels is then divided into two data sets, Primary and Secondary (PurpleAir, 2022).

In the PM2.5 bin, channel A & B Primary store mass concentration from count data for particles ~0.3µm to ~2.5µm for both "atmospheric" particles and "standard" particles (PurpleAir, 2022). The "atmospheric" and "standard" delineation is based on two different mass concentration conversion factors, to convert particle count to mass concentration. The "standard" particle entry data uses the "average particle density" of indoor particulate matter, while the "atmospheric" particle entry data uses the "average particle density" of outdoor particulate matter (PurpleAir, 2022). For this study, we used the Channel A Primary PM2.5 "atmospheric" particle entry data based on the characteristics of wildfire PM2.5 composition (PurpleAir, 2022).

4.1.1.2 UNbeaten Air Cleaner

Multiple UNbeaten Pet 300 PACs were also used for this study. This air cleaner is rated for an 800-square-foot room and can refresh air at 5x per hour on the high setting (UNbeatengroup, 2022). It is equipped with H13 True HEPA 5-stage filtration filters that remove 99.97% of airborne pollutants as small as 0.3 microns (UNbeatengroup, 2022). High-efficiency activated carbon accounts for roughly 80% of the filter, which has an estimated service life of 3-6 months (UNbeatengroup, 2022). For this study, each PAC was placed on setting 3 (high) and ran continuously for the length of the study. The clean air delivery rate (CADR), provided by the manufacturer, of the UNbeaten Pet 300 air cleaner is 177 cfm (UNbeatengroup, 2022).

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4.1.2 Sampling Setup

All wildfire smoke PM2.5 monitoring was conducted in a community located in the northwestern United States from August 27, 2021, through October 12, 2021. A total of nine PurpleAir-II-SD air quality sensors were strategically placed at three different facilities, identified by the local health department, and displayed in figure 1.

Figure 1. Facility Locations W/Elevation & Distance to NAAQS Air Station

Each facility was within four miles of the others and located less than three miles away from a NAAQS air station. Facility 1, Facility 2, and Facility 3 were equipped with three sensors each. The sensors were positioned close to standing head height (6 ft.) and attached to the wall. Two rooms were identified in each facility that were matched as close as possible based on volume, ventilation, occupancy, etc. One room in each of the facilities was equipped with an Unbeaten Pet 300 PAC. The PAC was placed on the opposite wall from the PurpleAir sensor, approximately 10 ft away at Facility 1, 15 ft away at Facility 2, and 40 ft away at Facility 3.

4.1.2.1 Facility 1

At Facility 1, a homeless shelter, two 124 ft^2 (992 ft^3) rooms with one window each were selected. A PurpleAir monitor was positioned on the wall furthest from the door to the hallway in each room. A portable air cleaner was placed 8 ft from the floor and 10 ft from the PurpleAir in room 2. Both rooms were located adjacent to each other, and were the furthest away from the indoor kitchen and cafeteria area. The third sensor was hung on the exterior of the building, directly outside of the two rooms and between their respective windows.

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Figure 2. PurpleAir Setup @ Facility 1

Figure 3. PAC Setup @ Facility 1

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Figure 4. Exterior Sensor Setup @ Facility 1

4.1.2.2 Facility 2

At Facility 2, a senior adult assisted living complex, two 460 ft^2 (3680 ft^3) rooms with two larger windows each were selected. Both rooms included a bedroom, bathroom, and closet space in the layout. A PurpleAir monitor was positioned on the wall between the bedroom and the bathroom, in each room. A portable air cleaner was placed on the ground level and 15 ft from the PurpleAir in room 2. The third sensor was placed directly outside the entrance to the building.

Figure 5. PurpleAir Setup @ Facility 2

Figure 6. PAC Setup @ Facility 2

Figure 7. Exterior Sensor Setup @ Facility 2

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4.1.2.3 Facility 3

At Facility 3, a school building, two 1,240 ft^2 (14,880 ft^3) rooms with multiple windows each were selected. A PurpleAir monitor was positioned on the wall midway between the room entrance and the windows, in each room. A portable air cleaner was placed 8 ft from the floor and 40ft from the PurpleAir in room 2. The third sensor was placed at an elevated level, on the exterior of the building. Each room was largely occupied (12 – 16 persons) during the weekdays, and empty on the weekends.

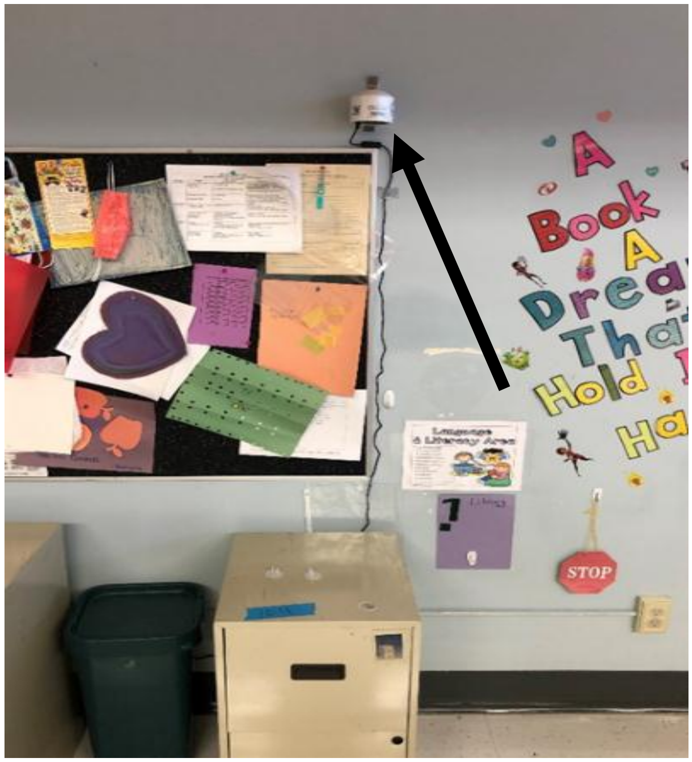

Figure 8. PurpleAir Setup @ Facility 3

Figure 9. PAC Setup @ Facility 3

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4.2 Data Analysis

4.2.1 Smoke Day Qualification

For this study, only data collected during wildfire events where the NAAQS Air Monitoring Station measured ambient PM2.5 concentrations of 50 $\mu g/m^3$ or greater during a 1-hour average, were considered. These were defined as "smoke days." For Facility 1, 11 "smoke days" were considered, corresponding to n=264 hourly concentrations at each sensor location. For Facility 2, 10 "smoke days" were considered, corresponding to n=240 hourly concentrations at each sensor location. For Facility 3, 11 "smoke days" were considered, corresponding to n=264 hourly concentrations at each sensor location. The PM2.5 concentrations measured at each facility were also compared to hourly data from the local NAAQS air monitoring station. A threshold was set to trim the data at ≥5 $\mu g/m^3$ according to the county air station. This threshold trimmed the data to n=234, n=215, and n=234 for Facility 1, Facility 2, and Facility 3, respectively.

