DO-IT-YOURSELF AIR FILTER PROJECT REPORT

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EXECUTIVE SUMMARY

When wildfires occur, there are many impacts a community may face. While some of these impacts are localized, other impacts, such as those from wildfire smoke, can affect a larger area and may cause delayed health effects to those exposed. Frontline communities that have suffered the effects of wildfire smoke have been recommended to invest in commercial portable air filters to mitigate health impacts from wildfire smoke exposure. While commercial air filters are effective, they often require significant investment and ongoing costs to replace expensive proprietary filters. Moreover, in the 2020 fire season, commercial portable air filter units were out of stock in much of California when people needed them most. Due to the smoke concentrations faced by many communities in the 2020 fire season, agencies began recommending Do-It-Yourself (DIY) air filter units as an alternative for those unable to obtain commercial portable air filters.

This report investigates the design options of DIY air filters and compares the efficacy of one popular design to that of a commercial portable air filter, a Medify MA-25. We assessed a box fan-based design with two filters arranged in a triangle because this design appeared to balance cost, performance, and ease of fabrication. We subsequently investigated filtration efficacy, power, and energy use, localized heating, noise generation, costs, and ease of assembly.

Filtration testing was completed by burning sheets of paper in an enclosed space and measuring PM2.5 (particulate matter 2.5 microns or less in size) concentration over time. This is somewhat different than the exposure case during a wildfire, where smoke is continuously present outside but provides a good approximation of a case where windows and doors are closed after the smoke has already infiltrated into a room, provided that the room is reasonably well sealed.

The DIY air filter unit was able to clear particulates from the room in 25 and 35 minutes on the high and low fan settings, respectively, significantly faster than the Medify MA-25 filter, which took 40 minutes and 3.4 hours on high and low, respectively. Power draw and energy consumption were similar for the DIY filter on either setting and the Medify filter on high, 33-53 watts, and 20-24 Watt-hours. On the low setting, Medify consumes about 25% as much energy and only requires 1.4 watts. On the high setting, we found that the DIY filter could raise temperatures by 0.36°C per hour (0.65°F per hour), insignificant over the less than 25 minutes the filter must be run, but impactful if the DIY filter were run continuously.

Noise generation was also similar for the DIY filter on either setting and the Medify filter on high, at 61-70 dBA. The Medify does not raise the room's noise level above the background level while on low, a feature that the DIY filter cannot replicate as-is, but which we found a path towards recreating. We were able to significantly reduce the noise level of the DIY filter by reducing the source voltage to 60-V. On the low setting, this reduced the noise generated from 61 dBA to 38 dBA, the latter of which was hardly distinguishable from the background level. This required a $55 Variac but could perhaps be achieved with a modification to the fan design, a promising area for future study.

The 30% initial cost, $71 compared to $220 for the Medify MA-25, is a main advantage of the DIY filter. In the first year, the DIY filter's cost reaches 40% of Medify's cost after a single filter replacement, reaching $110 compared to $270. In the longer-term, five years, the DIY filter's cost reaches 70% of Medify's $430 compared to $670.

Our DIY filter was relatively easy to construct, requiring no special skills and only common household tools (i.e., marking device, straight edge, and scissors). It took approximately one

hour for us to build. The main assembly challenge is in replacing filters, which cannot be done easily. The user must, in essence, rebuild the entire filter. This is in contrast to the Medify MA-25, which has filters that are easily replaced in seconds with no tools.

In summary, the DIY filter is significantly cheaper than the reference filter, more effective at removing particulates, and easy to assemble. It generates more noise as-is but has a promising path towards a low-noise version. The main area where the commercial portable filter outperforms the DIY filter is in terms of easy filter replacement. Finally, we note that the DIY filter is bulkier and somewhat uglier than the sleek Medify MA-25 unit.

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1 INTRODUCTION AND BACKGROUND

As wildfires become increasingly more common and impactful due to a combination of problematic forest management practices (Stephens et al. 2016), climate change (Westerling et al. 2011), and increased development on the urban-wildland interface (Kramer et al. 2019), the need to mitigate their impacts increases. While the direct loss of life and housing are tremendous, too are the delayed and acute health impacts of smoke inhalation from wildfires, leading to additional fatalities (Richardson et al. 2012).

Filtration of indoor air is an effective solution to reduce exposure to wildfire smoke particulates. Studies have shown that properly sized, high-efficiency, particulate air filters can reduce indoor concentrations of particulate matter (PM) by 80% to 85% (Air Now 2020; Laumbach 2019). But portable indoor air cleaners have significant upfront costs, ranging from $50 to $3,000 (Air Now 2020), with recommended filters costing at least $200 and ongoing expenses in the form of electricity and replacement filters costing $50 or more (Medify Air 2021a). Furthermore, like air conditioners during heatwaves (Russel 2019), air filters can fly off the shelves during forest fire season (Kreidler 2019), leaving many in need.

One common solution is do-it-yourself (DIY) filtration solutions, which can be made cheaply, and from easy-to-find parts such as fans and replacement filters (Montana Wildfire Smoke n.d.). However, these DIY solutions have been little studied, and their efficacy is mainly unknown (U.S. Environmental Protection Agency 2020). Therefore, we sought to develop and test an effective DIY filtration solution with key metrics of efficacy, affordability (both in terms of initial and ongoing costs), and availability.

2 LITERATURE REVIEW

2.1 Measurement of Critical Particles

Most studies of wildfire smoke composition have been focused on emissions from natural biomass fuels. As fires move into the developed wildland-urban interface (WUI) areas, more research is needed to assess the effects of combusting the complex mixture of natural and structural emissions on human health (Stone et al. 2019). In wildfire smoke, particulate matter (PM) with a diameter smaller than 2.5 micrometers (µm) are the most significant concern for public health (California Air Resources Board 2021). Particles with a diameter of 10µm, or less, often referred to as PM10, also contain the smaller particles classified under PM2.5. PM10 and PM2.5 can both have adverse health impacts, but PM2.5 include only ultrafine particles more likely to travel deep into the bloodstream and deposit deep within the lungs, while PM10 concentration includes larger particles that are more likely to deposit on surfaces but not reach deep into the lungs and bloodstream (California Air Resources Board 2021). Studies show short-term PM2.5 exposure can cause harm to "infants, children, and older adults with preexisting heart or lung diseases," while short-term PM10 exposure can impact people with "respiratory diseases, including asthma and chronic obstructive pulmonary disease (COPD)" (California Air Resources Board 2021). Furthermore, because more is known about the long-term health impacts of PM2.5 than PM10, we focus on PM2.5 concentrations in our study.

A recent study conducted by the Lawrence Berkeley National Laboratory (LBNL) compared PM2.5 concentration measurements of four low-cost monitors exposed to wildfire smoke. It concluded that, while the PurpleAir PA-II reported higher PM2.5 concentrations compared to other monitors, the PA-II had a consistent response to wildfire smoke, which means the measurements can be calibrated to increase accuracy (Delp and Singer 2020). One such calibration is the LRAPA correction. This algorithm was developed in the airshed of Lane County, OR, from measurement of PM2.5 aerosols "primarily driven by wintertime wood smoke from home wood heating" (LRAPA n.d.), making it a good match for measurement of PM2.5 from wildfires.

2.2 Optimal Filter for DIY Solutions

The efficiency standards of air filtration devices, such as heating, ventilation, and air-conditioning (HVAC) systems and portable air cleaners, are measured using either minimum efficiency reporting value (MERV) or clean air delivery rate (CADR) (Joseph et al. 2020). The MERV rating is based on the average removal efficiency across three particle size ranges: 0.3–1.0 µm, 1.0–3.0 µm, and 3.0–10.0 µm. MERV rating is typically used to evaluate the performance standards of filters used in HVAC systems (Joseph et al. 2020). Generally, if a filter has a high particle removal efficiency, it will have a higher MERV rating (Joseph et al. 2020). Furthermore, only filters with a MERV 11 or higher rating have their ability to remove at minimum 20% of small particles (0.3–1.0 µm) tested, and MERV 13 and higher-rated filters must achieve a minimum 50% percent removal efficiency for particles in this size range (U.S. Environmental Protection Agency 2018). See Appendix D for further detail.

Filter geometry must be considered when looking at MERV ratings because the thickness and depth of pleats affect the filter's ability to remove particles from the air. MERV 1-4 are generally flat panels that have a low particle removal efficiency for particles between 3.0 and 10.0 µm, MERV 5-12 have pleated panels with a higher particle removal efficiency for particles sizes 1.0 to 10.0 µm, and MERV 13-16 have heavier pleating and a higher particle removal efficiency for particles 0.3 to 10.0 µm (Appendix D). Therefore, a filter for a DIY unit that will be utilized for wildfire smoke should have a filter with at least a MERV rating of 13 because these filters can filter out a majority of ultrafine PM2.5 that can lead to health issues.

HEPA filters have their own standard but are similar to MERV 17-20 filter rating, as shown in Figure 1. However, caution is warranted because "there is no widely accepted definition of HEPA performance in consumer products" (U.S. Environmental Protection Agency 2018 p. 20). It is accepted that HEPA filters have the highest removal efficiency for particles 0.3 to 10.0 µm, but the performance of HEPA-home filter systems and HEPA-industrial filter systems are not necessarily the same (U.S. Environmental Protection Agency 2018).

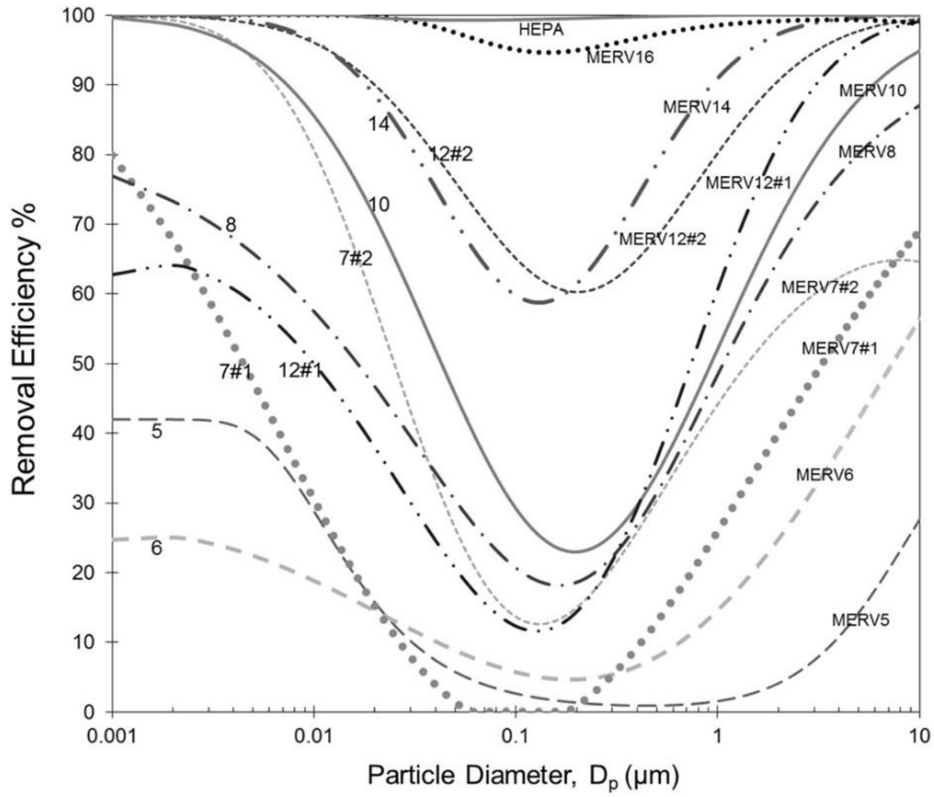


Figure 1. The removal efficiency of HVAC filters, including MERV 5 through MERV 16 and HEPA. (Azimi et al. 2014).

