The Secret Lives of Filters

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Civil & Mineral Engineering
UNIVERSITY OF TORONTO

Hub for Advancing Buildings

How do we improve indoor air quality?

1. Keep it Dry
2. Source Control
3. Ventilation
4. Air Cleaning

"If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure." ~ *Max von Pettenkofer, 1858*

Leviticus 14:33-53 New International Version (NIV)
33 The LORD said to Moses and Aaron, 34 "When you enter the land of Canaan, which I am giving you as your possession, and I put a spreading mold in a house in that land, 35 the owner of the house must go and tell the priest, 'I have seen something that looks like a defiling mold in my house.' 36 The priest is to order the house to be emptied before he goes in to examine the mold, so that nothing in the house will be pronounced unclea n and inspect the house. 37 He is to exami it has greenish or reddish depres than the surface of the wall, 38 the priest house and close it up for seven days. shall return to inspect the house. If the mo e is to order that the contaminated stones unclean place outside the town. alls of the house scraped and the materi to an unclean place outside the town. ones to replace these and take new clay a

43 "If th e house after the stones have been torn o lastered, 44 the priest is to go and exami d in the house, it is a persistent defiling mold; the house is unclean. 45 It must be torn down—its stones, timbers and all the plaster—and taken out of the town to an unclean place.

How do we improve indoor air quality?

1. Keep it dry
2. Source Control
3. **Ventilation**
4. Air Cleaning

III.

A HEALTHFUL HOME.

Household murder—Poisoning and starvation the inevitable result of bad air in public halls and private homes—Good air as needful as good food—Structure and operations of the lungs and their capillaries and air-cells—How people in a confined room will deprive the air of oxygen and overload it with refuse carbonic acid—Starvation of the living body deprived of oxygen—The skin and its twenty-eight miles of perspiratory tubes—Reciprocal action of plants and animals—Historical examples of foul-air poisoning—Outward effects of habitual breathing of bad air—Quotations from scientific authorities.—Pages 43–58.

IV.

SCIENTIFIC DOMESTIC VENTILATION.

An open fireplace secures due ventilation—Evils of substituting air-tight stoves and furnace heating—Tendency of warm air to rise and of cool air to sink—Ventilation of mines—Ignorance of architects—Poor ventilation in most houses—Mode of ventilating laboratories—Creation of a current of warm air in a flue open at top and bottom of the room—Flue to be built into chimney : method of utilizing it.—Pages 59–65.

V.

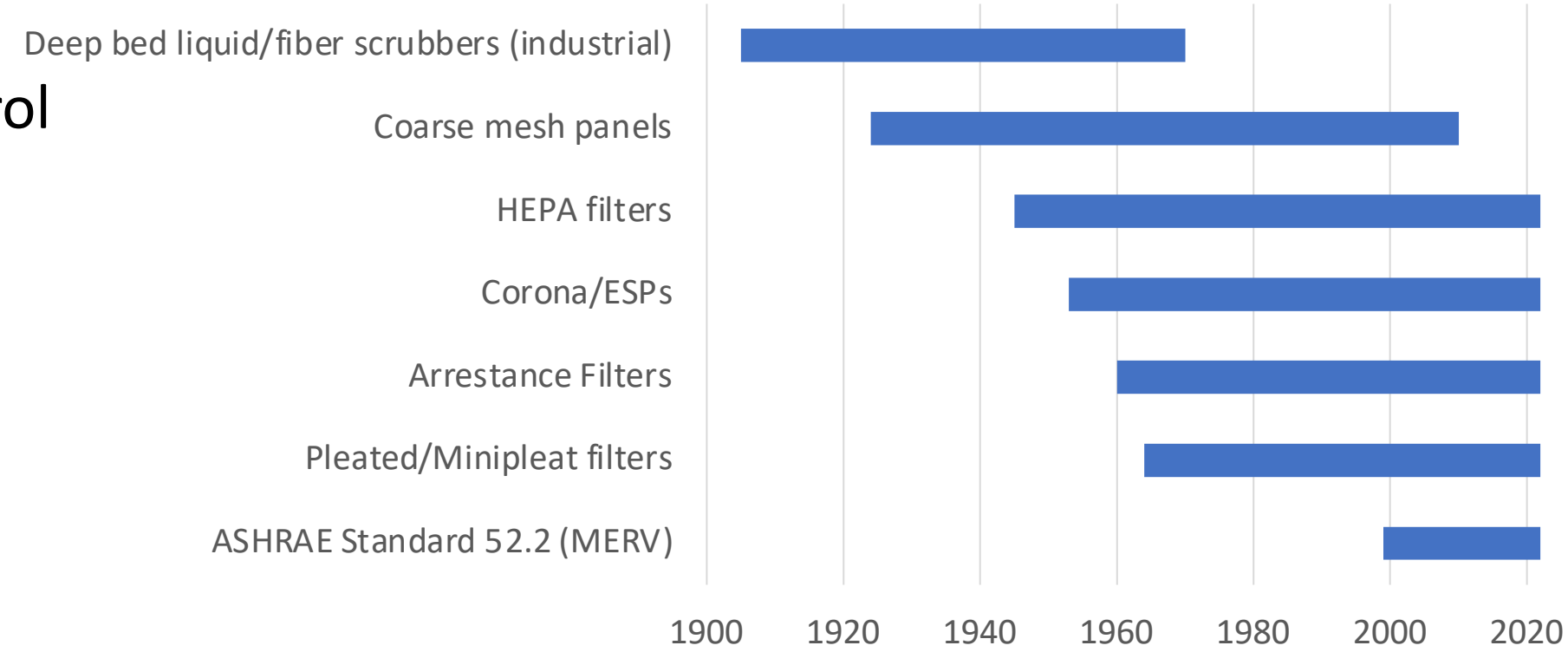
Beecher CE, Stowe H B. 1869. The American Woman's Home. New York: J.B. Ford and Company.

"When `the wise women buildeth her house,' the first consideration will be to the health of the inmates. The first and most indispensable requisite for health is pure air, both by day and by night."

"A learned physician also thus wrote to the author of this chapter: "The subject of the ventilation of our dwelling-houses is one of the most important questions of our times. How many thousands are victims to a slow suicide and murder, the chief instrument of which is want of ventilation!"

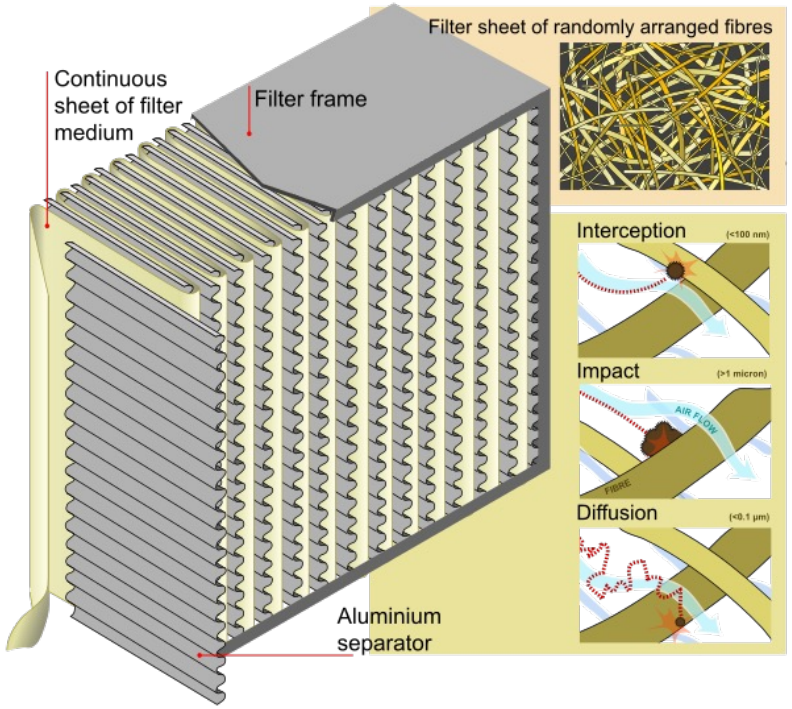
How do we improve indoor air quality?