4.2.2 Correction Factor

All data, either from the PurpleAir Map or SD cards, was downloaded as 1-hour averages measured in $\mu g/m^3$. After comparing concentration data from the exterior of each of the facilities to the local air monitoring station data, it was evident that the PurpleAir sensors were overestimating the ambient PM2.5 concentrations. A Bland-Altman Plot was used to visualize the difference in concentration measurements between the uncorrected outside measurements and the local air monitoring station measurements. Based on this overestimation, the correction factor equation from Barkjohn (2021) was applied to all data points, excluding the the local NAAQS air monitoring station data.

$$Corrected\ PM2.5\ \left(\frac{ug}{m^3}\right) = 0.524 * \left(PA\ PM2.5\ \left(\frac{ug}{m^3}\right)\right) - 0.0862 * (RH) + 5.75 \qquad (2)$$

where PA is PurpleAir sensor data, and RH is relative humidity

4.2.3 Statistical Analysis

Descriptive statistics were used to summarize mean PM2.5 concentrations for each sensor location at each facility. A time series plot was generated at each of the facilities to visually compare the PM2.5 concentrations at each of the sensor locations. The average percent differences were then calculated for: outside vs. inside w/o filter, inside w/o filter vs. inside w/ filter, and outside vs. inside w/ filter at each of the facilities. The percent differences were further categorized based on their PM2.5 range and corresponding Air Quality Index (AQI) description. The total theoretical time spent (hours) in each of the PM2.5 ranges was then calculated for each monitoring location at each facility.

Since data were not normally distributed, a Levene's test was used to test for equal variances between sensor locations at each facility. The null hypothesis was that all variances are equal, and the level of statistical significance was set at $\alpha = 0.05$. A Welch's one-way ANOVA Test, and Games-Howell ANOVA with pairwise comparisons and simultaneous tests were performed for mean differences between indoor w/o PAC, indoor w/ PAC, and ambient PM2.5 concentrations. The null hypothesis was that all means are equal, and the level of statistical significance was set at $\alpha = 0.05$. Finally, Chi-Square Goodness-of-Fit tests were performed on concentration data from each sensor location at each of the three facilities. The expected counts are outdoor concentration data, and the observed counts are

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indoor "no filter" and indoor "yes filter", separately. The null hypothesis was that there was no difference between the expected counts and the observed counts.

5. RESULTS

The mean 1-hour averaged, trimmed, and corrected data for each of the "smoke days" were categorized based on facility and sensor location. These mean concentrations for each sensor location at each facility are summarized in Table 1, with raw 1-hour concentration data in Appendix A. As shown in the table, the average outdoor concentration at Facility 1 was 42.17 $\mu g/m^3$, the average indoor "no filter" concentration was 31.52 $\mu g/m^3$, and the average indoor "yes filter" concentration was 22.67 $\mu g/m^3$. The average outdoor concentration at Facility 2 was 44.79 $\mu g/m^3$, the average indoor "no filter" concentration was 35.88 $\mu g/m^3$, and the average indoor "yes filter" concentration was 21.95 $\mu g/m^3$. The average outdoor concentration at Facility 3 was 42.65 $\mu g/m^3$, the average indoor "no filter" concentration was 37.20 $\mu g/m^3$, and the average indoor "yes filter" concentration was 30.66 $\mu g/m^3$. The measured outdoor concentration differences between each of the facilities can be attributed to geographic location. The measured indoor concentration differences between each of the facilities can be attributed to room size (sqft.), smoke infiltration, occupancy, and other indoor particulate matter contributors. Time-series plots for each sensor location, at each of the three facilities, are provided in Appendix B.

The average percent difference between each 1-hour averaged concentration was calculated for: outdoors vs. indoors "no filter", inside "no filter" vs. inside "yes filter", and outside vs. inside "yes filter" at each of the facilities. Summary average percent difference data are provided in Table one.

Table 1. Summary Average Percent Differences at each Facility

Facility #	Outdoor vs. Indoor "no filter"	Indoor "no filter" vs. Indoor "yes filter"	Outdoor vs. Indoor "yes filter"
Facility 1	-22.12 %	-34.36 %	-50.03 %
Facility 2	-15.00 %	-35.92 %	-47.37 %
Facility 3	-1.45 %	-15.67 %	-21.25 %

The number of ACH were calculated using equation one above, and illustrated in table two below. A CADR of 176.57 cfm was given by the manufacturer, and used in the calculations. The ACH presented below ignore any mechanical or natural ventilation in the rooms.

Table 2. Summary ACH for Rooms at each Facility

Facility #	Room Volume (ft^3)	CADR (cfm)	ACH
Facility 1	992	176.57	10.68
Facility 2	3,680	176.57	2.88
Facility 3	14,880	176.57	0.71

The US EPA and Montana Department of Environmental Quality provide public health advisories or levels of concern based on measured PM2.5 concentrations in community airsheds. The color-coded advisories are illustrated below. The measured duration (in hours) at each of the EPA PM2.5 ranges is illustrated for each facility in Figures 10 - 12. Note that the total time is only based on applicable "smoke days" data.

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- 0 – 12.0 $\mu g/m^3$(Good)
- 12.01 – 35.5 $\mu g/m^3$ (Moderate)
- 35.51 – 55.5 $\mu g/m^3$ (Unhealthy for Sensitive Groups)
- 55.51 – 250.5 $\mu g/m^3$ (Unhealthy/Very Unhealthy)

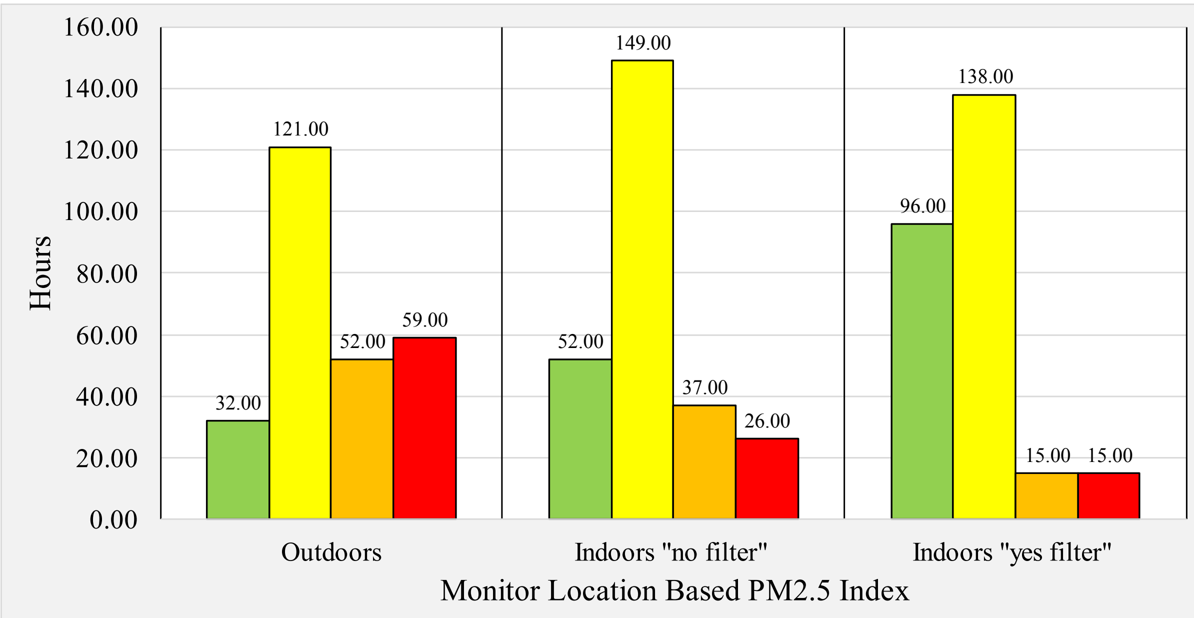

Figure 10. Facility 1 - Time Spent in Each AQI Description Based on Sensor Location