The clean air delivery rate (CADR) is a measure of effectiveness in reducing pollutants (Joseph et al. 2020). CADR is similar to the MERV rating systems since it is calculated based on removal efficiency of air pollutants of three pollutants of varying sizes: pollen (5 to 11 µm), dust (0.5 to 3 µm), and tobacco smoke (0.09 to 1.0 µm) (Joseph et al. 2020). When choosing a portable air cleaner, a consumer should consider the size of the room and what airborne pollutants they want to remove from the air. Generally, it is recommended that a portable air cleaner has a CADR rating for tobacco smoke particles, measured in volume per minute (e.g., ft^3/min), of at least 2/3 of the footprint (e.g., ft^2) of the room being cleaned, as shown in Table 1 (Joseph et al. 2020). Higher CADR relative to room size will increase the effectiveness.

Table 1. The estimated minimum CADR rating for rooms ranges from 100-600 ft^2. Data from the U.S. Environmental Protection Agency (2018).

Room Area (ft^2)	100	200	300	400	500	600
Minimum CADR (ft^3/m)	65	130	195	260	325	390

The Oregon Health Authority (2020) recommends that DIY air filters used for wildfire smoke utilize either HEPA or MERV 13+ filters that are 3-5 inches thick. Many sources recommend changing filters when they become visibly dirty (i.e., change color), if possible (Oregon Health Authority 2020). How fast an air filter can get visibly dirty is dependent on the air it is exposed to. For example, during the 2017 wildfire season, the Puget Sound Clean Air Agency had to change filters after one week of use, as depicted in Figure 8 (KUSA 9 News 2018).

Figure 2. The filter on the left was used for one week during the 2017 wildfire season and on the right is a new filter. Photo is from Puget Sound Clean Air Agency (KUSA 9 News 2018).

3 OBJECTIVE, CRITERIA, AND CONSTRAINTS

We aimed to design an air filter that effectively removes wildfire smoke, affordable (both in terms of initial and ongoing costs), available, *and* easy to assemble without special tools or skills. Effectiveness was measured against a Medify MA-25 filter, with the goal that the DIY filter remove PM2.5 nearly as quickly. Affordability constraints included an initial budget of $100, a little under half the cost of the MA-25, and ongoing costs no higher than that of the MA-25. Availability was not quantified but required that all parts be available from a single big box hardware store, such as Lowes, Home Depot, or Ace Hardware. Ideally, all parts would be available from any of these stores, but this was not assessed. Ease of assembly was based on assessing the skills required for construction and any tools required. This result was also not quantified but rather a qualitative assessment.

Another factor that we assessed was noise generated by the DIY filter. Noise can become an issue if it leads to reduced usage discouraging placement in sleeping spaces, where people spend a majority of their time (Batterman et al. 2013; Sulser et al. 2008). The noise was assessed by measuring generation, in dBA, during filter operation.

Finally, we considered power and energy usage during filtration, and the potential for this power, dissipated as heat, to warm up the room in which the filter is used. We did not set strict requirements for these values for various reasons: If constructed from available parts, the power draw was unlikely to be unreasonable; if energy usage were too high, this would show up in our assessment of ongoing costs; and if power draw were reasonable, the effect of room heating would also be within the range of other household appliances.

4 DESIGN DOWN SELECTION, DECISION JUSTIFICATION, AND DESIGN DETAILS

This section begins with a review and evaluation of popular DIY filter designs available on the internet, followed by a description and details of our selected design and justification for these decisions. Finally, we discuss two additions that can be made to the design: a battery pack for those with intermittent grid access; and a variable AC transformer used to lower the source voltage, which reduces fan speed, power consumption, and noise.

4.1 Popular Design Comparison

The most popular DIY filter design is the simple fan filter setup shown in Appendix C, in which a filter is taped to the inlet side of a fan. This cheapest, quickest, and easiest to assemble and is the first item listed in Table 2.

Table 2. Compilation of potential DIY air filter designs along with the estimated skillset that would be required to assemble the unit, costs associated with parts and equipment, and the estimated time it would take to build the unit.

Number	Design	Skill	Cost	Build Time
1	Simple fan filter	Easy	$ 55	5 minutes
2	Box Filter	Easy	$ 150	20 minutes
3	Bucket filter	Moderate	$ 70	1 hour
4	Plyboard double filter	Hard	$ 70	2-3 hours
5	Triangular-shaped filter	Easy	$ 70	25 minutes

We had several concerns relating to this design: First, without having additional filters in parallel, the flowrate will be lower. Furthermore, since the filter is adjacent to the fan, there will be dead spots of zero flow at the center and edges, exacerbating this effect. This compares negatively to a design with spacing between the fan and the filter, which allows air to achieve a more uniform flow across the filter and thus a higher total flowrate. Second, because of the low flowrate, especially near the fan's center, we were worried that the fan motor would overheat, a risk several sources have highlighted (Puget Sound Clean Air Agency 2021).

The second filter design, the Box Filter, is too expensive as it required four filters to be attached to the box fan. As shown in Table 2, its price is expected to be well more than $100. This box filter design is shown in Appendix C, Figure C-2.

The third filter design, the bucket filter (see Appendix C, Figure C-3) was eliminated from contention because no MERV-13 or better filters are available in this form factor. We were also concerned that this design would require strength, skill, and power tools to drill many holes into a bucket.

The fourth design in Table 2, the plyboard double filter (Appendix C, Figure C-4), requires woodworking, again implying that the user has strength, skill, and access to power tools. This, in addition to the cost of procuring wood, disqualified the design from further consideration.

Finally, the fifth filter design and the preferred one, a triangular-shaped apparatus (Appendix C, Figure C-5) with two filters on the inlet side, appeared to address all the concerns we had with the other options: The cost is well under $100, no special skills, materials, or tools are needed to construct it, and the multiple parallel filters are not butted up against the fan.

4.2 Design Details

The filter's final design is composed primarily of two 20” by 20” MERV 13 filters and a 20” by 20” box fan, forming an equilateral triangle, as shown in Figure 3. The design uses cardboard cutouts at the top and bottom, salvaged from the box the fan came in, to create a sealed duct between the fan and filters. The device is affixed and sealed together with duct tape. A list of materials, not including required tools, is presented in Table 3. Instructions for assembly and use are provided in Appendix F.

Figure 3. Our DIY triangle-shaped filter unit. Note the location of the on knob for turning the filter on (near the top right). It is important not to enclose the knob when assembling the filter.

Table 3. Required parts and equipment for triangle-shaped filter design.

Item	Make/Model	Purpose	Qty	Unit Price
MERV 13 filter	Filtrete Model #MA02DC-6	filtration	2	$19.97
20” Box fan	Utilitech Model #FB50-16HB	circulation for filter	1	$20.98
Premium duct tape	3M Model #2835-L	attaching and sealing	1	$9.98
Cardboard	Box from the box fan	Cover open areas	1	“free”

4.3 Design Justification

We initially planned to modify the triangle design into a diamond with two filters on the inlet and two on the outlet. The inlet side would use MERV 8 filters while the outlet used MERV 13 so that the relatively expensive MERV 13 filters would need to be replaced less. However, procurement considerations forced reversion to the single triangle design. Home Depot does not carry many MERV-rated filters. Instead, they use their own proprietary FPR ratings. FPR 10 appears to be comparable to a MERV 13 rating (Air Force One Plumbing Heating & Air 2020); however, since the literature on FPR is sparse compared to the industry standard MERV, we thought it best to avoid these filters. Therefore, we direct prospective shoppers away from Home Depot. Lowe’s has a wide selection of MERV 13 filters, but no MERV 8 filters were available at the Lowes we investigated (Lowes of San Francisco). MERV 5 was their only option below MERV 11, and MERV 5 filters are ineffective at filtering PM2.5. MERV 11 are quite a bit more expensive, $10 each, and could reduce the flowrate too much *and* make the filter design too expensive.

However, the design of the box fan that is commonly available at Lowes, also shown in Figure 3, also provided a challenge to the diamond design. This fan has the knob on the front face, preventing placement of filters on the front face as the diamond design would require. This means that prospective filter builders would have to go to *two* stores, particularly problematic in areas with only one such store. By returning to the single triangle design, assembly is more straightforward, the upfront cost is reduced, and parts are more easily obtainable at one location.

4.4 Battery

Most utility providers in California have begun periodically shutting down areas of the grid during wildfire season when the risk of wildfires is high. For this reason (or for any loss of power), a battery with a portable solar panel can be a good backup plan which enables filtration during bad air quality days. (U.S. Environmental Protection Agency 2021c). The minimum power required in our application is 60 Watts, the box fan's rated power with a small margin. Having the battery pack available is advantageous for other reasons, too: it provides a means of charging household devices like phones and laps. Charging communication devices might prove essential during the wildfire season. Adding a solar panel with a portable can give additional life to the battery pack during prolonged outages.

The cheapest solar plus battery option we identified costs \$260, with \$120 coming from the solar panel and \$140 for the backup battery. Panel and battery pack are shown in Figure 4.

Figure 4. A backup portable power bank (Amazon.com, Inc. 2021b), and a portable solar panel that can be used with a battery (Amazon.com, Inc. 2021a).

The 151-watt-hour battery pack holds enough charge to run the DIY filter seven times, based on our findings in Section 6.3. This is sufficient to clear a 35-m^3 room twice a day over the course of a 3-day outage without the panels. The 50-watt panel can collect at least 100 watt-hours per day in all months but December and January in Arcata (Dunlap et al. 1994), enough to run the filter five times per day for an outage lasting any length of time. That said, the battery pack and solar panel are not part of our main design, they are additions that can easily be made for a moderate investment.