1. Keep it Dry
2. Source Control
3. Ventilation
4. **Air Cleaning**



Data from Burroughs et al. (2020) *ASHRAE Trans*

Upper: Temeku, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons
Lower: Robert Aleck, www.cynexia.com



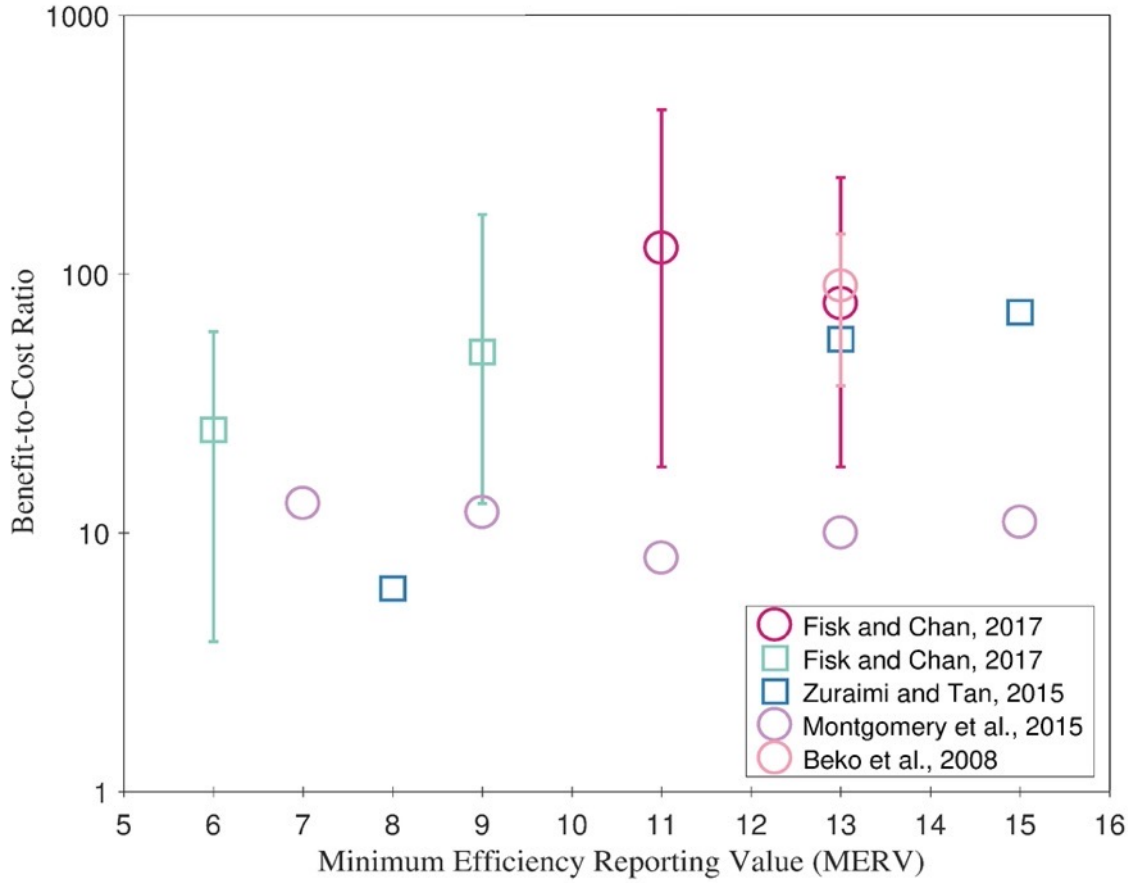
LadyofHats, Public domain, via Wikimedia Commons

By Janwikifoto - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10650999

From a HVAC perspective

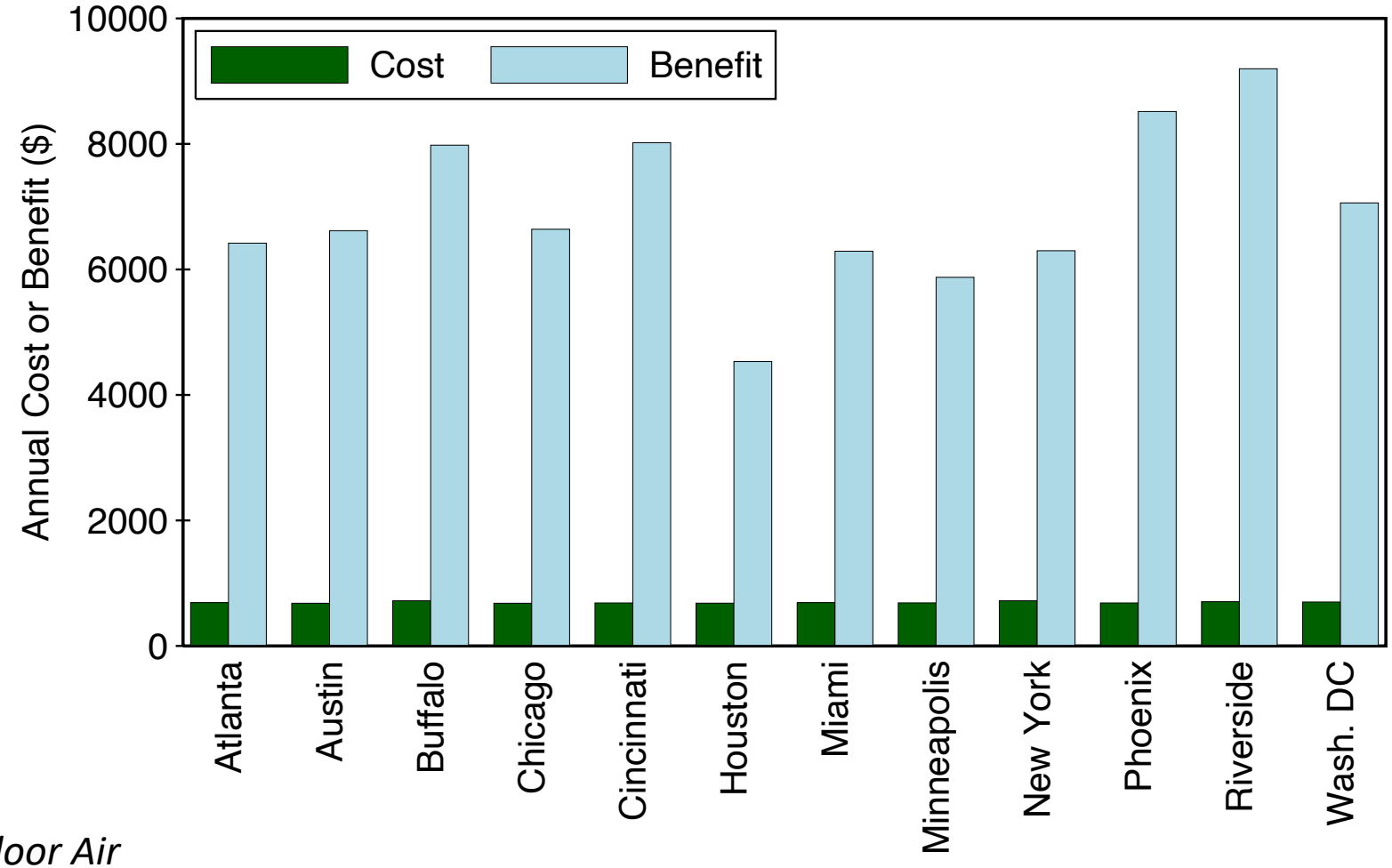
- Filters use energy
- Filters are a maintenance item
- Filters negatively impact cooling performance
- Benefits of filtration aren’t clear