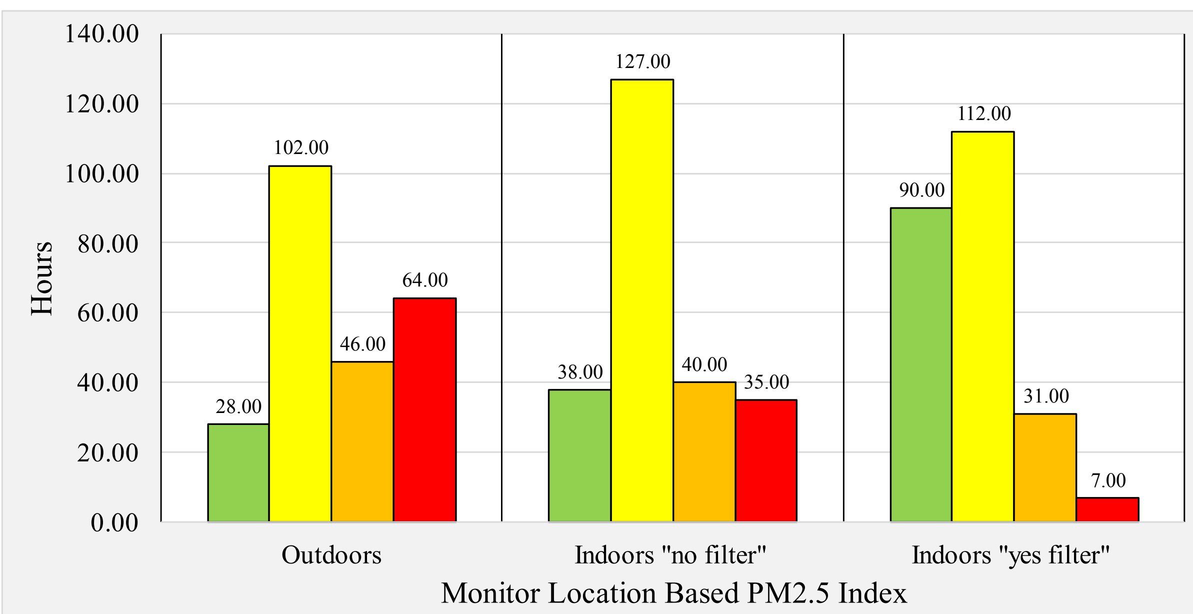

Figure 11. Facility 2 - Time Spent in Each AQI Description Based on Sensor Location

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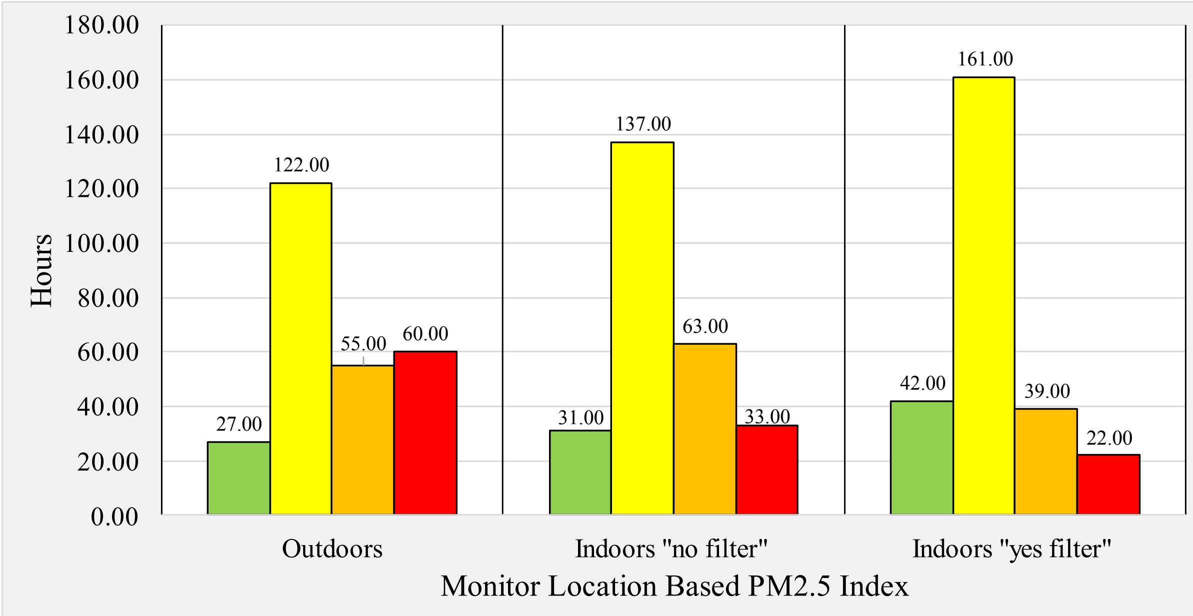

Figure 12. Facility 3 - Time Spent in Each AQI Description Based on Sensor Location

A Levene's test was used to determine if there was homogeneity of variance between the sensor locations at each of the three facility locations. At facility 1, the outdoor PM2.5 concentrations had a significantly different standard deviation ($p < .05$) than both indoor concentrations. At facility 2, the indoor "yes filter" concentrations had a significantly different standard deviation ($p < .05$) than the indoor "no filter" and outdoor concentrations. At facility 3, the outdoor PM2.5 concentrations had a significantly different standard deviation ($p < .05$) than both indoor concentrations.

At least one variance was different for each sensor location at each of the three locations. As a result, a one-way ANOVA was used along with the Games-Howell test to compare combicountries of statistical group differences between the sensor locations at each of the three facility locations. At facility 1, each sensor location was grouped separately, corresponding to PM2.5 concentration means that are all significantly different ($p < .05$). At facility 2, each sensor location was grouped separately, corresponding to PM2.5 concentration means that are all significantly different ($p < .05$). At facility 3, the outdoor sensor and indoor "no filter" sensor were grouped together, while the indoor "yes filter" sensor had a PM2.5 concentration mean that was significantly different ($p < .05$). Interval plots for Facility 1, Facility 2, and Facility 3 are provided below in Figure 13, Figure 14, and Figure 15 respectively.

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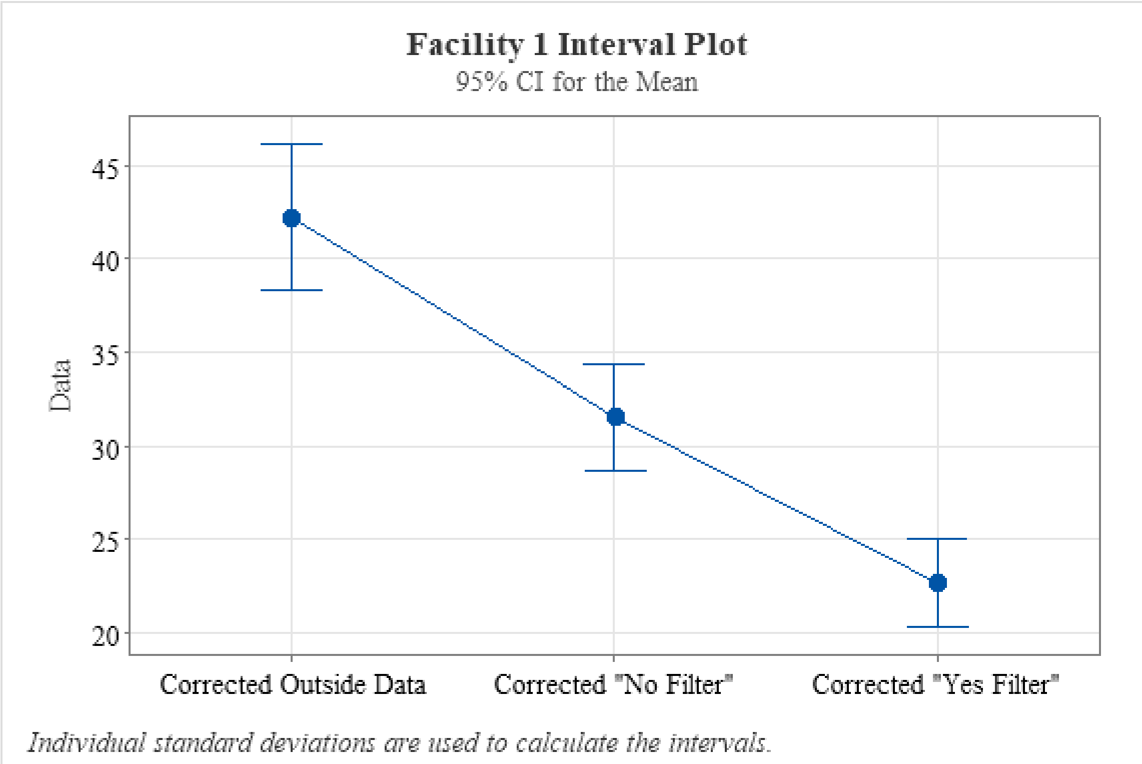