4.5 Extra-Low Speed Setting

Because the lowest-speed setting on the box fan is still relatively high, as evidenced by the power draw (Section 6.3) and noise (Section 6.5), we sought to test an extra-low speed setting by reducing the source voltage. We accomplished this by plugging the fan into a 5-amp variable output autotransformer, as shown in Figure 5, which we bought for \$55. We set the transformer to 60-V for subsequent tests, with the fan on low; thus, this setting is referred to as "60V-Low."

This was not a fully experimented upon setup, rather, we chose a setting by feel and sound, which still moved air but appeared to be quiet.

This piece of equipment is not meant to represent part of our design. It is intended to demonstrate what is possible were fan designers to add an extra-low speed setting. That said, for users with an extra $55 or who already have the equipment, it is plausible to use the device as shown, so we consider it an optional add-on.

Figure 5. Assembled air filter unit plugged into a variable AC transformer set to 60-V (bottom right).

5 EVALUATION METHODS

5.1 Filtration Efficacy

We expected the PM 2.5 concentration to follow an exponential decay (Dacunto et al. 2015; Ghosh et al. 2018). To determine the decay coefficient, we burned two sheets of paper in an enclosed room with doors and windows closed and fit the observed data using an exponential decay to approximate the decrease in PM2.5 concentration over time:

$$C(t) = C_o e^{-kt} \qquad \text{Equation 1}$$

Where *C(t)* is the concentration (µg/m^3) at time *t*, C_o is the initial concentration (µg/m^3), *e* is the mathematical constant (approximately 2.71828), and *k* is the rate of decay (minutes^{-1}).

We tested in an indoor bedroom with a footprint of 11’ 10” x 13’ 3” not including the closet, which is 3’ x 4’ 10” (and is isolated by a sliding door). The ceiling of the whole room, including the closet, is 7’ 11”. The volume of the room is thus 1240 ft^3, which is equivalent to 35.1m^3. The closet adds an additional 115 ft^3 or 3.25 m^3.

The PurpleAir (PA-II) air quality monitor was mounted on a wooden stand 51 inches from the ground and connected to a local WiFi network. The burn station, which consisted of a large pot on a 22-inch-tall table, was set up adjacent to the door to allow the investigator to observe the burn from outside the testing area with the door nearly shut while being close enough to observe and attend to safety. A 12-inch desk fan was set on the floor against the wall of the test area, centered between the PA-II monitor and burning station, oscillating on the lowest speed setting. The relative locations of these three features can be seen in Figure 6

Figure 6. Test area setup as viewed from the doorway. Note the PA-II sensor in the far corner, the fan in the middle of the frame, and the burn station in the foreground, behind the door.

The PurpleAir website was used to monitor PM concentration within the room, and once the PM concentration fell below 10-µg/m^3, the test was deemed completed, and the final time was recorded. We downloaded data from the PurpleAir website using the LRAPA correction factor and no time averaging and analyzed the data from both sensor channels. All trials were trimmed to the start and end time which was recorded, then trimmed further to when the filter was turned on (except baseline runs with no filtration, which was instead trimmed to the time at which peak PM2.5 concentration occurred). Each run and the aggregate dataset of all valid runs by filter and setting were fitted using R's nls (nonlinear least-squares) fitting function (DataCamp, Inc. 2021) with Equation 1 to calculate run-specific and aggregate C_o and k values.

5.1.1 Filtration Time to Eliminate Particulates.

In order to determine how many hours a filter needs to run to clear the room, we used the same decay curve equation with the best fit on the dataset. The room is assumed to be clean when the final concentration is below 10 µg/m^3, with the initial concentration, $\overline{C_0}$, defined by historical data since the literature on the topic of typical values during wildfires is sparse.

The historical data for Hoopa, taken to be an example,[1] was downloaded over its period of record, which included 2019 and 2020. As depicted in Figure 7, 9.9% of intact days had high levels of particulate, over 84 µg/m^3, with a mean value of 309 µg/m^3, and an exponent-of-mean-of-logarithm of 264 µg/m^3. This latter value is used as our $\overline{C_0}$, since it considers the shape of the

[1] From a purple air sensor at 41.047117 -123.675233, using sensor A, LRAPA correction, "PM2.5_ATM_ug/m3" data averaged over 60-minute intervals. This is considered to provide a conservative estimate, since the 2020 wildfire season was extreme. (H. Vreeland, personal communication, March 25, 2021).

decay curve. Based on the 9.9% figure, we assume a staggering *36 days per year requiring filtration.*

Thus,

$$t = \frac{-1}{k} \ln\left[\frac{10}{264}\right] = \frac{3.273}{k} \qquad \text{Equation 2}$$

Where *k*, in particular to a filter & setting combination (five total for our purposes).

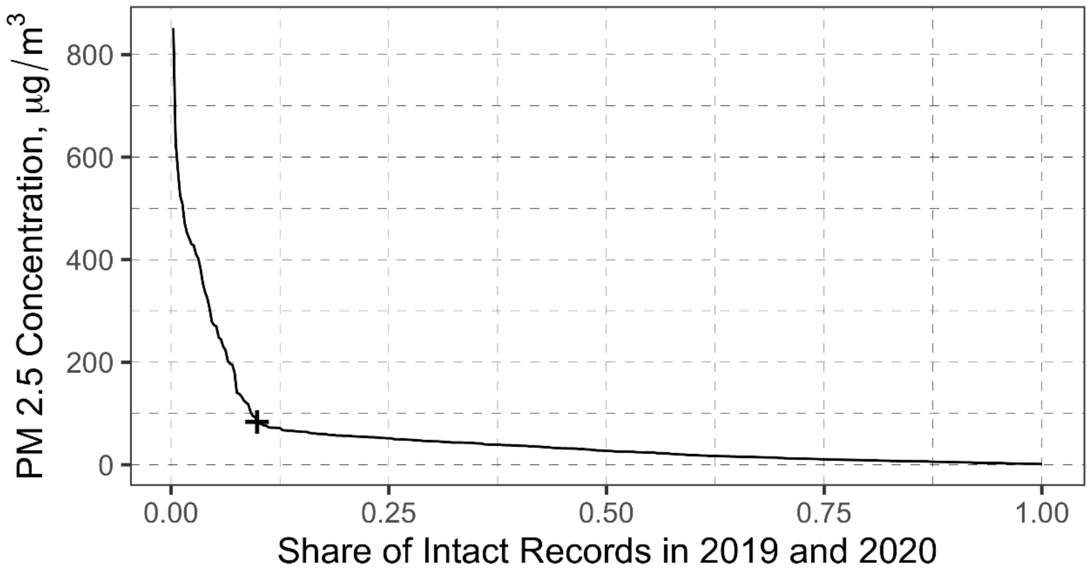


Figure 7. The y-axis shows the daily maximum PM2.5 concentration level for each intact record, 384 in total. The dot at x=0.099, y=84.29 indicates that 9.9% of the time, PM2.5 concentration levels were greater than 84 µg/m³.

5.2 Flowrate/Clean Air Delivery Rate

We used the decay rate of PM concentration in the room and the room volume (measured to be 35 m^3) to calculate the filter's clean air delivery rate, which, combined with the filtration efficacy, can produce an estimate of the airflow rate.

5.3 Power Consumption

The air filter was set in an open space and plugged into the Poniie PN1500 Energy Monitor, which was plugged into the wall. The filter was turned on at each setting (high and low) and allowed to stabilize power consumption. Power consumption was recorded three times for each setting, with 10-20 minutes between trials.

5.4 Room Heating

Our customer raised concerns about the heat generated by the filters (K. Stewart, personal communication, March 25, 2021). Energy consumption is a reasonable proxy for heat generated since this energy is all turned to heat through friction and wire resistance. In practice, the room will radiate and convect some of this heat away, but as a first approximation, we can ignore this effect, knowing that we will thus overestimate room heating.

We modeled the room like a five-sided (ignoring the floor) box (see room dimensions in Section 5.1) made from gypsum (i.e., ½" drywall) with a specific heat of 950 J/kg/°C (Ang and Wang 2004), a "density" of 10.2 kg/m^2 for ½" drywall, and thus a thermal mass of 137 Wh/°C. The air inside the room has a specific heat (at constant pressure, C_p) at standard temperature and pressure, 0.00121 J/cm^3/k (Wikipedia contributors 2021), and a much less significant thermal mass of 11.8 Wh/°C. The rate of heat input is taken from the electricity consumption calculated by the methods in Section 5.3, and temperature rise per unit time is thus calculated by dividing the rate of energy input by the sum of the two thermal masses.

5.5 Initial and Ongoing Cost Estimates

Component cost estimates, including tape, filters, and box fan, are derived from Lowes' pricing. Cardboard and tools are assumed to be available to the user.

Medify filter unit and replacement filters pricing for comparison are based on data from the Medify website. The Medify MA-25 costs $216 with tax, and replacement filters cost $45, assuming no subscription (Medify Air 2021a). Shipping costs are not included in these estimates.

Based on Medify's guidance, air filters should be changed out every 2,500 hours or every 3-4 months with genuine Medify air filters (Medify Air 2021a). However, the guidance we received from a filtration expert cast significant doubt upon this simple metric. Moreover, cleaning heavily polluted air must degrade the filter faster than operating on pure air. Based on these considerations, we assume filters last only one month of operation or as little as two weeks during the heavy smoke season (H. Vreeland, personal communication, March 25, 2021). Based on the assumed 36 high-smoke days, we estimate two sets of filters per year are needed. For consistency, we assume the same lifetime for the MERV filters in the DIY design, though these may, in practice, last a different amount of time due to differing construction methods and materials.

The cost of electricity is also calculated, assuming each of the same 36 high-smoke days requires the user to run the filter twice. Each filter runs as many hours as the design needs to clear the room for a particular setting, using the method defined in Section 5.1.1. Energy is defined as power, calculated for each filter/setting combination as in 5.3, times this duration. The cost of this electricity is calculated from PG&E's 2021 residential tiered rate plan, assuming the owner remains in the first tier and thus, has a cost of $0.24/kWh (Pacific Gas and Electric Company 2020).

We calculate initial, one-year, and 5-year costs of ownership using the above assumptions for each filter at each setting (high and low only) without including any price escalation, inflation, taxation, or discounting of future costs.