Particle Filtration is obvious target for investment



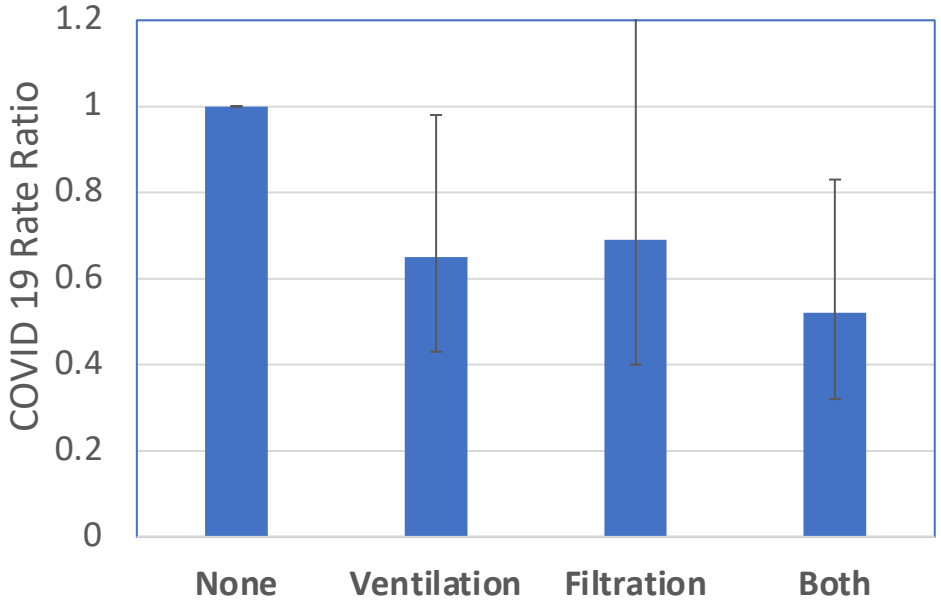
Alavy and Siegel (2019) *Sci Tech Built Environ*

Ozone Filtration – Benefits

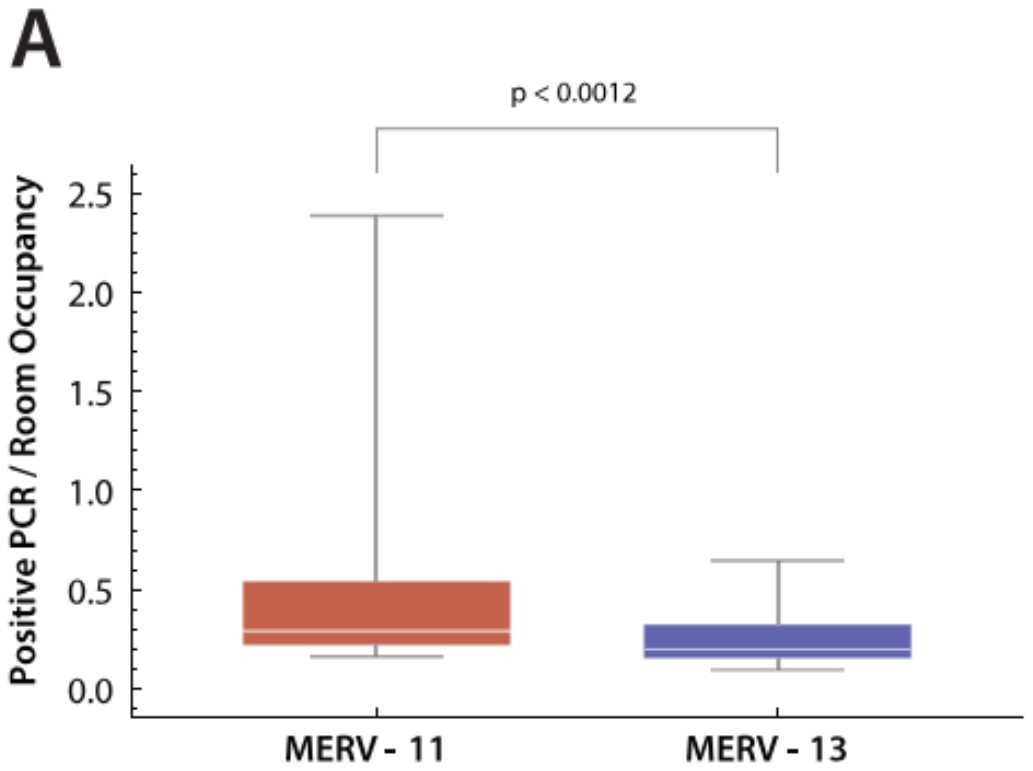


Aldred et al. (2016) *Indoor Air*

Filtration & COVID-19



Data from Gettings et al. (2021) *MMWR*



Zand et al. (2024) PLoS ONE

ASHRAE …emain
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COMMENTS OF DONALD R. BAHNFLETH, PRESIDENT
AMERICAN SOCIETY OF HEATING, REFRIGERATING
AND AIR-CONDITIONING ENGINEERS

IAQ 86 OPENING SESSION
APRIL 20, 1986

Good afternoon, and thank you for joining us for this very important conference on Managing Indoor Air for Health and Energy Conservation. During the next four days, we will hear from experts in indoor air quality. A diverse group of talented men and women from around the world will present us with the latest findings in virtually every aspect of the issue.

More than 100 authors will present papers, either orally during the 12 sessions or in poster sessions on Monday and Tuesday. They represent government, corporations, universities and colleges, private laboratories. All of them have worked for months to gather the data for their presentations and they have done it for one purpose: because they believe it important to provide solutions to indoor air quality problems.

ASHRAE has organized and is co-sponsoring with the Department of Energy and the Environmental Protection Agency this conference for the same reason. Because indoor air quality is an important issue. In fact, ASHRAE believes that indoor air quality is and will remain the single most important health issue facing us in the 1980's. Unacceptable indoor air quality can impair our health, affect our sense of well-being, and affect our productivity in terms of both lost time and loss of productive effort.

Years ago, whenever there was a problem regarding the indoor air, we usually tried what I call "granny's solution." We just threw open the door or the window and brought in outside air. Today, we might not always want to bring in unfiltered uncontrolled outside air. In some cities, what's outside could be worse than what's inside. Large amounts of outside air also require expending large amounts of energy for heating and cooling. Concern for the IAQ issue is still growing.

The way we live today, spending more than 90 percent of our time indoors, creates the need for a better knowledge of what contaminants are present in the indoor environment and their effect on people. The issue of indoor air quality is a sleeping giant whose time has come, The total number of serious health effects related to IAQ in non-industrial buildings have been miniscule compared to the total building stock. But there have been enough to indicate that a problem exists. Fortunately, addressing the situation this early gives us time to move rationally. The issue does not need to be sensationalized. We do not need knee-jerk reactions.