Figure 13. Facility 1 Interval Plot

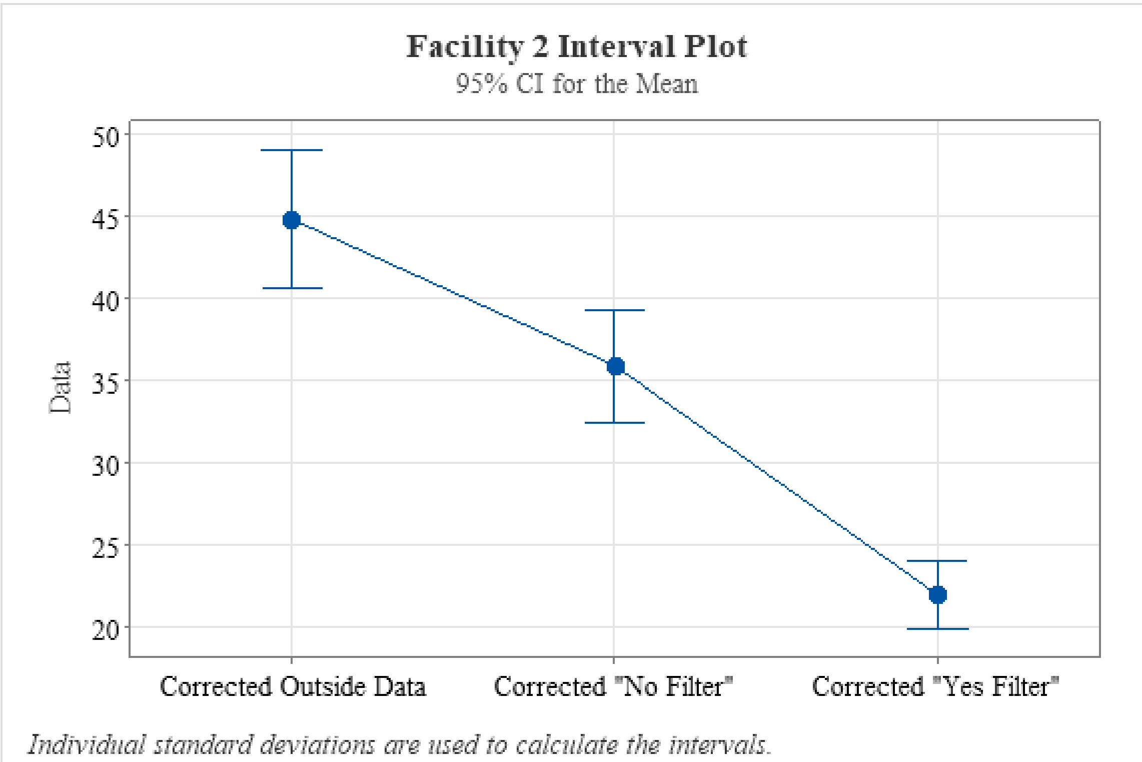

Figure 14. Facility 2 Interval Plot

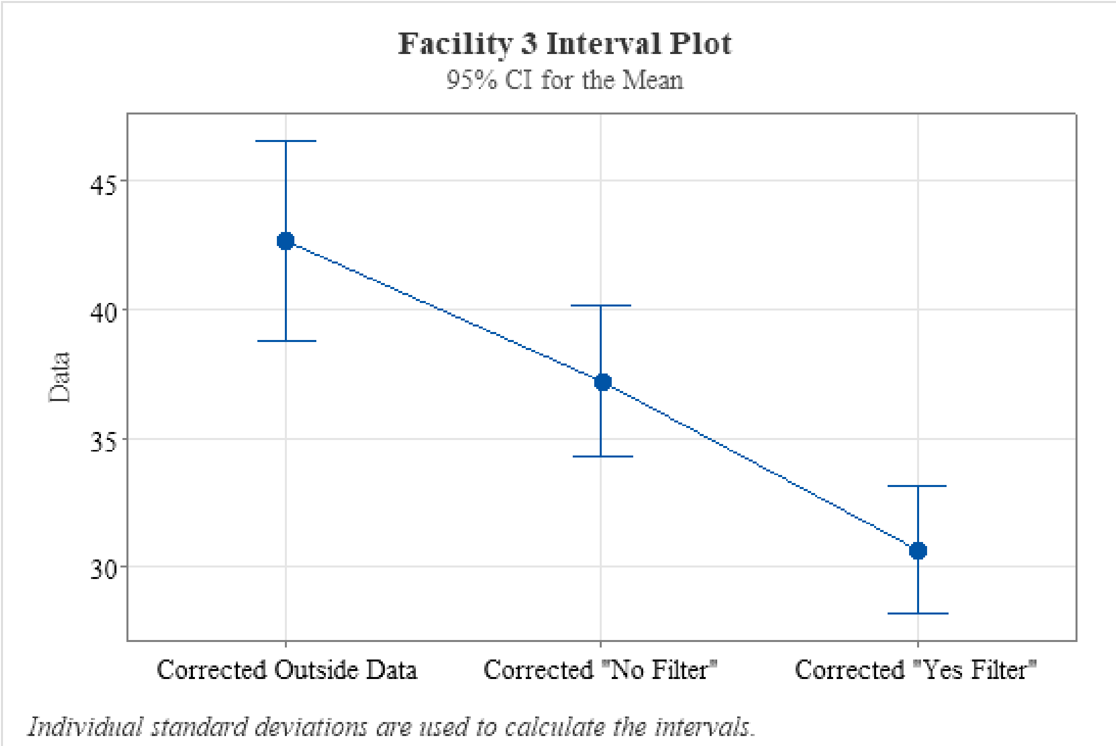

Figure 15. Facility 3 Interval Plot

A Chi-Square Goodness-of-Fit test was performed on concentration data from each sensor location at each of the three facilities. The expected counts at each of the facilities were outdoor concentration data, while the observed counts at each of the facilities were indoor concentration data from either "no filter" or "yes filter" designated rooms. Each test resulted in a significant discrepancy in fit between the observed and expected values. The plots for Facility 1, Facility 2, and Facility 3 are provided below in Figures 16 - 21.