5.6 Noise

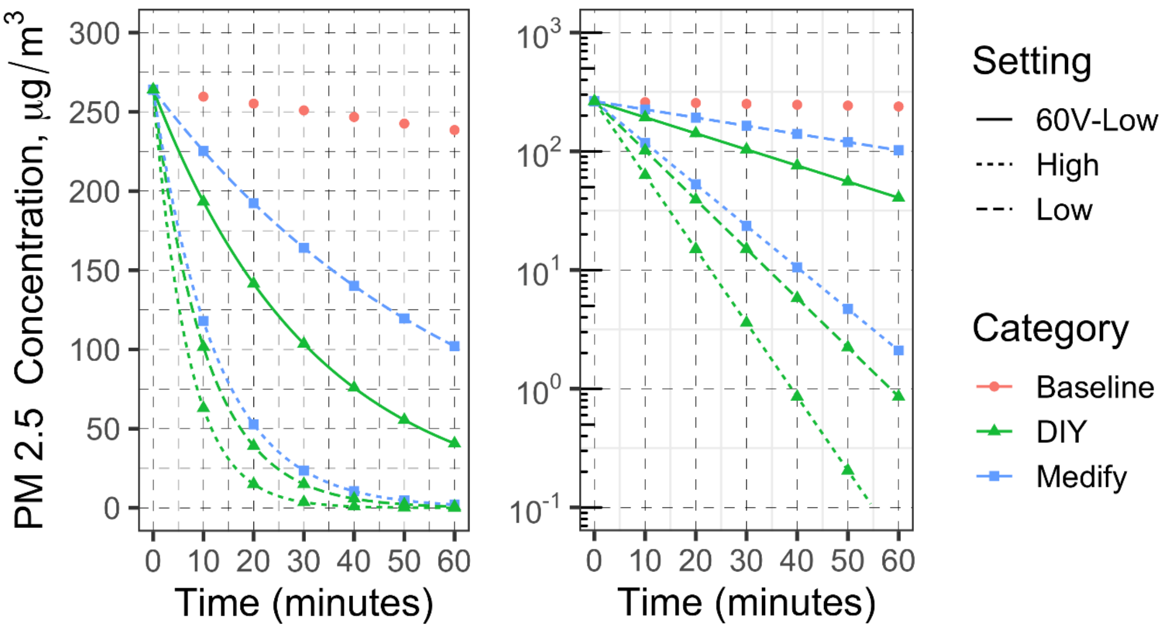
Noise level of the filters (DIY and Medify) were measured using the SoundPrint app on an iPhone X. Measurements were taken on the outlet side of each filter, two feet away from the center with the microphone (the bottom face of the phone) aimed *away* from the outlet of each device. SoundPrint records a 15-second average and 15-second maximum volume in dBA.

Each device was measured three times at each setting. Mean-of-mean values and max-of-max values are reported in this report (all raw data are provided in Appendix A). The operator was required to hold their breath during each measurement as the device picked up the sound of their breathing.

6 RESULTS

6.1 Filtration Efficacy

Figure 8 depicts the particulate decay rate for both filters, assuming a starting concentration of 264 µg/m^3 as defined in Section 5.1.1. The linear plot, Figure 8 (a), makes it clear that the DIY on both settings and the Medify on high clean air much faster than other options, while Figure 8 (b) shows that the DIY filter's superiority is still significant: After 30 minutes, the DIY filter on high reduces the concentration below 3 µg/m^3, while the concentration with the Medify is nearly *ten times* higher, about 25 µg/m^3. The data that went into creating these fits are presented in Appendix E.



(a) (b)

Figure 8. Particulate decay rate across the full set of filters and settings tested, compared to baseline. Shown on a linear scale ((a), left), and a logarithmic scale ((b), right).

Table 4 shows similar information in a tabular format. Clearly, the Medify filter on high, and the DIY filter on either high or low clean the room *very* quickly, while the Medify filter on low lags significantly, and the DIY filter on low with input voltage reduced to 60-V falls in the middle. Additionally, it should be noted that although the room clears in 32 hours without filtration in test conditions, this would not occur were the outside air to remain contaminated with particulates, as would be the cause during a forest fire.

Table 4. The rate of decay coefficients for a fit of all runs by filter setting, low and high, of the Medify MA-25 unit compared with the DIY unit on low and high, and no filtration). Each is

shown ± one standard deviation. Calculated decay time, from 264 µg/m³ to 10 µg/m³, a function of k*, is also shown.*

Filter	Filter Setting	k (minutes^{-1})	Decay Time [264 to 10 µg/m³]
None	None	0.0017±0.00058	32 hours (1,900 minutes)
Medify	Low	0.016±0.001	3.4 hours (200 hours)
Medify	High	0.081±0.0086	0.67 hours (40 minutes)
DIY	60V-Low	0.031±0.00069	1.75 hours (105 minutes)
DIY	Low	0.095±0.015	0.57 hours (34 minutes)
DIY	High	0.143±0.031	0.38 hours (23 minutes)

6.2 Clean Air Delivery Rate

Using the method outlined in Appendix B, we calculated a clean air delivery rate and flowrate for the filters. The clean air delivery rate takes into account the filter's efficacy. The Medify filter on low has a vastly lower flowrate, which explains (or is explained by) the low filtration rate relative to the other options. By our calculation, the DIY filter on high provides twice the circulation of the Medify and nearly two times the clean air.

*Table 5. The flowrate of the Medify MA-25 unit on low and high settings, compared to the manufacturer's rating. The method is described in Appendix B. * assumes a filtration efficiency of 87%.*

Filter	Filter setting	Clean air delivery rate (m³/hr)	Flowrate (m³/hr)
Medify	Low	33.6	33.6
Medify	High	170	170
DIY	60V-Low	65.1	74.8*
DIY	Low	200	230*
DIY	High	300	350*

6.3 Power Consumption and Heat Generation

Table 6 presents the results of our power consumption measurement. Note that the Medify filter consumes significantly less power than the DIY filter, even with the Medify at the highest setting and the DIY filter at its lowest. With the extra-low setting (60V-Low), the DIY filter's consumption is quite a bit lower than the Medify on high but much higher than the Medify on low. Note also the small parasitic power consumption of the Medify. Left plugged in for a year without being turned on, it would consume 5.2 kWh, while the DIY filter has a true off switch that reduces the load to zero. Continuing its trend of being an outlier, the Medify filter on low consumes by far the least energy to clean the room. All of the remaining options – Medify on high, DIY on low, DIY on high, and DIY on Low with 60-V input – consume similar amounts of energy. In reality, it is unlikely that turning the DIY filter from low to high would reduce the energy needed since much of that energy heats the air as it causes compression and shear in the fluid. More likely, it is an expression of experimental error.

Table 6. Calculated average power consumption used in the cost model. No measurements for the medium setting were measured for either air filtration unit.

Filter	Setting	Average Power Consumption (W)	Energy consumption (Wh) [264 to 10 μg/m^3]
Medify	Off	0.59	-
Medify	Low	1.44	4.9
Medify	High	33.07	22
DIY	Off	0	-
DIY	60V-Low	13.06	22.9
DIY	Low	41.74	24
DIY	Medium	47.98	-
DIY	High	53.21	20

We calculate the rate of temperature rise while the DIY filter is running on high to be as high as 0.36°C/hr (0.65°F/hr) for the 35 m^3 room assumed. This is relatively insignificant if the filter is only run for our requisite 23 minutes twice a day but could become meaningful if the filter is operated consistently, injecting enough heat each day to raise the temperature by 8.6°C (16 °F). This amount would naturally be even larger for a smaller room. Eventually, the room's temperature will stabilize due to increased heat loss through convection and radiation, but if this temperature is too high, the room could require cooling through A/C. (Not by opening the windows.)

6.4 Initial and Ongoing Cost Estimates

Based on our assumptions of 36 high smoke days per year, two runs of the filter per day, filters run 27 to 250 hours per year, requiring between 350 and 1700 Wh, and incurring filter replacements twice per year. Combining this with $50 for Medify filter replacements, $40 for DIY filter replacements, and $0.24/kWh leads to annual electricity costs of $0.08 to $0.41 and annualized filter costs of $80 or $100. These costs are rolled up into the cost summary presented in Table 7. Regardless of the setting, the DIY filter is vastly cheaper than the Medify filter, about 1/3 the price in the short term and two-thirds in the medium term (in the extremely long term, it would approach four-fifths). The cost of additional duct tape and cardboard is not included since cardboard is in principle available for free, and very little of the duct tape is used each time filters are replaced.

Table 7. Summary of major and minor costs, along with one- and five-year costs of ownership without taking into account the time value of money. In the first year, the filter cost is halved because of the original filter.

Filter	Setting	Initial Cost	Electrical Cost Per Year	Annual Filter Cost	One-Year Cost of Ownership	Five-Year Cost of Ownership
Medify	Low	$216	$0.08	$100	$266	$666
Medify	High	$216	$0.38	$100	$266	$668
DIY	Low	$71.00	$0.41	$80	$111	$433
DIY	High	$71.00	$0.35	$80	$111	$433

6.5 Noise

We observed that the reference Medify filter on the low setting produces virtually no noise discernable from the background level, which was taken in a relatively quiet area of a large city (San Francisco). The DIY filter on high produces the most noise, while on low and medium, it produces a comparable level to the Medify filter on high. Reducing the source voltage of the DIY filter successfully reduced its noise level from 61dBA to 38dBA, a very significant reduction.

Table 8. Summary of noise measurement results.

Filter	Setting	Mean of Average Reading (dBA[1])	Max of Max Reading (dBA)
None	None	32	46[2]
Medify	Low	33	35
Medify	High	65	70
DIY	60V-Low	38	41
DIY	Low	61	63
DIY	Medium	67	68
DIY	High	70	72

[1] The software used reports values in dBA, but since the device is uncalibrated, there is no validation of the measurement.
[2] 46 dBA was momentarily picked up due to a person next door speaking.

6.6 Ease of Use

Once assembled, the DIY air filter only needs to be plugged in, and the knob on the front turned on to either 1, 2, or 3 (low, medium, or high settings). The user needs to make sure the air filter unit is not left unattended and to monitor the condition of the filter panels. In order to change the filters, the filter unit will have to be completely disassembled. When doing so, the tape should be cut to avoid damage to the cardboard when removing the filters.

7 REPLICABILITY & ACCESSIBILITY ASSESSMENT & RECOMMENDATIONS FOR USERS

We had access to several large hardware stores from which to source components, choosing to utilize Lowes for all purchases. Users living in areas without access to a large hardware store such as Lowes (we recommend against Home Depot, since, as noted, they do not have many MERV rated filters in stock) have several options to obtain components, including checking a local smaller hardware store, ordering components online, or driving to a large hardware store.

In general, electrical apparatuses can cause fires and should not be left unattended. In particular, consumers should be cautious of older box fans that do not provide automatic shutoffs in case of overheating and are therefore even more dangerous. If an older box fan must be used, extra care should be taken when sleeping or otherwise not present.

There is no foolproof timeline by which to change filters (H. Vreeland, personal communication, March 25, 2021), but there are some general guidelines that can be followed: If the filter shows any color change, it should be replaced. If the filter produces a smokey odor, it should be replaced since this can be a sign it is dangerous off-gassing particles. If the filter is being run continuously during a smokey period, the filter should be changed every one to two weeks. (H. Vreeland, personal communication, March 25, 2021).