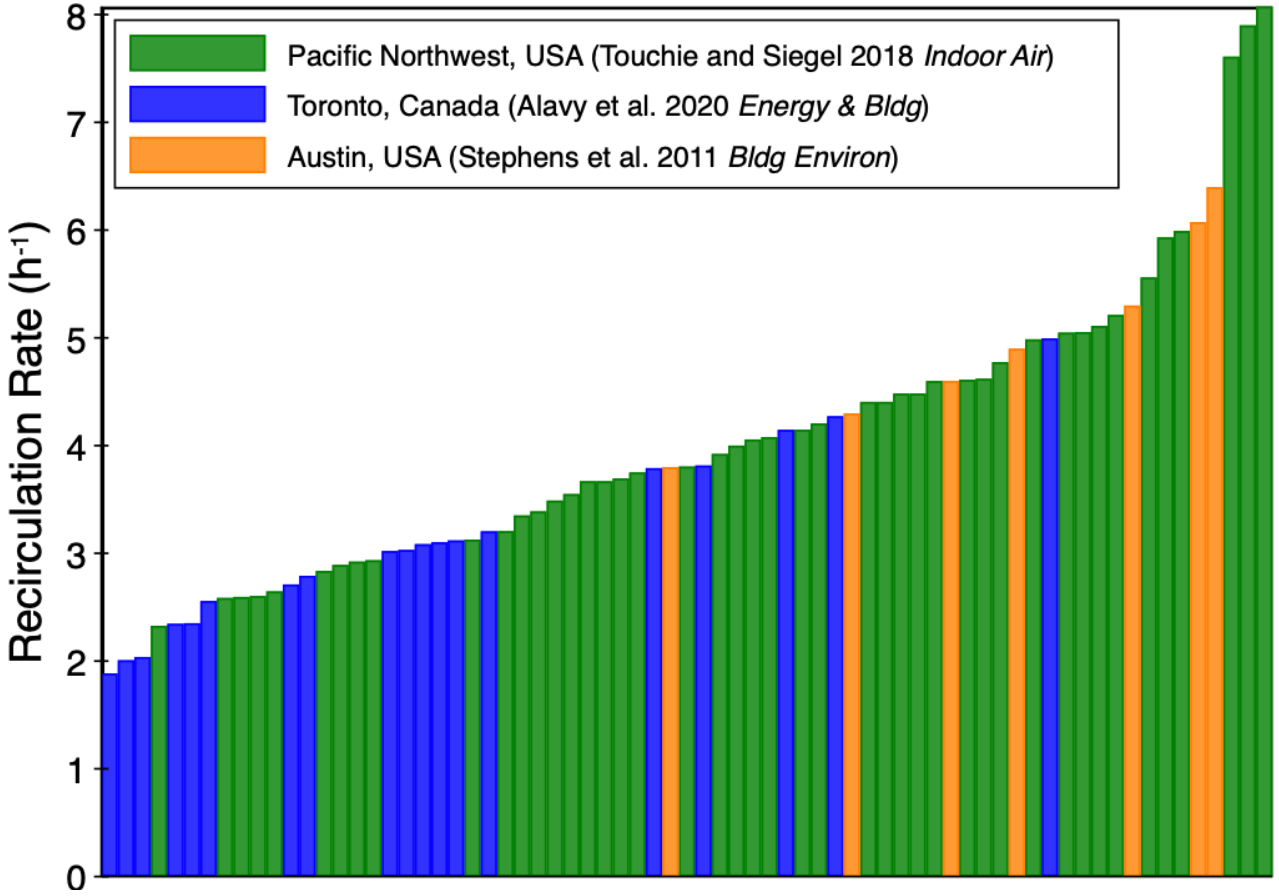
Why No Investment in Filtration?

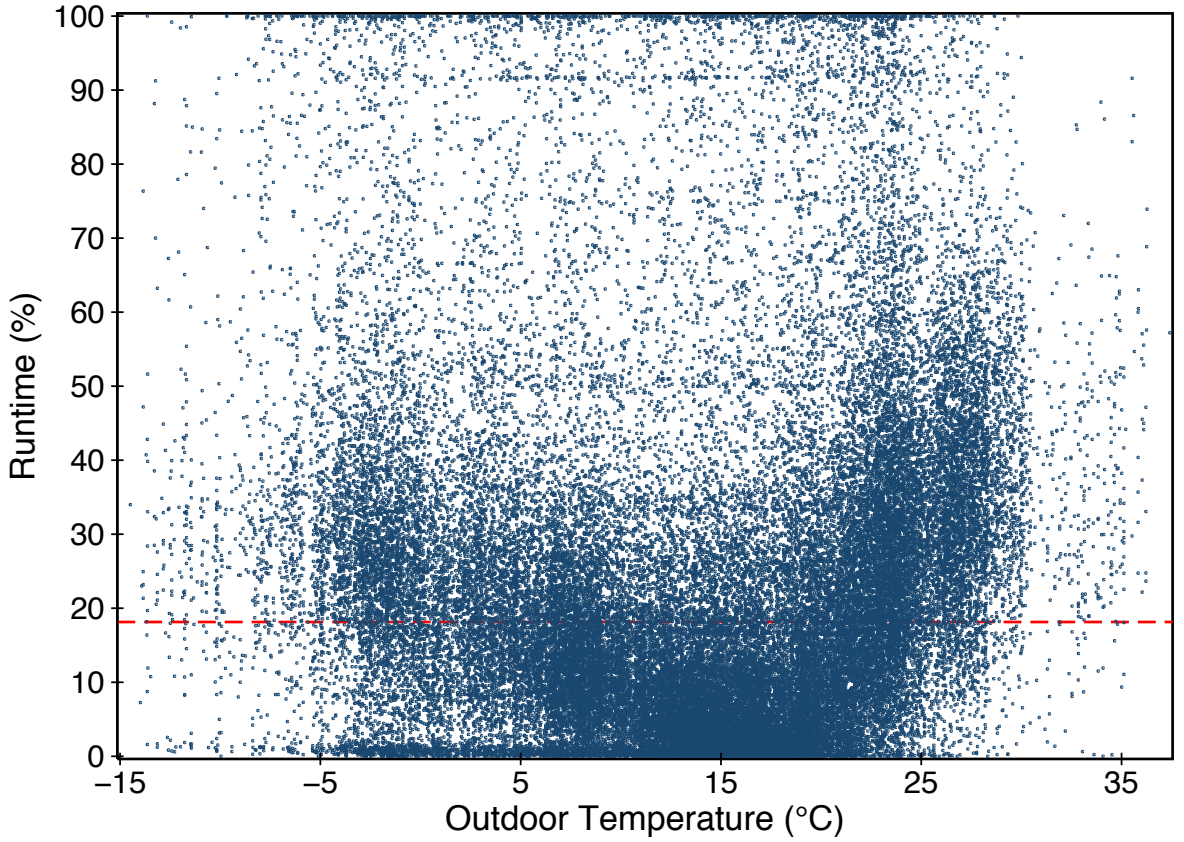
1. Context matters
2. Energy concerns
3. There be pirates

Filtration: Context is Everything

- The virus/particle/droplet/contaminant has to get to the filter
- The filter has to remove the virus/particle/droplet/contaminant
- The removal to the device has to contribute substantially to overall removal