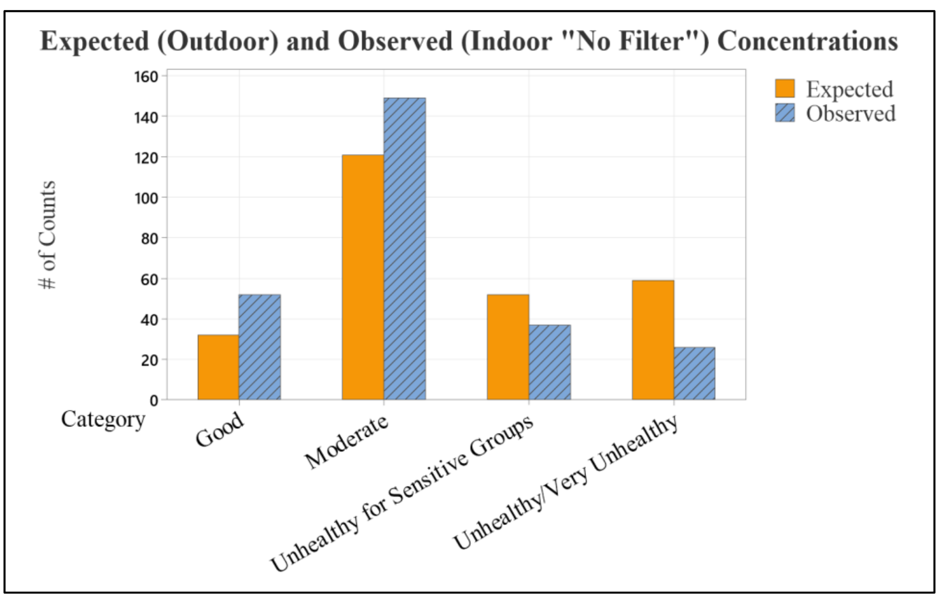

Figure 16. Facility 1 Expected (Outdoor) and Observed (Indoor "No Filter") Concentrations

https://doi.org/10.5281/zenodo.8105756

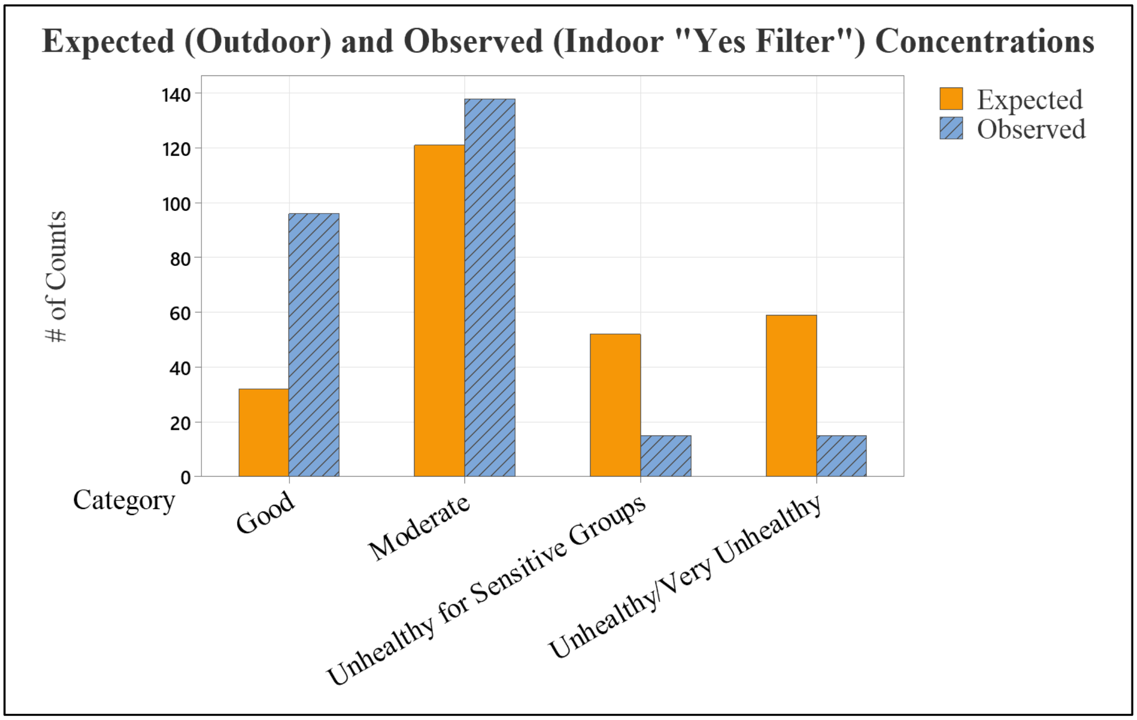

Figure 17. Facility 1 Expected (Outdoor) and Observed (Indoor "Yes Filter") Concentrations

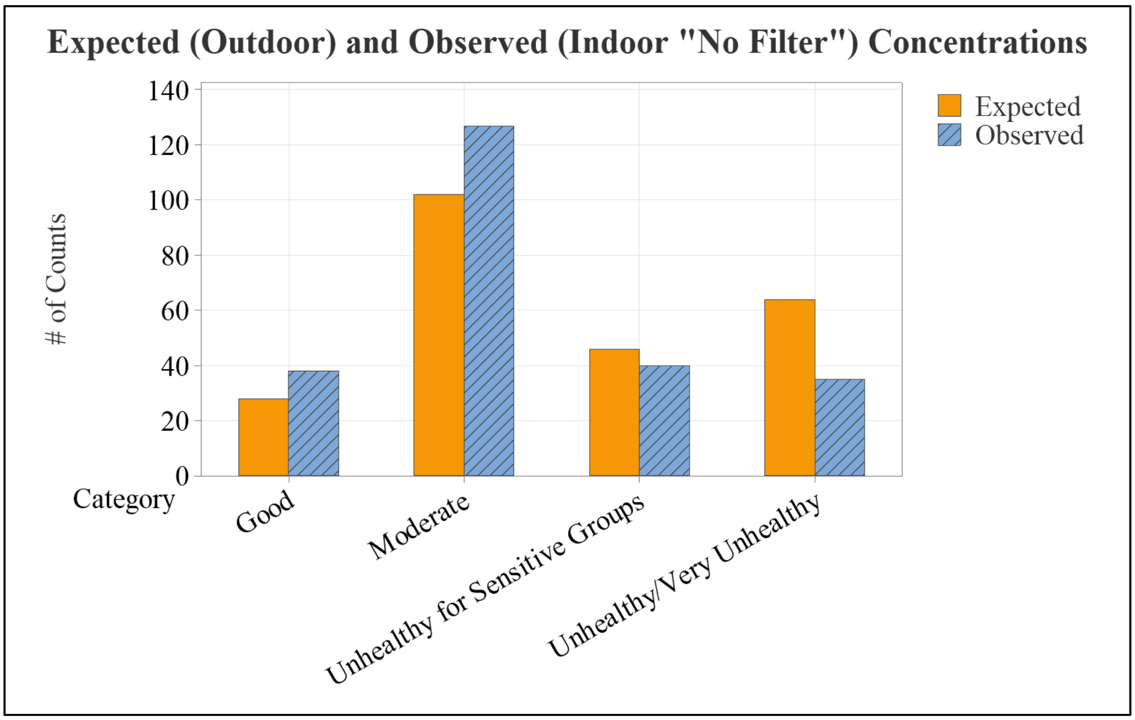

Figure 18. Facility 2 Expected (Outdoor) and Observed (Indoor "No Filter") Concentrations