As mentioned previously, replacing the filter of the DIY device requires full disassembly and reassembly of the unit. This is a time-consuming process, as the user will already know from experience. When doing so, the user should have the recommended materials and tools ready, including replacement cardboard and duct tape.

As noted in Section 5.6, the DIY filter is rather loud, even on low. Thus, it may not be suitable for continuous operation by those sensitive to noise. However, this can be mitigated by altering either the fan or the source voltage to reduce its speed. One effective way to do so is to reduce the source voltage to 60-V.

7 DISCUSSION AND CONCLUSION

Home air filters have the potential to provide significant health benefits to those in smokey areas by removing harmful particulates from the air they breathe. The commercial portable air filter we tested, a Medify MA-25, can clear a bedroom-sized volume of air in 40 minutes or 3 hours on its high and low settings, respectively. In contrast, our DIY filter can clear the room in 23 to 34 minutes.

The 30% initial cost, $71 compared to $220 for the Medify MA-25, is a main advantage of the DIY filter. In the first year, the DIY filter's cost reaches 40% of Medify's cost after a single filter replacement, reaching $110 compared to $270. In the longer-term, five years, the DIY filter's cost reaches 70% that of Medify's $430 compared to $670.

Power draw and energy consumption were similar for the DIY filter on either setting and the Medify filter on high, 33-53 watts, and 20-24 Watt-hours. On the low setting, the filter consumes about 25% as much energy and only requires 1.4 watts. On the high setting, we found that the DIY filter could raise temperatures by 0.36°C per hour (0.65°F per hour), insignificant over the less than 25 minutes the filter must be run, but impactful if the DIY filter were run continuously.

Noise generation was also similar for the DIY filter on either setting and the Medify filter on high, at 61-70 dBA. The Medify does not raise the room's noise level above the background level while on low, a feature that the DIY filter cannot replicate as-is, but which we found a path towards recreating: We were able to significantly reduce the noise level of the DIY filter by reducing the source voltage to 60-V. On the low setting, this reduced the noise generated from 61 dBA to 38 dBA, the latter of which was hardly distinguishable from the background level. This required a $55 Variac but could perhaps be achieved with a modification to the fan design, a promising area for future study.

Our DIY filter was relatively easy to construct, requiring no special skills and only common household tools (i.e., marking device, straight edge, and scissors). It took approximately one hour for us to build. The main assembly challenge is in replacing filters, which cannot be done easily. The user must, in essence, rebuild the entire filter. This is in contrast to the Medify MA-25, which has filters that are easily replaced in seconds with no tools.

In summary, the DIY filter is significantly cheaper than the reference filter, more effective at removing particulates, and easy to assemble. It generates more noise as-is but has a promising path towards a low-noise version. The main area where the commercial portable filter outperforms the DIY filter is in terms of easy filter replacement. Finally, we note that the DIY filter is bulkier and somewhat uglier than the sleek Medify MA-25 unit.

8 REFERENCES

Air Force One Plumbing Heating & Air. (2020). "What You Should Know Before Purchasing Filters." *Air Force One*, <https://www.airforce1plumbing.com/what-you-should-know-before-purchasing-filters/> (Mar. 26, 2021).

Air Now. (2020). "Wildfire Smoke Factsheet: Indoor Air Filtration."

Amazon.com, Inc. (2021a). "Amazon.com : 200W Portable Power Station, FlashFish 40800mAh Solar Generator with 110V AC Outlet/2 DC Ports/3 USB Ports, Backup Battery Pack Power Supply for CPAP Outdoor Advanture Load Trip Camping Emergency. : Garden & Outdoor." <https://www.amazon.com/Portable-FlashFish-Generator-Adventure-Emergency/dp/B07T48L6CF/ref=pd_bxgy_img_2/141-3022596-6234928?_encoding=UTF8&pd_rd_i=B07T48L6CF&pd_rd_r=62ec1423-5543-413d-8675-9114bbca246b&pd_rd_w=V5mXq&pd_rd_wg=aBHFc&pf_rd_p=f325d01c-4658-4593-be83-3e12ca663f0e&pf_rd_r=W3ARHBKCMRHQC6YZM7DG&refRID=W3ARHBKCMRHQC6YZM7DG&th=1> (Apr. 1, 2021).

Amazon.com, Inc. (2021b). "Amazon.com : 50W 18V Portable Solar Panel, Flashfish Foldable Solar Charger with 5V USB 18V DC Output Compatible with Portable Generator, Smartphones, Tablets and More : Garden & Outdoor." <https://www.amazon.com/Portable-Flashfish-Compatible-Generator-Smartphones/dp/B07VYHB4RP/ref=pd_bxgy_img_2/132-6902441-7542957?_encoding=UTF8&pd_rd_i=B07VYHB4RP&pd_rd_r=a444c51a-39a8-4281-bb7c-ca2b0d8589cc&pd_rd_w=9S3En&pd_rd_wg=PiyjH&pf_rd_p=f325d01c-4658-4593-be83-3e12ca663f0e&pf_rd_r=JYM4FMSXE1830JTFGEEX&psc=1&refRID=JYM4FMSXE1830JTFGEEX\> (Apr. 1, 2021).

Ang, C. N., and Wang, Y. C. (2004). "The effect of water movement on specific heat of gypsum plasterboard in heat transfer analysis under natural fire exposure." *Construction and Building Materials*, 18(7), 505–515.

Azimi, P., Zhao, D., and Stephens, B. (2014). "Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin." *Atmospheric Environment*, 98, 337–346.

Batterman, S., Du, L., Parker, E., Robins, T., Lewis, T., Mukherjee, B., Ramirez, E., Rowe, Z., and Brakefield-Caldwell, W. (2013). "Use of free-standing filters in an asthma intervention study." *Air Quality, Atmosphere & Health*, 6(4), 759–767.

California Air Resources Board. (2021). "Inhalable Particulate Matter and Health (PM2.5 and PM10) | California Air Resources Board." <https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health> (Mar. 20, 2021).

Dacunto, P., Klepeis, N., Cheng, K.-C., Acevedo-Bolton, V., Jiang, R.-T., Repace, J., Ott, W., and Hildemann, L. (2015). "Determining PM2.5 calibration curves for a low-cost particle monitor: Common indoor residential aerosols.” *Environmental science. Processes & impacts*, 17.

Dahl, T. (2016). “A DIY Air Filter For Your Shop That Anyone Can Build.” *Popular Mechanics*, <https://www.popularmechanics.com/home/how-to-plans/how-to/a21300/diy-air-filter/> (Mar. 6, 2021).

DataCamp, Inc. (2021). “nls function - RDocumentation.” <https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/nls> (Apr. 1, 2021).

Delp, W. W., and Singer, B. C. (2020). “Wildfire Smoke Adjustment Factors for Low-Cost and Professional PM2.5 Monitors with Optical Sensors.” *Sensors*, Multidisciplinary Digital Publishing Institute, 20(13), 3683.

Dunlap, M. A., Marion, W., and Wilcox, S. (1994). *Solar radiation data manual for flat-plate and concentrating collectors*. NREL/TP--463-5607, 10169141.

Ghosh, N., Sherali, N., Hiranuma, N., Banerjee, P., Sherali, S., Romero, R., Rogers, J., Bennert, J., Vitale, J., Saadeh, C., and Revanna, C. (2018). “Air Pollution With 2.5 Micron Particulate Matters and Testing the Decay of the Aerosol Concentration as a Function of Time to Compare the Efficiency of AHPCO® and Bi-Polar Units in Reducing the Indoor Particle Counts.” *European Scientific Journal, ESJ*, 14(6), 26.

Heffernan, T. (2019). “How to DIY an Air Purifier.” *Wirecutter: Reviews for the Real World*.

Henry, M. (2020). “MERV 8 vs MERV 12 Air Flow Comparison in March 2021.” *Comparison Talk*. <https://comparisontalk.com/merv-8-vs-merv-12-air-flow/>. (Apr. 1,2021).

Joseph, G., Schramm, P. J., Vaidyanathan, A., Breysse, P., and Goodwin, B. (2020). “BRACE Technical Report Series.” 36. <https://www.cdc.gov/air/wildfire-smoke/socialmedia/Wildfire-Air-Filtration-508.pdf>. (Apr.1, 2021).

Kramer, H. A., Mockrin, M. H., Alexandre, P. M., and Radeloff, V. C. (2019). “High wildfire damage in interface communities in California.” *International Journal of Wildland Fire*, 28(9), 641.

Kreidler, M. (2019). “Demand soars for air purifiers in new era of Western wildfires, as smoke raises health fears.” *The Sacramento Bee*, <https://web.archive.org/web/20201119094637/https://www.sacbee.com/news/local/health-and-medicine/article233622082.html> (Mar. 2, 2021).

KUSA 9 News. (2018). “This DIY air filter for wildfire smoke is less than $20.” *KUSA.com*, <https://www.9news.com/article/news/health/this-diy-air-filter-for-wildfire-smoke-is-less-than-20/73-585858249> (Mar. 24, 2021).

Laumbach, R. J. (2019). “Clearing the Air on Personal Interventions to Reduce Exposure to Wildfire Smoke.” *Annals of the American Thoracic Society*, 16(7), 815–818.

LRAPA. (n.d.). “PurpleAir-Correction-Summary.pdf.” <https://www.lrapa.org/DocumentCenter/View/4147/PurpleAir-Correction-Summary> (Feb. 12, 2021).

Medify Air. (2021a). “MA-25 Replacement Filter Set.” *Medify Air*, <https://medifyair.com/products/ma-25-replacement-filter-set> (Mar. 24, 2021).

Montana Wildfire Smoke. (n.d.). “How to build a Do-It-Yourself Fan/Filter Room Air Cleaner.” <https://web.archive.org/web/20201124155507/https:/www.montanawildfiresmoke.org/diy-fan-filter.html> (Mar. 2, 2021).

Oregon Health Authority. (2020). “Do It Yourself (DIY) Air Filter.” 2.

Puget Sound Clean Air Agency. (2021). “DIY Air Filter | Puget Sound Clean Air Agency, WA.” <https://pscleanair.gov/525/DIY-Air-Filter> (Mar. 29, 2021).

Pacific Gas and Electric. (2020). “Residential-Rates-Plan-Pricing-2020.pdf.” <https://www.pge.com/pge_global/common/pdfs/rate-plans/how-rates-work/Residential-Rates-Plan-Pricing-2020.pdf> (Apr. 1,2021).

Richardson, L. A., Champ, P. A., and Loomis, J. B. (2012). “The hidden cost of wildfires: Economic valuation of health effects of wildfire smoke exposure in Southern California.” *Journal of Forest Economics*, 18(1), 14–35.