Airflow, In-situ efficiency, Effectiveness



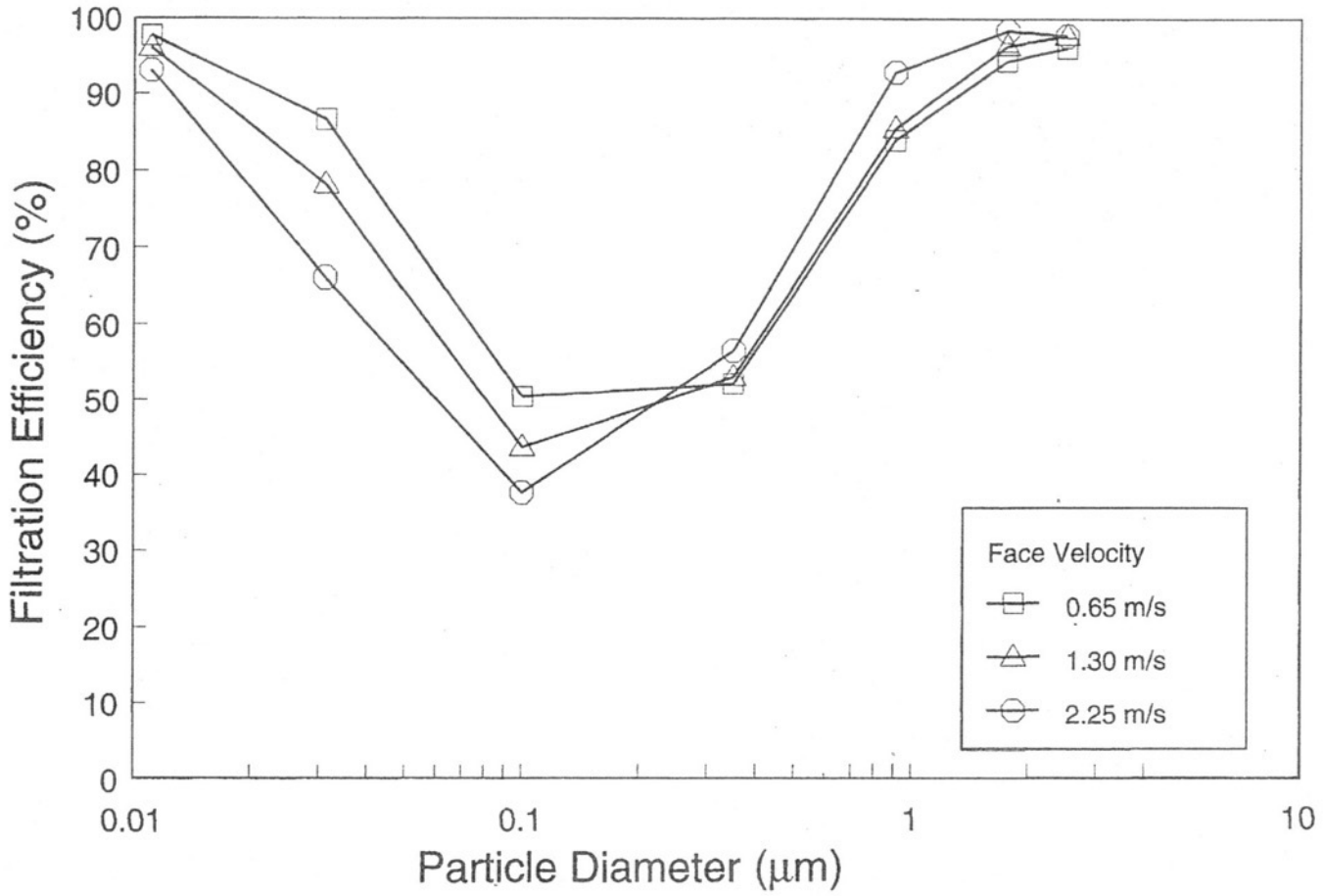


Data from: Touchie and Siegel (2018) *Indoor Air*

Recirculation: home volumes that pass through filter when system operates

Runtime: Fraction of time that system operates

Efficiency: Classic U-shaped Curve



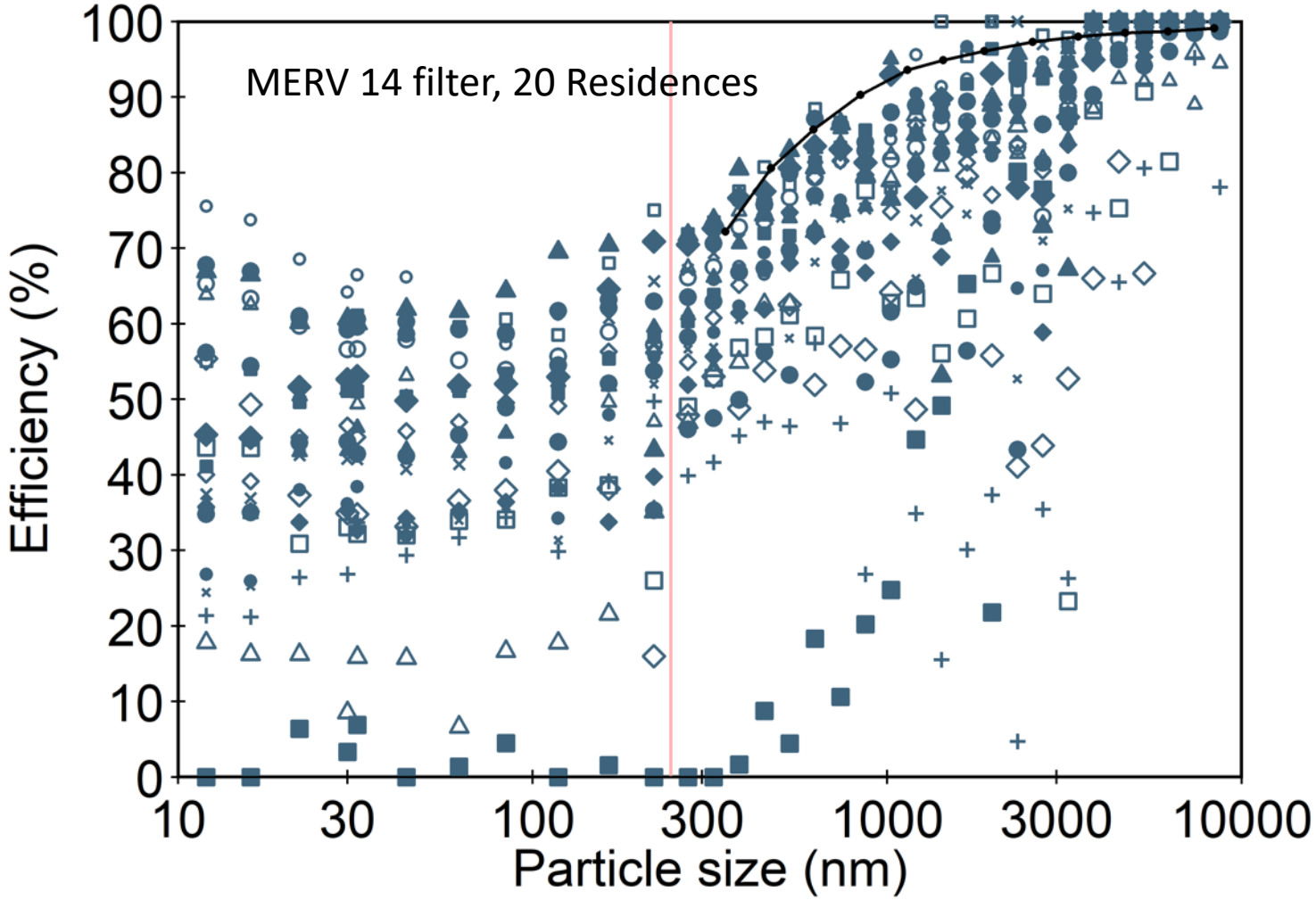
Ref: Hanley et al. (1994) *Indoor Air*

Table 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, µm		
	Range 1 0.30 to 1.0	Range 2 1.0 to 3.0	Range 3 3.0 to 10.0
1	N/A	N/A	$E_3 < 20$
2	N/A	N/A	$E_3 < 20$
3	N/A	N/A	$E_3 < 20$
4	N/A	N/A	$E_3 < 20$
5	N/A	N/A	$20 \le E_3$
6	N/A	N/A	$35 \le E_3$
7	N/A	N/A	$50 \le E_3$
8	N/A	$20 \le E_2$	$70 \le E_3$
9	N/A	$35 \le E_2$	$75 \le E_3$
10	N/A	$50 \le E_2$	$80 \le E_3$
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$