https://doi.org/10.5281/zenodo.8105756

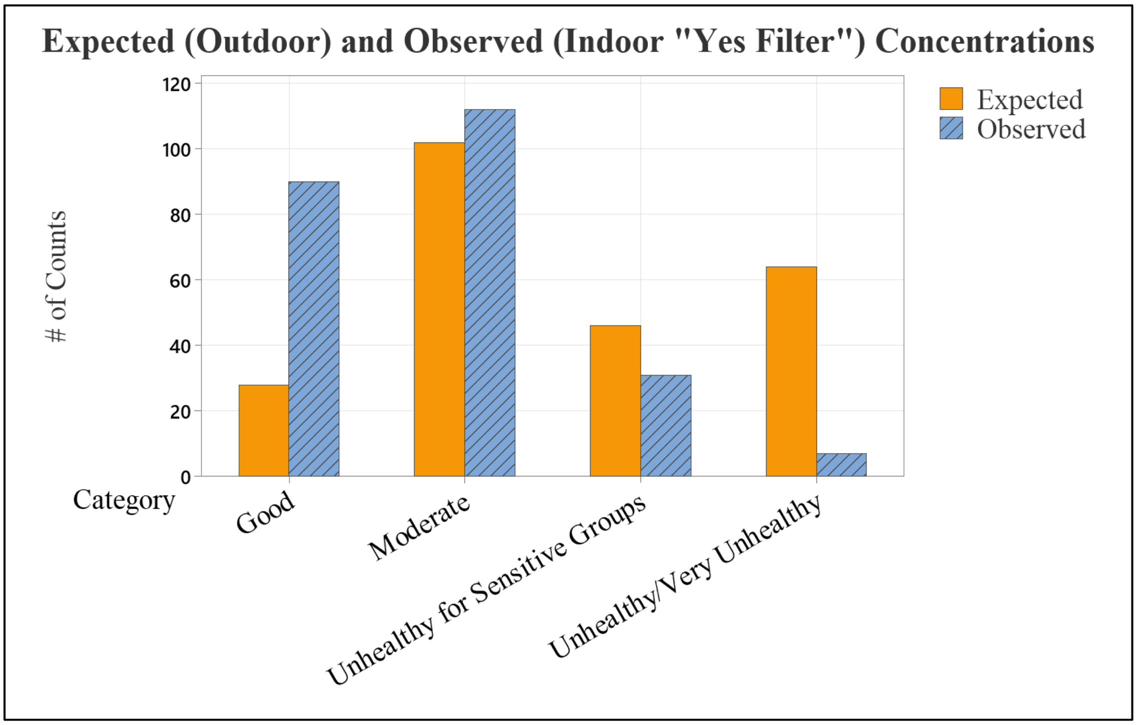

Figure 19. Facility 2 Expected (Outdoor) and Observed (Indoor "Yes Filter") Concentrations

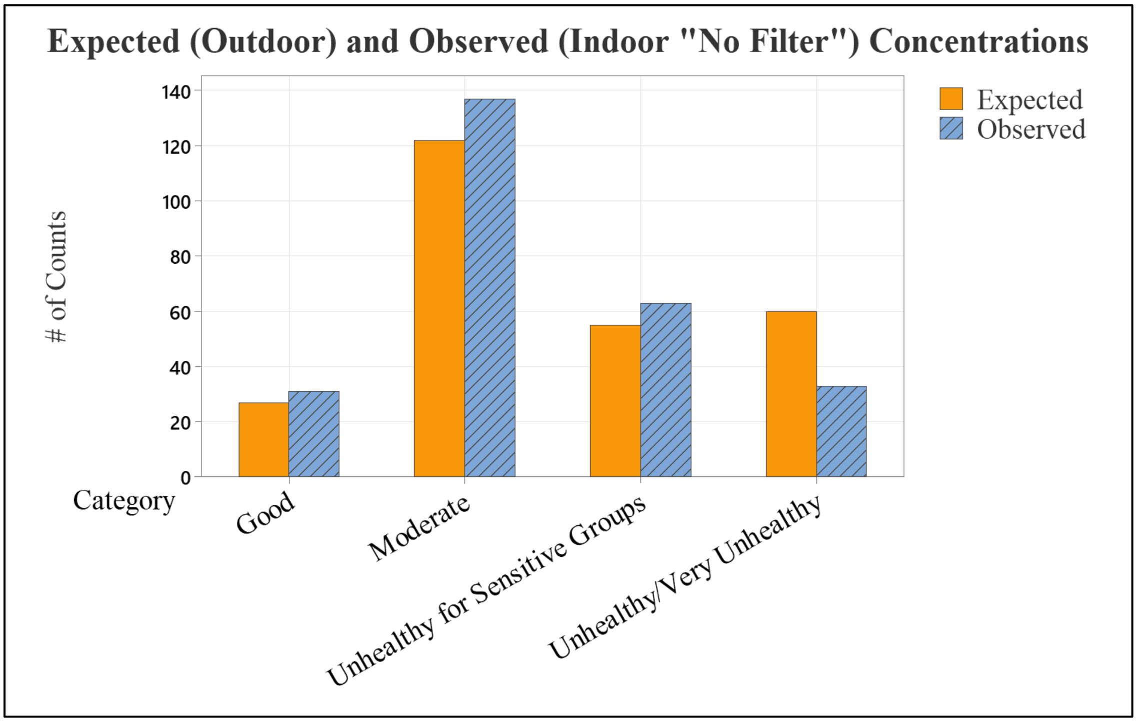

Figure 20. Facility 3 Expected (Outdoor) and Observed (Indoor "No Filter") Concentrations

https://doi.org/10.5281/zenodo.8105756

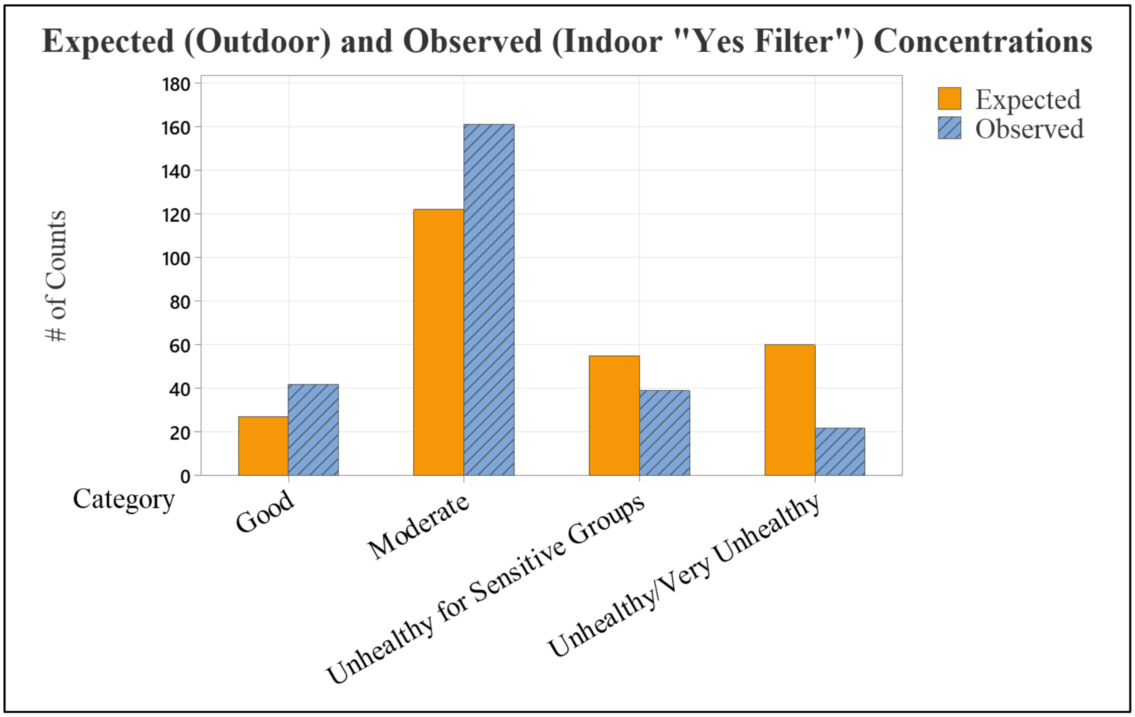

Figure 21. Facility 3 Expected (Outdoor) and Observed (Indoor "Yes Filter") Concentrations

6. DISCUSSION

The primary objective of this study was to evaluate the effectiveness of staying indoors during a wildfire event and staying indoors with a PAC during a wildfire event. The first aim was to compare the mean PM2.5 concentrations at each sensor location, at each of the three facilities. The results indicated that the average outdoor concentrations at each facility were within 6% of each other.