Russel, M. (2019). “Air conditioners, fans, kiddie pools selling out amid Bay Area heat.” <http://web.archive.org/web/20201125114119/https:/www.sfchronicle.com/business/article/Air-conditioners-a-Bay-Area-rarity-are-selling-13968796.php> (Mar. 2, 2021).

Stephens, S. L., Collins, B. M., Biber, E., and Fulé, P. Z. (2016). “U.S. federal fire and forest policy: emphasizing resilience in dry forests.” *Ecosphere*, 7(11), e01584.

Stone, S. L. (2019). *Wildfire Smoke - A Guide for Public Health Officials*. Environmental Protection Agency, 88.

Stone, S. L., Sacks, J., Lahm, P., Clune, A., Radonovich, L., D’Alessandro, M., Wayland, M., and Mirabelli, M. (2019). “Wildfire Smoke: A Guide for Public Health Officials.” 88.

Sullivan, M. (2020). “Top 3 DIY Air Purifiers and How to Make Them.” *Oh So Spotless*, <https://ohsospotless.com/diy-air-purifiers/> (Apr. 1, 2021).

Sulser, C., Schulz, G., Wagner, P., Sommerfeld, C., Keil, T., Reich, A., Wahn, U., and Lau, S. (2008). “Can the Use of HEPA Cleaners in Homes of Asthmatic Children and Adolescents Sensitized to Cat and Dog Allergens Decrease Bronchial Hyperresponsiveness and Allergen Contents in Solid Dust?” *International archives of allergy and immunology*, 148, 23–30.

Tom Builds Stuff. (2020). “Better Box Fan Air Purifier.” <https://tombuildsstuff.blogspot.com/2013/06/better-box-fan-air-purifier.html>. (Apr.1,2021).

Trethewey, R. (2021). “How to Make a DIY Air Filter.” *This Old House*, <https://www.thisoldhouse.com/green-home/22231148/diy-air-filter> (Apr. 1, 2021).

U.S. Environmental Protection Agency. (2018). “Residential Air Cleaners - A Technical Summary.” 74.

U.S. Environmental Protection Agency. (2020). “Reducing Exposure to Wildfire Smoke: How Effective Are Do-It-Yourself And Solar-Charged Air Cleaners?” <https://www.epa.gov/sites/production/files/2020-10/documents/diy_air_filters_fact_sheet.pdf> (Mar. 2, 2021).

U.S. Environmental Protection Agency. (2021a). “What is a HEPA filter?” *US EPA*, Overviews and Factsheets, <https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1> (Mar. 17, 2021).

U.S. Environmental Protection Agency. (2021b). “What is a MERV rating?” *US EPA*, Overviews and Factsheets, <https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1> (Mar. 17, 2021).

U.S. Environmental Protection Agency. (2021c). “Cleaner Indoor Air During Wildfires Challenge.” *US EPA*, Overviews and Factsheets, <https://www.epa.gov/air-research/cleaner-indoor-air-during-wildfires-challenge> (Apr. 1, 2021).

Westerling, A. L., Bryant, B. P., Preisler, H. K., Holmes, T. P., Hidalgo, H. G., Das, T., and Shrestha, S. R. (2011). “Climate change and growth scenarios for California wildfire.” *Climatic Change*, 109(S1), 445–463.

Wikipedia contributors. (2021). “Table of specific heat capacities.” *Wikipedia, The Free Encyclopedia*.

W.W. Grainger, Inc. (2020). “The Complete Air Filter MERV Rating Chart - Grainger KnowHow.” <https://www.grainger.com/know-how/equipment-information/kh-what-is-merv-rating-air-filter-rating-chart.html> (Mar. 25, 2021).

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APPENDIX A NOISE MEASUREMENT DATA

Table A-1 presents raw data of noise measurements taken on a quiet weekday morning. Data are presented without time of measurement and are not shown in order of collection. For additional information, please contact the authors. *Reference #3 trial includes noise picked up by a neighbor clearing their throat.

Table A-1 Summary of noise measurement results.

Trial	Filter	Setting	Average Reading	Max Reading
1	Medify	Low	33	35
2	Medify	Low	33	35
3	Medify	Low	32	33
1	Medify	High	67	71
2	Medify	High	65	71
3	Medify	High	63	68
1	DIY	Low	59	60
2	DIY	Low	61	62
3	DIY	Low	62	63
1	DIY	Medium	66	68
2	DIY	Medium	67	68
3	DIY	Medium	67	68
1	DIY	High	70	72
2	DIY	High	71	72
3	DIY	High	70	72
1	None	None	32	36
2	None	None	31	31
3	None	None	32	46*
1	DIY	60V-Low	37	40
2	DIY	60V-Low	38	39
3	DIY	60V-Low	39	41

APPENDIX B DECAY RATE BASED FLOWRATE CALCULATION METHODOLOGY, EXPLAINED

It follows from an intuition that if a perfectly efficient air filter, when turned on, reduces particulate concentration in an enclosed space by 1% in a brief period of time, that it has filtered 1% of the air in that space, and thus:

$$Flowrate = 1\% \cdot Volume$$

Or more generally:

$$Flowrate = \Delta \cdot Volume$$

where Δ is the fractional decrease in particulate concentration (for small Δ).

If the filter is only 50% efficient at removing particulates, it will take twice the flowrate to achieve the same decrease in particulates, and thus:

$$Flowrate = \frac{\Delta}{\eta} \cdot Volume$$

Where η is the filtration efficiency.

Given our decay curve of the form:

$$C(t) = C_o e^{-kt}$$

The instantaneous rate of particulate removal when the filter is turned on is the derivative of the decay curve at $t = 0^+$:

$$\frac{dC}{dt} = -kC_o e^0 = -kC_o$$

The fractional *decrease* (the negative of the removal rate), Δ is:

$$\frac{kC_o}{C_o} = k$$

The flow rate of the filter using this method is thus, approximately:

$$Flowrate = \frac{\mathrm{k}}{\eta} \cdot Volume$$

And suppose we assume the filter to be perfectly efficient, which is a reasonable assumption for a HEPA filter filtering PM2.5 (e.g., the medify filter). In that case, the flow rate reduces to the clean air delivery rate:

$$Flowrate = k \cdot Volume$$

On the other hand, for the MERV 13 filters, we use, η is 87% for particles 1.0 to 3.0 microns in size and 62% for particles 0.3 to 1.0 microns.

APPENDIX C POPULAR DIY AIR FILTER OPTIONS

This appendix presents photos of popular DIY air filter options that have been shared with the general public as alternatives to commercial air filters.

Figure C-1. Traditional simple DIY box fan filter assembly only requires one filter either attached to the front or back of the box fan (Heffernan 2019).

Figure C-2. An "upgraded" version for the traditional DIY box fan filter, there are four air filters that are attached to the box fan (Trethewey 2021).

Figure C-3. The Bucket filter utilizes a filter roll material that can be fitted to the bucket, and holes are drilled through the bucket to allow airflow (Sullivan 2020).

Figure C-4. The Plyboard double filter requires a wooden frame to be assembled to hold the filters so they are not attached directly to the box fan, which will also allow for easier access when the filters need to be replaced (Dahl 2016).

Figure C-5. Triangular-shaped filter design is also an "upgraded" version of the traditional simple box fan setup. It incorporates two filters, and the gap between the air filters is sealed with cardboard and duct tape (Tom Builds Stuff 2020).

APPENDIX D SUPPLEMENTAL MERV RATING TABLE

Table D-1 presents the level of MERV ratings, pollutant, and particle size the level rating can remove from the area it is filtering and what application the panel rating is typically used in. The information within the table was referenced from multiple sources: Residential Air Cleaners: A Technical summary (U.S. Environmental Protection Agency 2018), the EPA’s Indoor Air Quality website for MERV rating and HEPA filters (U.S. Environmental Protection Agency 2021a; b), Air Filter Rating Chart by Grainger Editorial Staff (W.W. Grainger, Inc. 2020) and Wildfire Smoke: A Guide for Public Health Officials (Stone 2019).

Table D-1. MERV ratings and their filter types. The filter description lists filter characteristics, what particles they can remove from the area, and which setting they are generally utilized in.

MERV Rating	**Average Particle Size Removal Efficiency**			**Filter Description**
	Particle Size (µm)			
	0.3-1.0	**1.0-3.0**	**3.0-10.0**	
MERV 1-4	-	-	<20%	▪ Flat-panel filters with a thickness that can range from 1-2 inches. ▪ Overall, low particle removal efficiency (pollen, dust, and carpet fibers) ▪ Generally utilized in residential furnaces and window air conditioning units.
MERV 6	-	-	50%	▪ These are usually pleated filters. The more pleats on the filter allow for more surface area to be covered when removing particles from your space(Henry 2020). ▪ Overall, higher particle removal efficiency when compared to flat panel filters (pollen, dust, carpet fibers, and mold). ▪ Generally utilized in commercial and industrial buildings.
MERV 8	-	-	85%	
MERV 10	-	50 - 65%	>85%	▪ Heavier pleated than the lower MERV rating filters. ▪ Higher particle removal efficiency for smaller particles, when compared to lower MERV, rated panel filters (pollen, various dust types, carpet fibers, and mold).
MERV 12	-	80 - 90%	>90%	

<table>
<tr><th rowspan="3">MERV Rating</th><th colspan="3">Average Particle Size Removal Efficiency</th><th rowspan="3">Filter Description</th></tr>
<tr><th colspan="3">Particle Size (µm)</th></tr>
<tr><th>0.3-1.0</th><th>1.0-3.0</th><th>3.0-10.0</th></tr>
<tr><td></td><td></td><td></td><td></td><td>▪ Generally utilized in hospital laboratories and higher-end buildings.</td></tr>
<tr><td>MERV14</td><td>75 - 84%</td><td>>90%</td><td>>90%</td><td rowspan="2">▪ Extended depth and heavily pleated filters.
▪ Higher particle removal efficiency for the smallest particle size, when compared to previous MERV, rated panels (pollen, various dust types, mold, pet dander, tobacco smoke, and bacteria).
▪ Generally utilized in general surgery rooms, hospital inpatient rooms, and smoking areas).</td></tr>
<tr><td>MERV 16</td><td>>75%</td><td>>85%</td><td>>90%</td></tr>
<tr><td>HEPA (MERV 17-20)</td><td colspan="3">Removes at least 99.97% for particle sizes as small as 0.3.</td><td>▪ Have deeper pleats and more surface area compared to MERV 14-16 filters.
▪ Better efficiency at removing fine and ultrafine particles when compared to other filter types (can remove various microscopic particles from the area).
▪ Generally utilized in areas that require sanitized conditions (hospital surgery rooms, pharmaceutical facilities, and hazardous handling facilities).</td></tr>
</table>

APPENDIX E FILTRATION RESULTS

This appendix provides plots of decay curves for PM2.5 particles within the testing area without filtration (Figure E-1), with the Medify MA-25 air filter (Figure E-2), and with the DIY air filter (Figure E-3). Calculated exponential decay coefficients are also calculated for each sensor in each trial during the three experiments and presented in Table E-1, Table E-2, and Table E-3.