ASHRAE Standard 52.2-2017

Lab Efficiency is Not In-situ Efficiency



Li and Siegel (2020) *Indoor Air*

Image: Courtesy Geoffroy Allard

Efficiency: Filter Aging

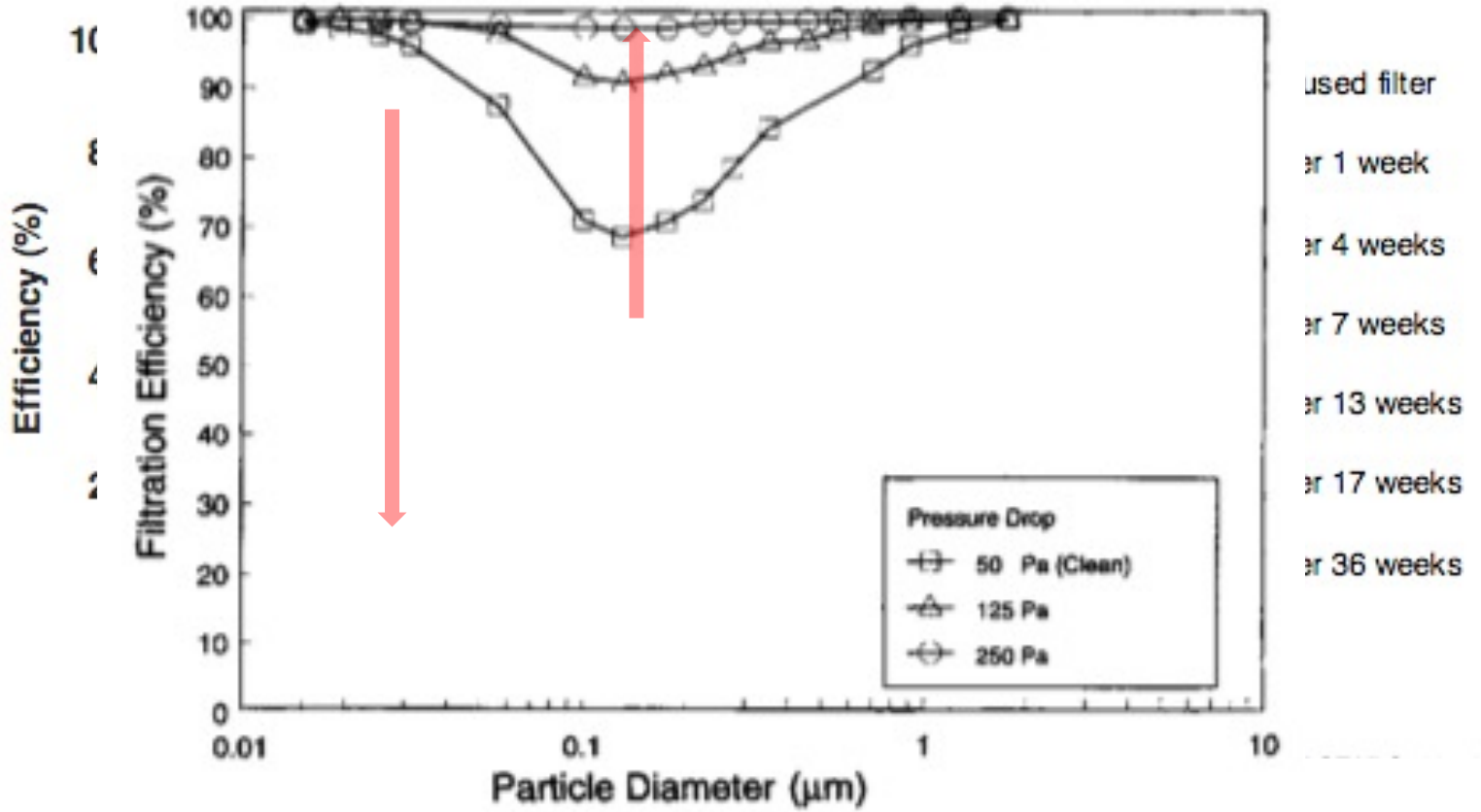


Fig. 6 The effect of dust load on the fractional filtration efficiency of a pocket filter of non-woven fiber media at 1.3 m/s

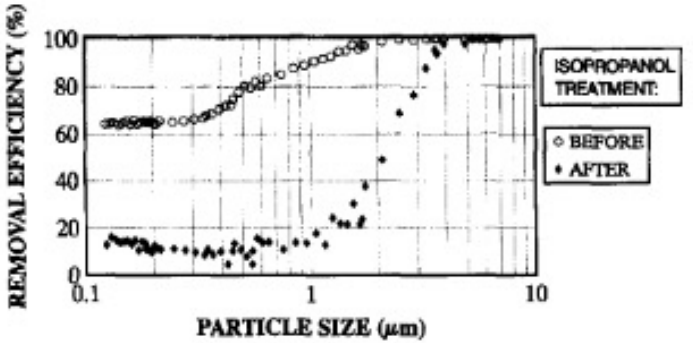


Fig. 2. Effect of isopropanol treatment on the removal efficiency of an "EU7" electret filter, flow velocity 0.33 m/s.

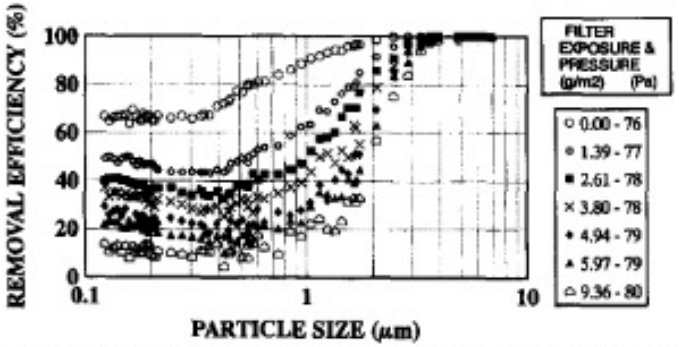


Fig. 3. Effect of diesel fume aerosol on the removal efficiency of an "EU7" electret filter, flow velocity 0.33 m/s.

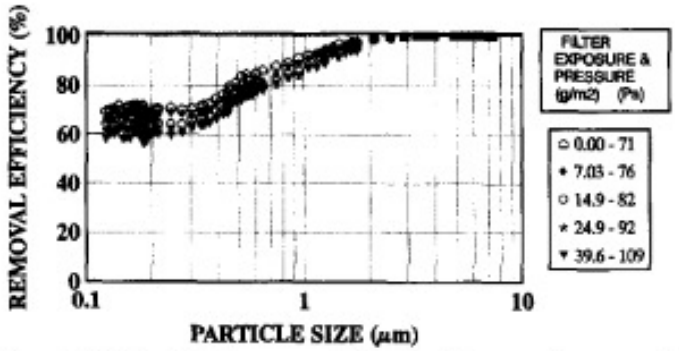
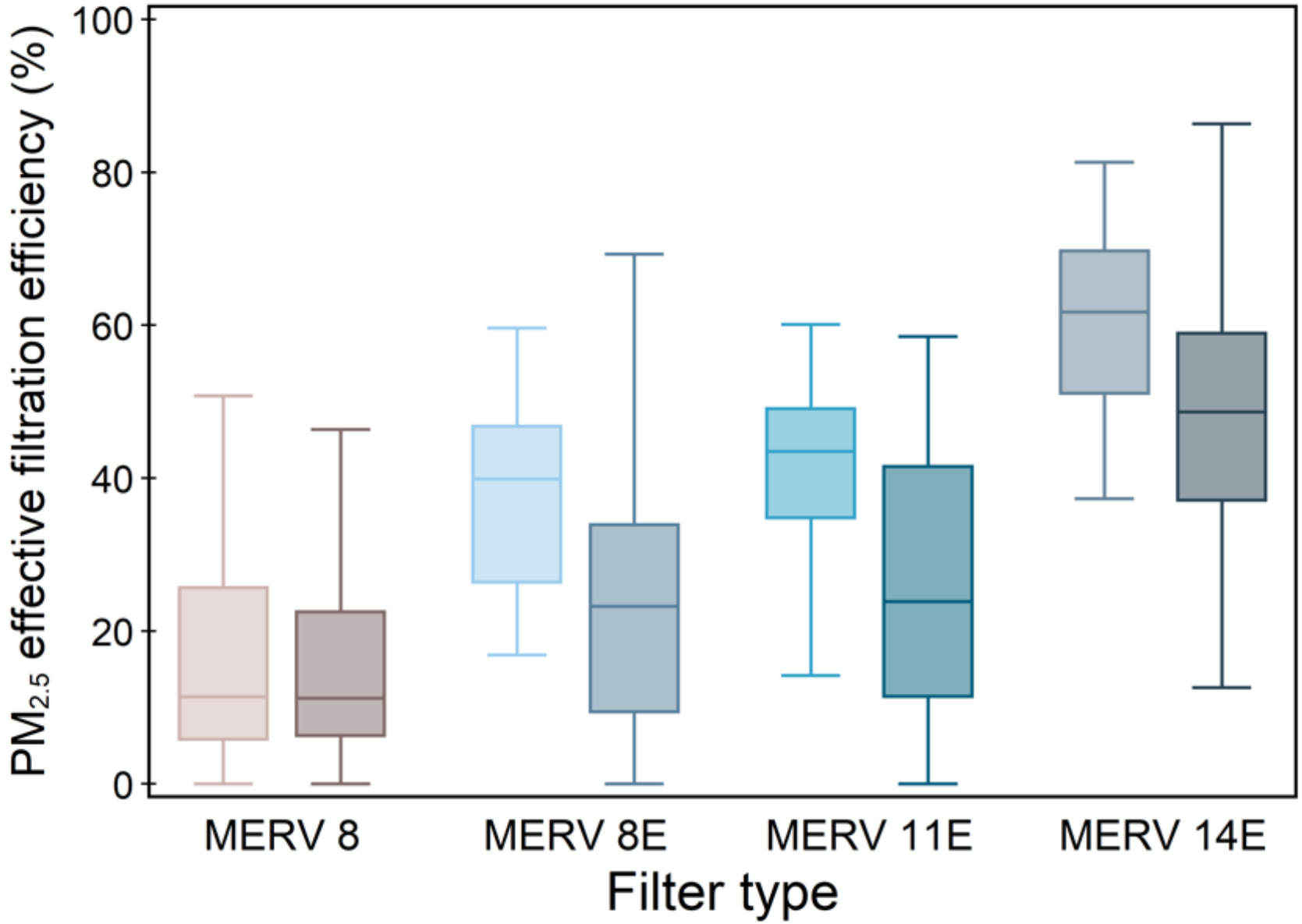