An assessment of the average percent differences between each facility, and corresponding sensor locations revealed that as room volume at each facility increased, the percent difference in PM2.5 concentrations between outdoor and indoor “no filter” sensor locations decreased. Similarly, as room volume at each facility increased, the percent difference in PM2.5 concentrations between outdoor and indoor “yes filter” sensor locations decreased. Overall, a decrease in PM2.5 concentrations was seen while being indoors with or without a PAC.

The second aim was to assess the total amount of time that each population group had spent in each EPA PM2.5 concentration range. Comparing the outdoor and indoor “yes filter” sensor locations at Facility 1, the number of hours spent in the unhealthy/very unhealthy range was decreased from 59 to 15 (74.58% decrease), while the number of hours spent in the good/moderate range was increased from 153 to 234 (52.94% increase). At facility 2, the number of hours spent in the unhealthy/very unhealthy was decreased from 64 to 7 (89.06% decrease), while the number of hours spent in the good/moderate range was increased from 130 to 202 (55.38% increase). At facility 3, the number of hours spent in the unhealthy/very unhealthy was decreased from 60 to 22 (63.33% decrease), while the number of hours spent in the good/moderate range was increased from 149 to 203 (36.24% increase).

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An assessment of the ACH for each room size at facility 1, facility 2, and facility 3 revealed that the UNbeaten PAC was only large enough for the rooms at facility 1 based on a recommendation of 5 ACH minimum (Salimifard, 2020). During wildfire events, the Association of Home Appliance Manufacturers recommends an ACH of 7.5 (AHAM, 2021). Having a higher ACH presents greater opportunities for air pollutants to be removed, resulting in cleaner indoor air (AHAM, 2021).

The relative risk of chronic obstructive pulmonary disease (COPD), lung cancer in adults (LC), ischemic heart disease (IHD), acute lower respiratory infection in children (ALRI), and stroke with PM2.5 exposure has been reported (Burnett, 2014). This information is useful when comparing the time spent in each EPA PM2.5 concentration range, with possible health outcomes. For example, reducing an exposure from 100 ug/m3 to 35.5 ug/ m3 would reduce the relative risk of lung cancer from 1.55 to 1.25 (Burnett, 2014).

6.1 Study Limitations

Each of the facilities are equipped with ventilation systems that are operated/maintained independently. A facility built in recent years with a well-maintained ventilation system will perform more favorable than an old facility with a poorly maintained ventilation system.

Similarly, the infiltration of wildfire-induced PM2.5 can depend on leaving doors and windows open, and the seal around the doors and windows. The occupants of each room at each facility were urged to keep the windows and doors to the exterior closed as much as possible. During regular check-ins, it was noted that the occupant in the indoor “no filter” room at Facility 2 was opening the window throughout the day. There were no other incidents for open windows at any of the other sensor location.

The number of occupants at each facility also differed, with 1-2 at Facility 1, 1-2 at Facility 2, and 12-16 at Facility 3. Facility 1 was only occupied during the night, Facility 2 was occupied during the day and night, and Facility 3 was only occupied during the day.

7. CONCLUSION

This study evaluated the effectiveness of staying indoors during a wildfire event and staying indoors with a PAC during a wildfire event. Previous studies have revealed that portable air cleaners are an effective intervention to decrease the concentration of wildfire-induced PM2.5 indoors. These results suggest that even if a portable air cleaner is not available, staying indoors is still an effective option to decrease wildfire PM2.5 exposure. The use of a PAC greatly reduces the amount of time an occupant is exposed to unhealthy/very unhealthy concentrations of wildfire-induced PM2.5. The PAC performed most efficient at or below its designed room square footage, but still offered a smaller decrease in PM2.5 for the larger square footage.

In terms of the vulnerable population, the indoor PM2.5 concentration should be at or below 35.5 $\mu g/m^3$, as to stay below concentrations that are unhealthy for sensitive groups. Further research should be performed to include a larger number of facilities and sensor locations, potentially including sensors in ventilation/HVAC systems. A potential limitation that may have influenced the PM2.5 concentrations reported is the amount of indoor PM2.5 that was produced during the study period.

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APPENDIX A

Raw 1-hour averaged, trimmed, and corrected concentration data for each sensor location at each facility during all “smoke days” are provided here: Appendix A - Raw Data

APPENDIX B

Time-series plots for each of the three facilities, each including 1-hour averaged, trimmed, and corrected concentration data for each sensor location during all “smoke days” are shown below:

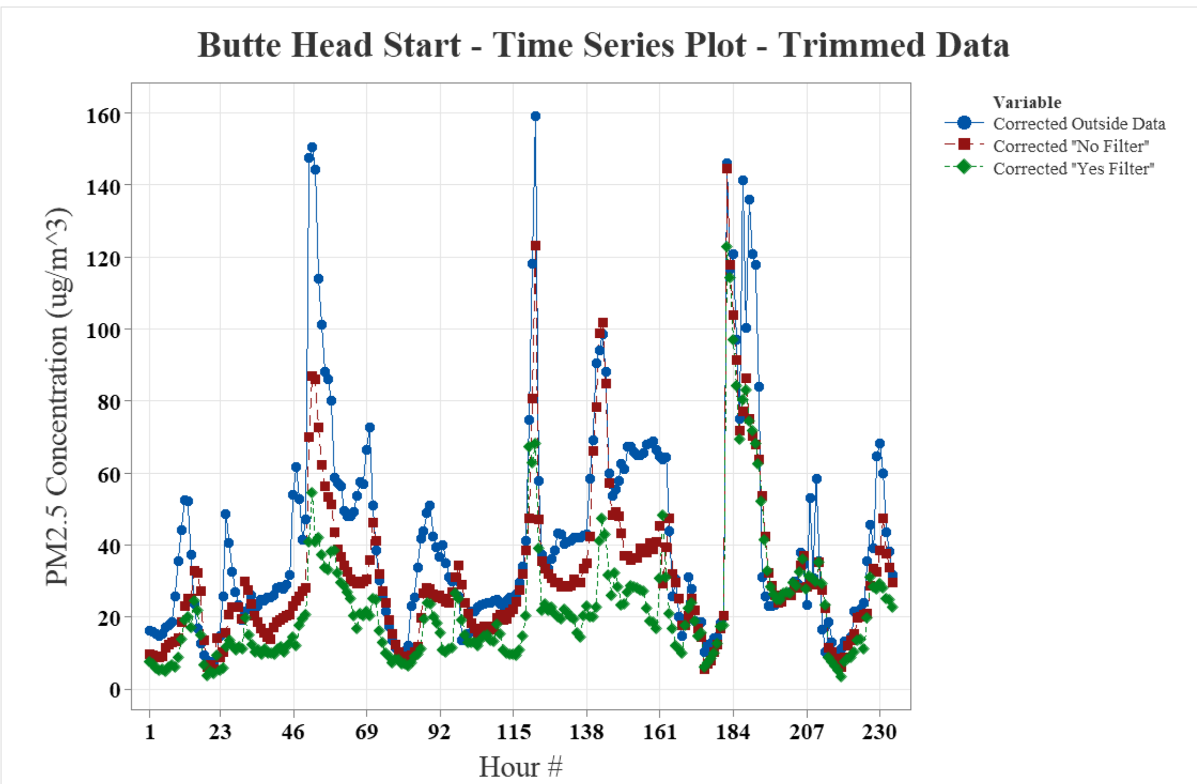

Figure 22. Time Series Plot - Facility 1 - Trimmed Data

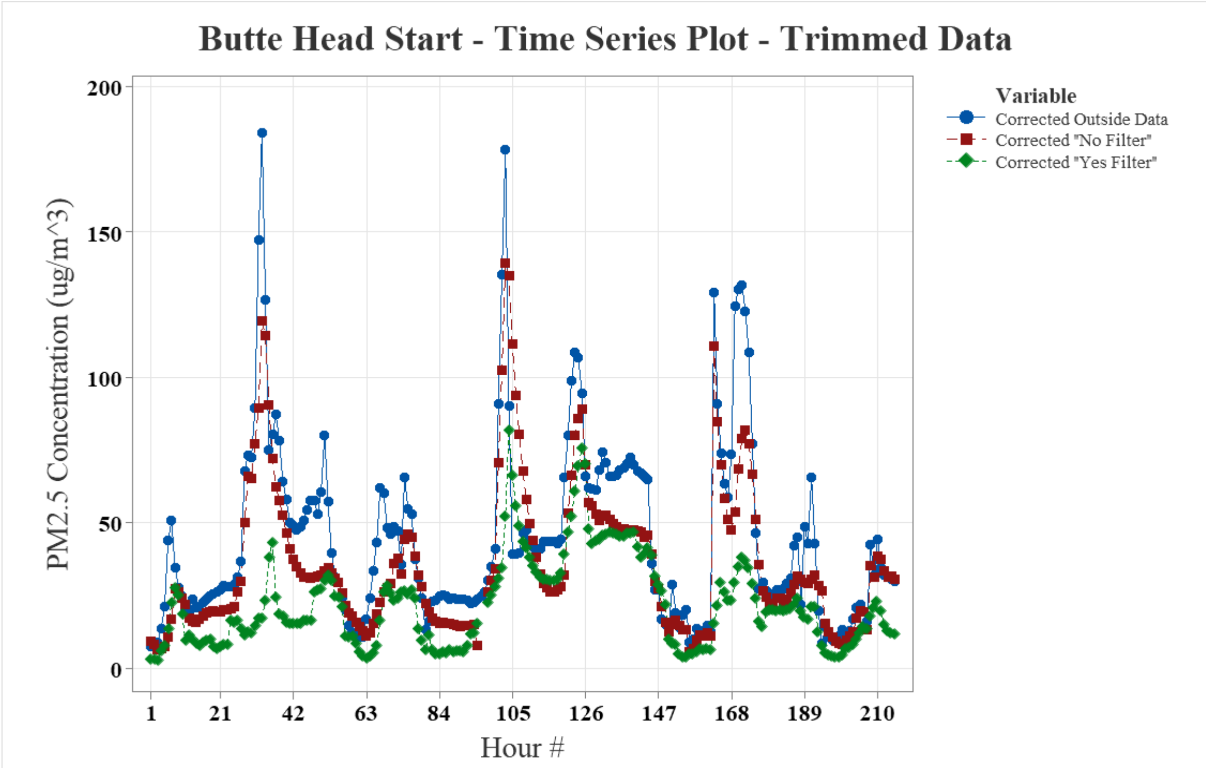

Figure 23. Time Series Plot - Facility 2 - Trimmed Data

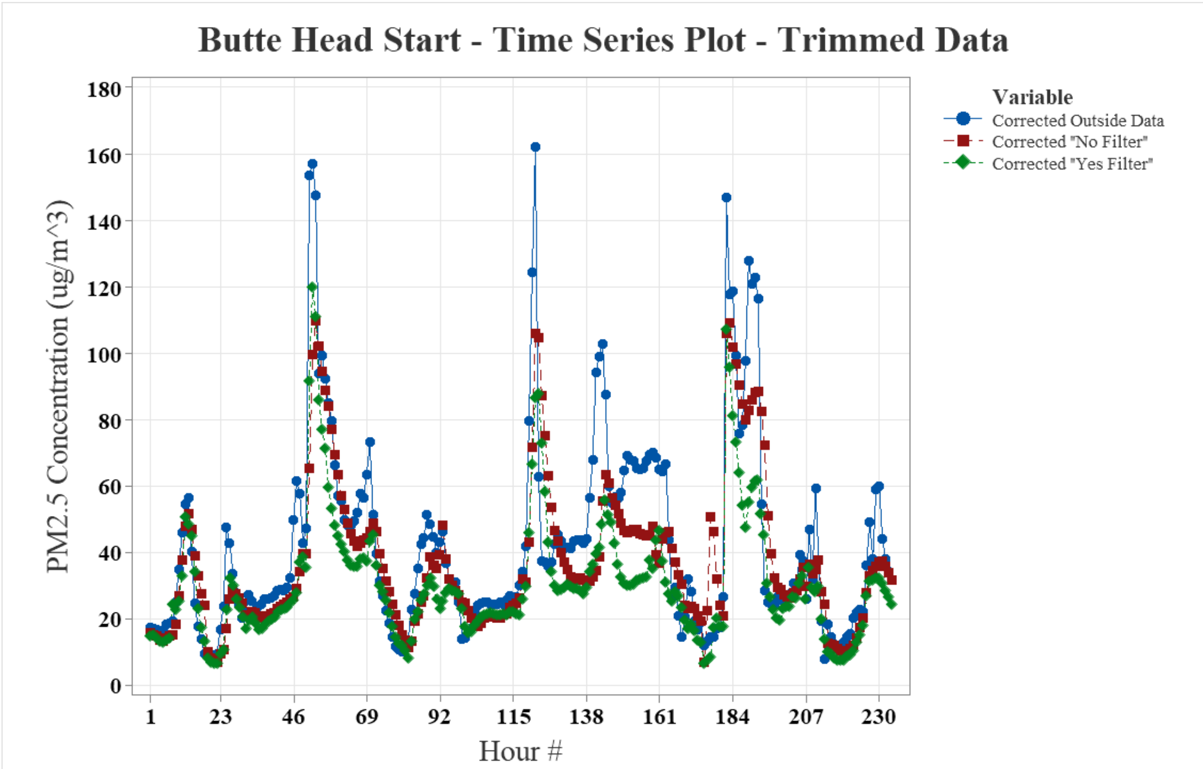

Figure 24. Time Series Plot - Facility 3 - Trimmed Data

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MAIN AUTHOR

Mr. Layne Willis is a graduate student at Montana Tech. Layne earned his bachelor’s degree in civil engineering at MSU and, recently, his master’s degree in industrial hygiene. Layne worked with Drs. Dan Autenrieth and Julie Hart in the Department of Safety, Health, and Industrial Hygiene. Layne completed his research on the effectiveness of low-tech, low-cost air purification systems for vulnerable populations in the Butte area during wildfire smoke events.

Working with the Bute Silver-Bow Health Department, the team identified three groups: senior citizens at the Springs, the young at Butte Head Start, and the underprivileged at the Butte Rescue Mission. Layne had to first meet his population on a personal level. He placed air monitors and air purifiers in specific locations for two months. Air quality measurements were taken during the two-month smoke season in residences with air purifiers. Findings revealed that staying indoors reduces exposure, and the air purifiers further reduced exposure to harmful air pollutants. The research provides evidence of effective and affordable interventions for disadvantaged and vulnerable citizens.

CITATION:

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