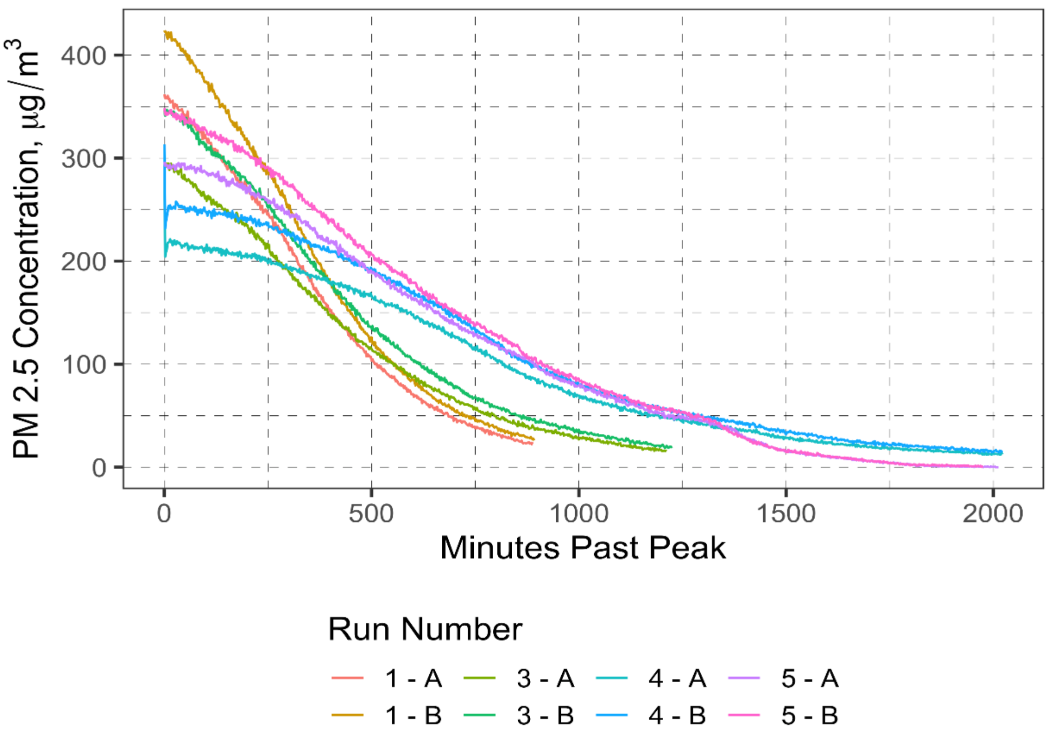

Figure E-1. Decay curves for PM 2.5 concentration within the test area with no filtration device.

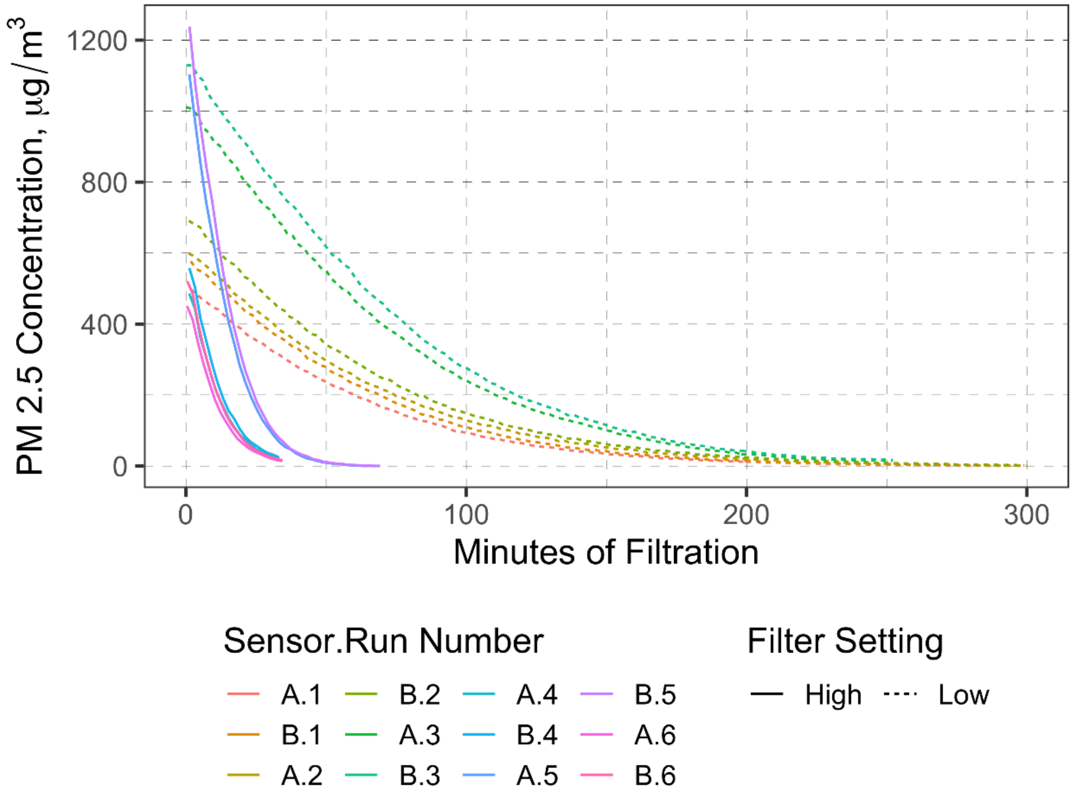

Figure E-2. Decay curves for PM 2.5 concentration with the test area for both the low and high settings of the Medify MA-25 filter unit.

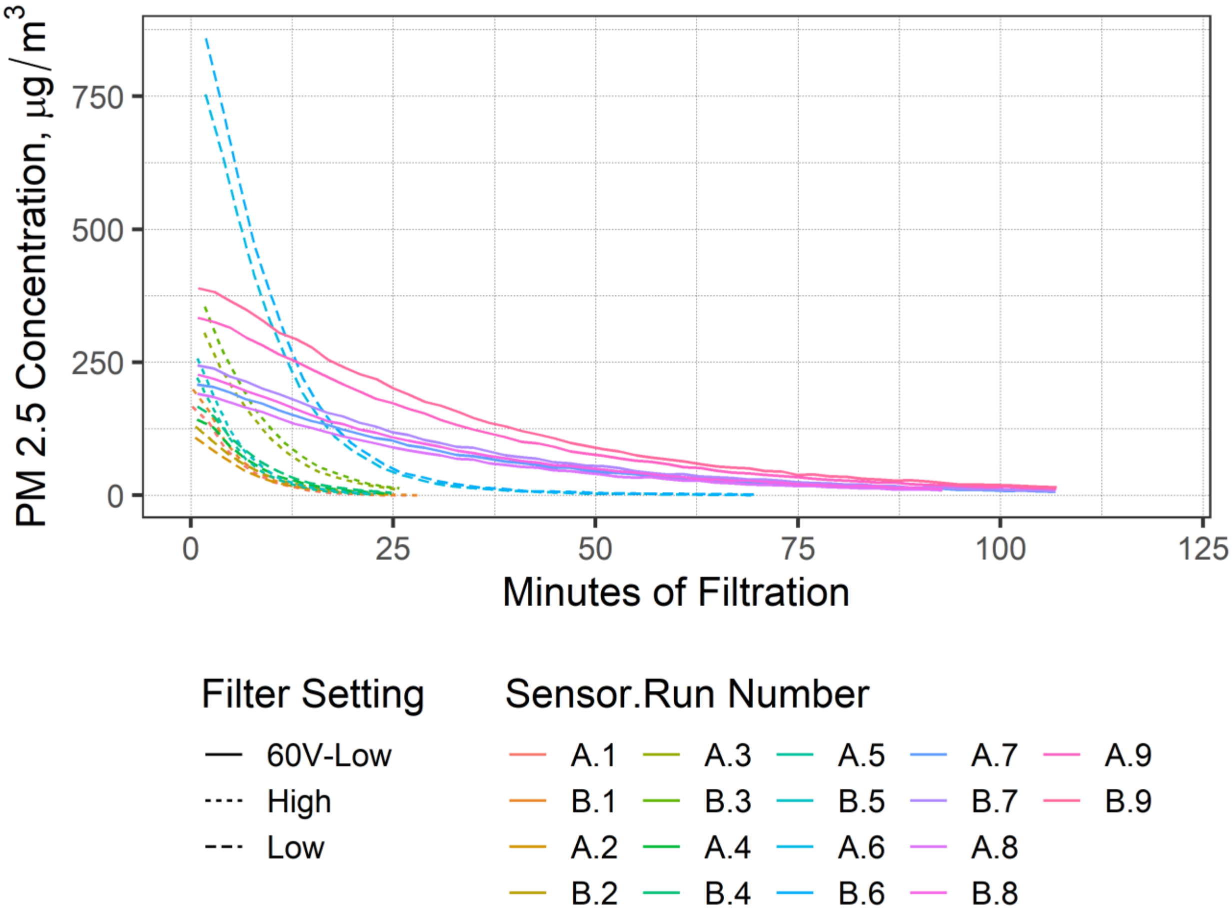

Figure E-3. Decay curves for PM 2.5 concentration with the test area for both the low and high settings of the DIY filter unit, with the 60V-Low setting (input voltage set to 60-V, filter set to low).

Table E-1. C_o and k (rate of decay) coefficients for each valid test run and the aggregate coefficients for a fit of all valid runs results for the test area with no filter. Run 2 omitted due to a testing error.

Run Number - Sensor	C_o (µg/m^3)	k (minutes^{-1})
1 - A	413	0.0026
1 - B	485	0.0026
3 - A	333	0.0022
3 - B	395	0.0022
4 - A	263	0.0012
4 - B	306	0.0012
5 - A	353	0.0015
5 - B	402	0.0015

Table E-2. C_o and k (rate of decay) coefficients for each valid test run with the Medify MA-25 air filter.

Run Number - Sensor	Filter Setting	C_o ($\mu g/m^3$)	k ($minutes^{-1}$)
1 - A	Low	537	0.017
1 - B	Low	622	0.017
2 - A	Low	642	0.016
2 - B	Low	740	0.016
3 - A	Low	1089	0.015
3 - B	Low	1223	0.015
4 - A	High	572	0.094
4 - B	High	657	0.093
5 - A	High	1267	0.078
5 - B	High	1425	0.078
6 – A	High	498	0.096
6 - B	High	583	0.095

Table E-3. C_o and k (rate of decay) coefficients for each valid test run with the DIY air filter.