Fig. 4. Effect of Arizona road dust loading on the removal efficiency of an "EU7" electret filter, flow velocity 0.33 m/s.

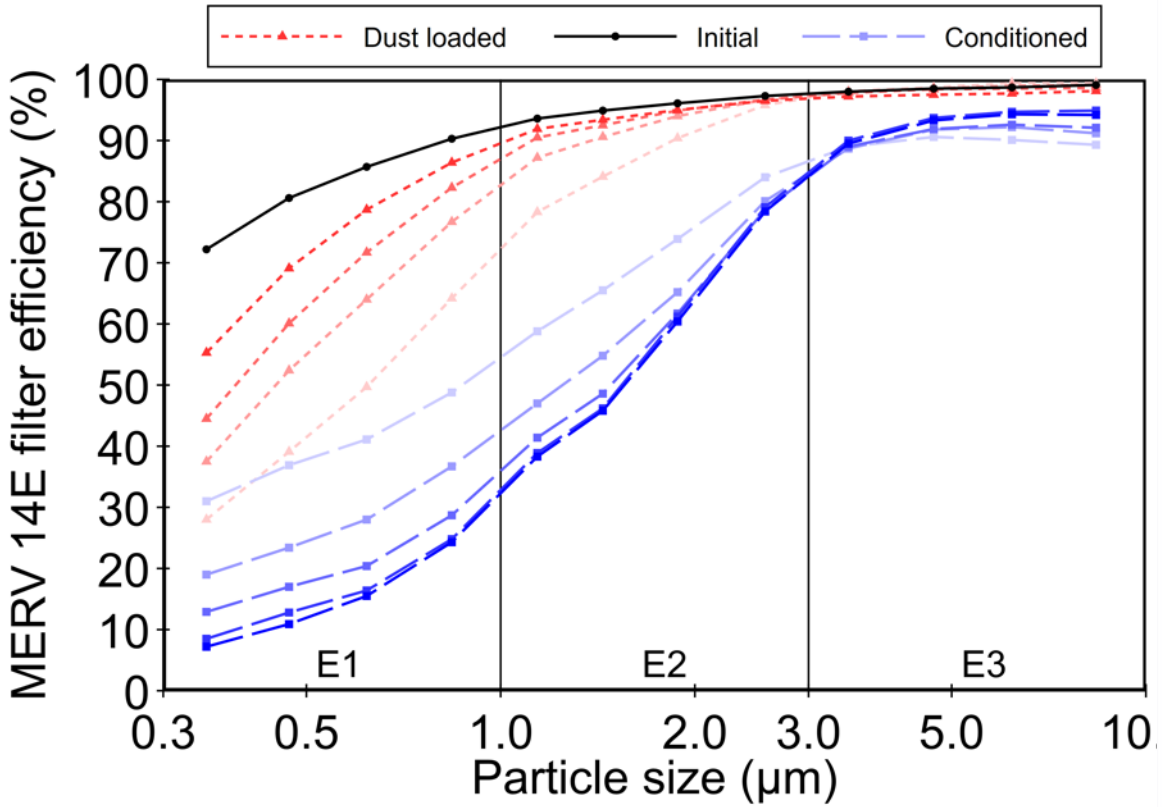
Refs: Hanley et al. (1994) *Indoor Air*, Lehtimäki et al. (2002) ASHRAE RP-1189 Report

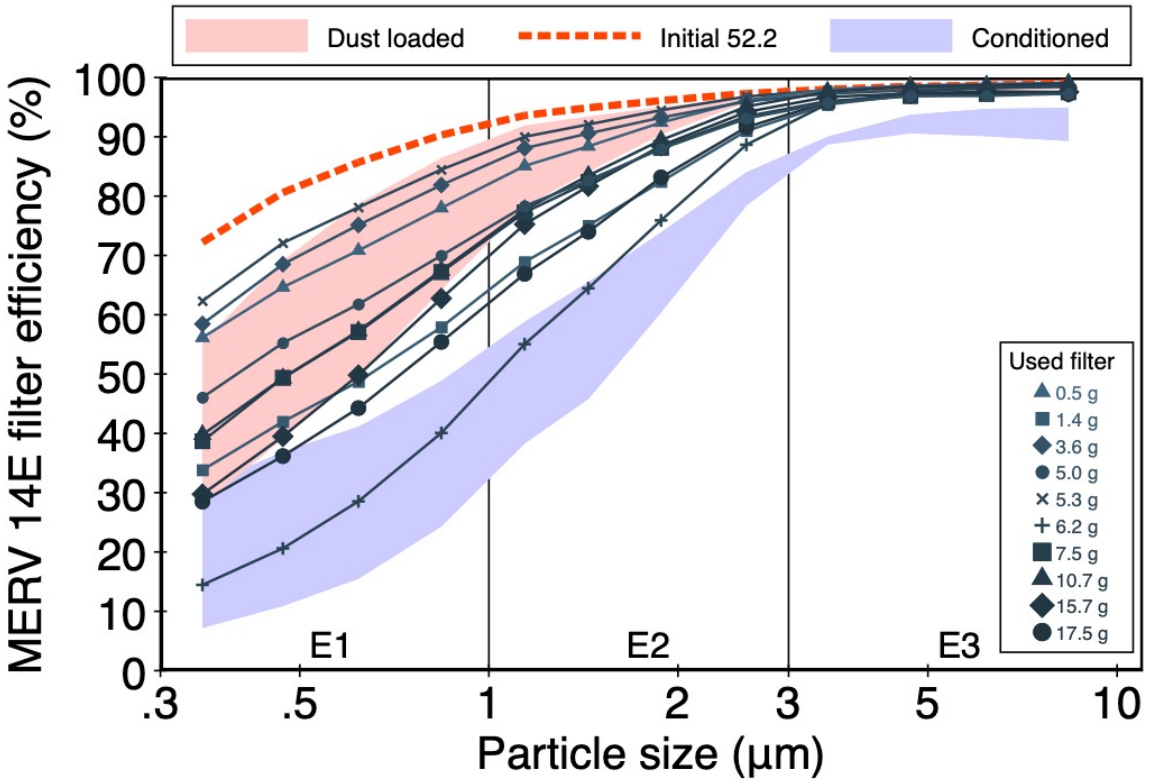
Lehtimäki & Heinonen (1994) *Bldg Environ*