Run Number - Sensor	Filter Setting	C_o ($\mu g/m^3$)	k ($minutes^{-1}$)
1 - A	High	183	0.18
1 - B	High	218	0.19
2 - A	Low	122	0.15
2 - B	Low	145	0.14
3 - A	High	387	0.13
3 - B	High	450	0.13
4 - A	Low	170	0.14
4 - B	Low	199	0.13
5 - A	High	265	0.20
5 - B	High	309	0.20
6 - A	Low	973	0.12
6 - B	Low	1110	0.11
7 - A	60V-Low	223	0.032
7 - B	60V-Low	261	0.031
8 - A	60V-Low	203	0.032
8 - B	60V-Low	241	0.032
9 - A	60V-Low	364	0.031
9 - B	60V-Low	424	0.031

APPENDIX F ASSEMBLY AND USAGE MANUALS

The following manuals are adapted from our Appropedia page, https://www.appropedia.org/FiltAirs_DIY_air_filter.

1. Assembly

Assembly instructions are provided below.

1.1. Determining Filter Placement

Verify which side of the fan is the inlet and outlet side. You can do this by plugging in the fan and turning the unit on. The side that blows air out, the high-pressure side, is the outlet side, and the side that doesn't is the inlet, the low-pressure side. We chose to place our filters on the inlet side for two reasons, the first being that the inlet side has lower pressure than the outlet side and will suck everything together when the unit is turned on. As opposed to placing the filters on the outlet side, which has higher pressure and will push the filters apart when turned on. The second reason was that the specific model of a box fan that we used has the knob on the outlet side, therefore by assembling the DIY unit, you would be covering the knob to switch the box fan on. If the model of box fan you have has a knob on the top, you have more leeway to place the panels on either side you choose, but we recommend using the inlet side regardless. The panel filters also have an arrow on them that indicates the direction of flow. When attaching the filter to the box fan, verify that your filters have the arrow pointing towards the inlet side, the arrow pointing towards the fan.

1.2. Power Cord

The model of the box fan that we used had the power cord coming from the bottom of the inlet side. To avoid taping the cord and trapping it within the filter design, make sure you tape around the cord.

1.3. DIY Unit Assembly

1. Place the unit face down with the inlet side up.
2. Place one filter on the unit and align it with the edge of the box fan and verify that the arrow is facing the box fan. Use a couple of pieces of duct tape to hold the filter in place, like a hinge. Repeat on the other side with the second filter.

Figure F-1. Place a couple of pieces of duct tape to hold the placement of the filter when attaching it to the box fan.

3. Sit the unit up, pull both filters out to form a triangle, and secure the point of the triangle with a couple of pieces of duct tape to hold it in place. Helpful tip: when attaching the duct tape to the end of both filters, it is recommended to crease the duct tape to (folding the tape in half with the sticky side facing the filters) and place it on each side of the filters to get a better seal between both filters.

Figure F-2. Filters should be aligned in a triangle shape and the edges of the two filters secured together to keep the shape in place.

4. Using the box that the box fan came in or other cardboard material (that has at least 20"x 20" dimensions, preferably more to be easier to work with), place your partially assembled unit on the cardboard and trace the area of the "triangle" using a pencil/marker, leaving a little extra on the bottom to have cardboard to attach to the box fan. Cut out this triangle and use it to trace out another triangle.

Figure F-3. Cutting out the cardboard triangles that will be used to seal the openings between the filters on the top and bottom.

5. Place one triangle on top of the filters, making sure the cardboard slightly overlaps onto the filters and box fan, and secure with a co couple of small pieces of duct tape.

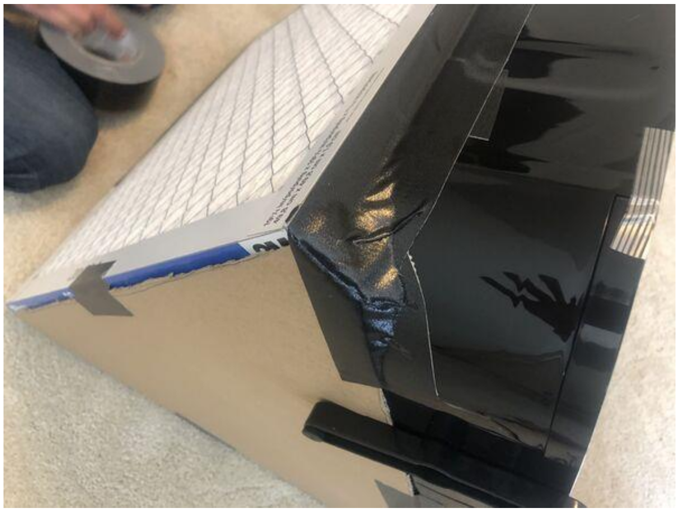

Figure F-4. Using duct tape, secure the cardboard triangles to the top and bottom of the unit to hold them in place.

6. Gently fold the edges of the cardboard to sit flush against the box fan and secure with duct tape.

Figure F-5. The edge of the cardboard triangle is gently folded to the box fan and secured with duct tape.

7. Flip the unit so the bottom of the fan is facing up. Attach the other triangle to the bottom and make sure to move the power cord so that it is hanging out of the triangle (and not taped inside!). Repeat steps 5 and 6 on the bottom side.

Figure F-6. Before securing the bottom triangle, make sure to pull the power cord out first and tape it to the unit to hold it in place.

8. Lay the unit down with the box fan on the ground and the point of the triangle facing up, and begin adding more tape to secure and, more importantly, seal any gaps in the filter unit assembly. Repeat on each edge of the air filter unit, nine edges total, making sure that the duct tape is flush against the edges and no gaps are visible.

Figure F-7. Close-up of one of the edges of the unit after it was secured with duct tape.

9. The unit is assembled and ready to be used. Place the unit sitting upright in an open area and plug it in to begin using.

Figure F-8. DIY triangular-shaped air filter unit fully assembled.

2. Usage

The following section discusses the recommended best practices for operation and maintenance for the DIY air filter, including consideration of filter placement in rooms, filter management and replacement intervals (including a general estimate of how long to use a filter), factors that may affect system operation and maintenance in different climate zones, and other related issues. A video of the user manual for our triangular-shaped air filter unit is hosted here:

2.1. Turning the air filter on

Taking the power cord, plug in the unit to a wall outlet as shown in Figure F-9(the standard wall outlet voltage for US homes is 110). Then select which speed setting you would like, 1, 2, or 3 (low, medium, or high).

Figure F-9. Plugging in and turning on the air filtration device.

2.1.1. Room considerations and specifications

When using this DIY air filter to clear particulates from a room, it is recommended that you use a room that can be enclosed (i.e., windows and doors can be shut), and any heating vents can be closed. This design is well suited to a typical size bedroom (approximately 10' x 12' with an 8' ceiling), from which it can purge all wildfire smoke essentially in about 20 minutes on high or 40 minutes on low. Actual performance will depend on the selected fan and filters.

2.1.2. When to use and how often to use

When to use this unit is up to you. We recommend using this air filter whenever air quality is bad, and you should use your best judgment and, if available, check the PurpleAir website (or any other real-time PM 2.5 reporting website) to verify the air quality within the area. You can also use this unit anytime you would like to remove any particulates such as pollen, dust, mold, and tobacco smoke within your home. This unit does produce a fair amount of noise when being used, therefore if you are sensitive to noise, you can use this as needed when ambient outside and indoor air quality is good, there is no need to use the air filter.

If using this unit during a wildfire event, you should, if available, check the PurpleAir website (or any other real-time PM 2.5 reporting website) to monitor for high levels of particulate matter within your area. But if you see and smell smoke either within your home or surrounding your home, that is a good indicator that you should probably use an air filter to clean indoor air. Based on our test runs, the DIY air filter unit on the high setting takes approximately 20 mins to clean high levels of PM2.5 with an average-sized bedroom that is enclosed, and if used on the lowest setting, it takes approximately double this time.

2.1.3. Where to place the air filter in the room

The air filter should be placed where it will have unrestricted airflow within the room and have access to a wall outlet. Neither the inlet filters nor the outlet side should be against a wall.

Do not place the air filter in the corner of a room. We understand that the air filter appears to fit perfectly in the corner of the room, but that will restrict airflow and reduce the air cleaning rate.

Figure F-10. Where and where not to place the air filtration device during operation.

2.1.4. When to change the air filters

Currently, there is no set answer on when filters for DIY air filter units should be changed during bad air quality usage that is not due to an extreme event such as wildfire. For commercial filters, such as Medify Air, they recommend that their filters be changed every 2500 hours or 3-4 months, but this is merely a "guidance" and can be highly variable given where you live and what particulates you are exposed to.

For our DIY unit, we recommend that if this is being used for *heavy wildfire smoke*, we recommend that it is changed at least every two weeks. You should inspect the filters periodically to check filter quality. If the filters look *dirty* (i.e., dark, yellow, or any different color from when they were purchased) or if you smell *smokiness* (this is a sign that particles are off-gassing from the filter) coming from the filter, these are good indicators that the filters should be swapped out. But again, you should use your best judgment when it comes to when the filters should be replaced.

One thing to keep in mind when changing the air filters is that you will have to disassemble the whole unit to remove the old filters. *Carefully* remove all the tape from the cardboard, and it does not matter if the old filters are damaged in the removal process because you will be disposing of these anyways. We recommend that you have extra cardboard in case that the cardboard is damaged in the removal process and more duct tape and scissors to reassemble the air filter once the new filters are in place.

2.1.5. Checking seals and edges

Periodically the duct tape around the filters and box fan should be checked to ensure they are flush and not peeling off of any components to ensure that there are no gaps in the unit. But with premium duct tape, we noticed that the edges still were in good condition after being assembled a month ago, thus reinforcing our recommendation to purchase premium duct tape if available in your location and if it is within your budget.

2.1.6. Safety

With newer models of box fans, overheating is not a huge issue, given that most models have an automatic shut-off feature when the fan gets too hot. For this reason, it is not recommended to use this filter design with older box fans. But as such, the box fan should NEVER be left unattended in the room or when out of the house.

It is also recommended that people with children keep an eye that they do not stick their fingers or any other object through the front panel of the fan as they can cause harm to themselves and the unit.

DO NOT use this air filter in an area that has water present, such as a bathroom, because that can lead to electrocution.

If you hear any *weird* noises from the air filter, stop use and investigate what is the cause of the noise to see if it is a small object trapped in the filters and remove it to avoid damaging the unit. Again, if the filters are still in good condition, *carefully* disassemble the unit to find the issue and then reassemble when solved.

This product was designed and tested in San Francisco, CA, so it is possible that if used in other climate zones different from the test area, other issues may arise that affect the overall performance of the unit.

Figure F-11. Do not place water on top of the air filter or use it around other sources of water, such as a bathroom sink, toilet, or bath.