Li and Siegel (2020) *Indoor Air*

Standard 52.2 Efficiency Change



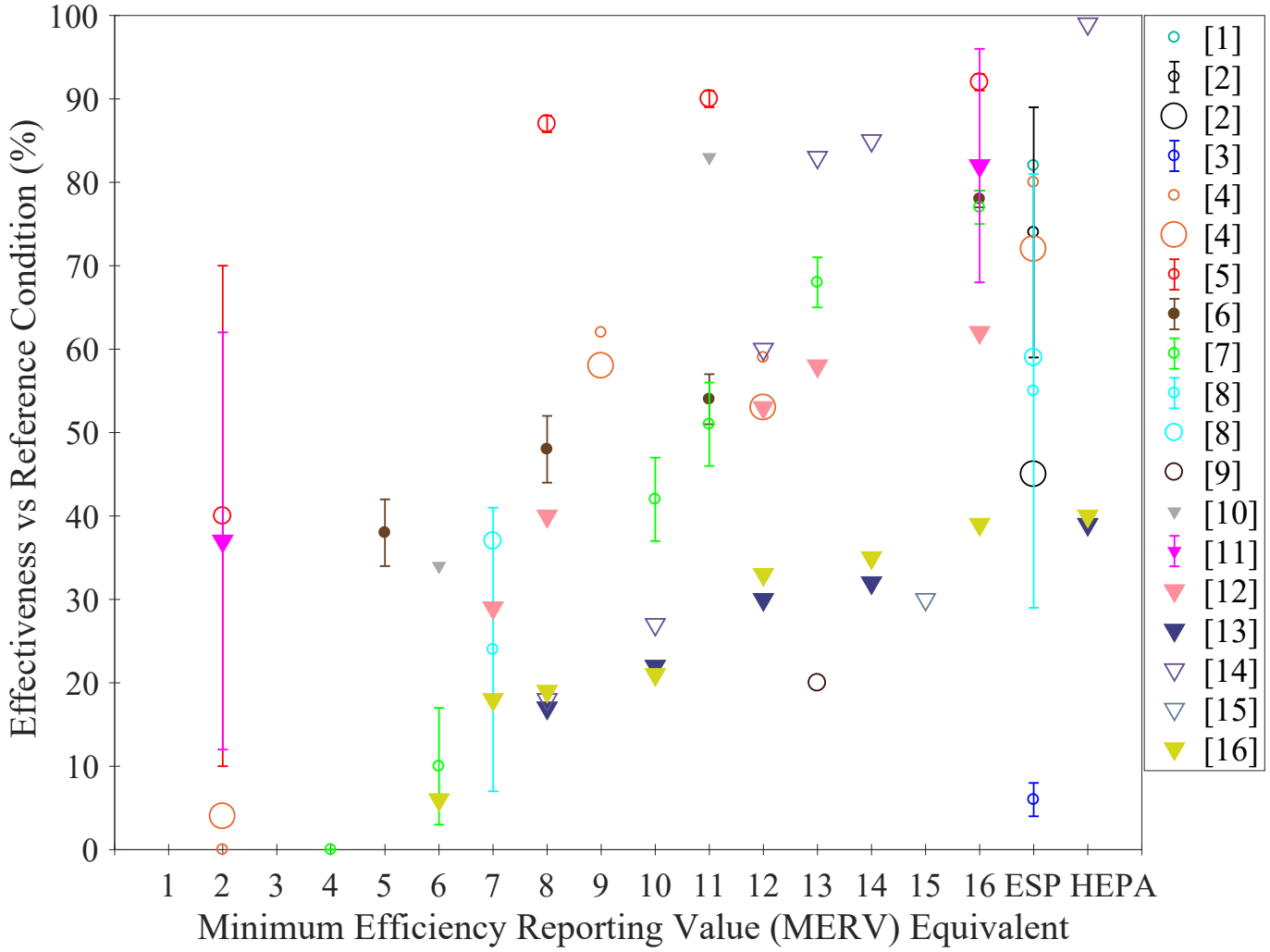


Li and Siegel (2020) *Sci Tech. Built Environ.*

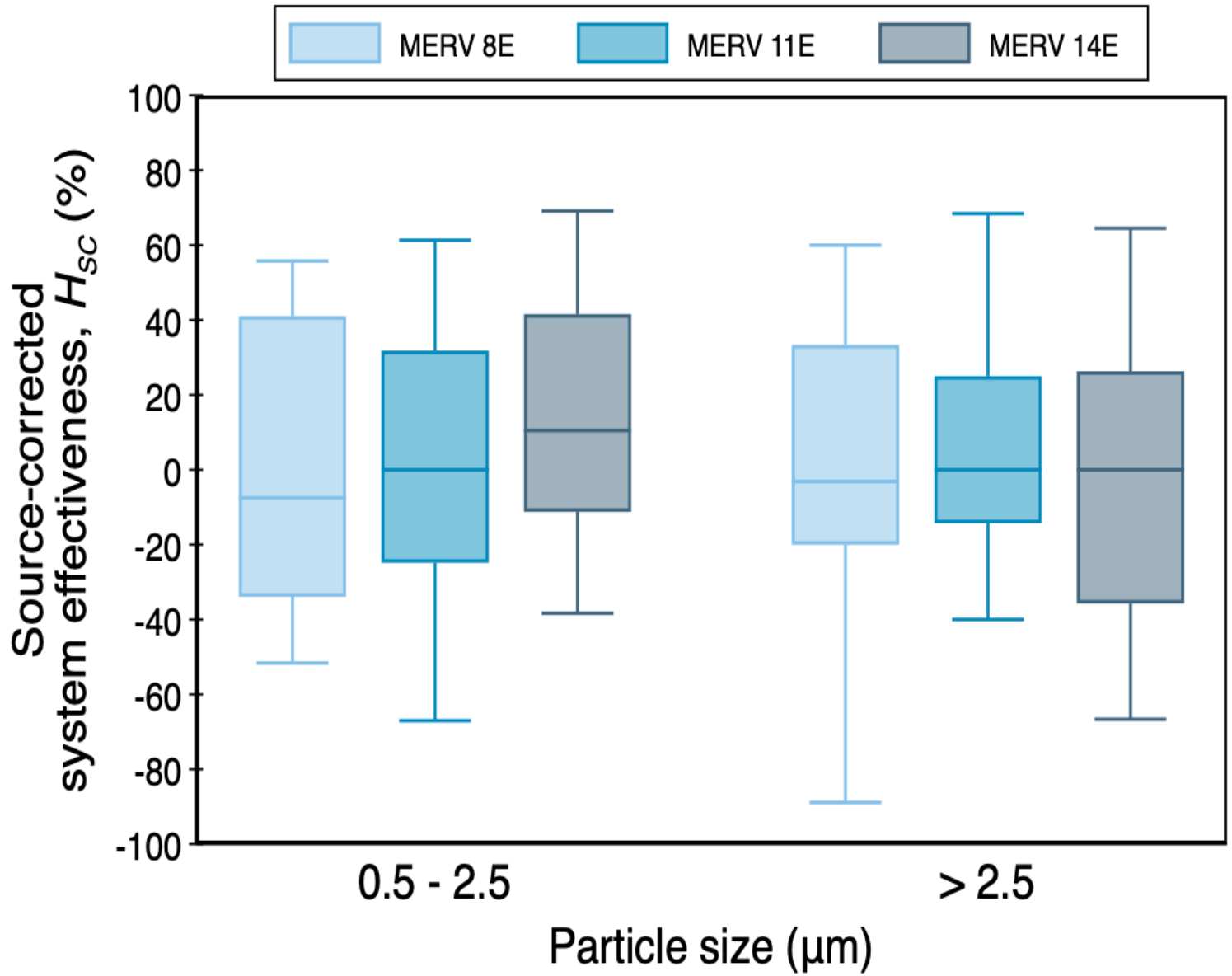
Putting it all Together: Filter Effectiveness

$$H = 1 - \frac{C_{filter}}{C_{baseline}}$$

Ref: Miller-Leiden et al. (1996) *JA&WMA*



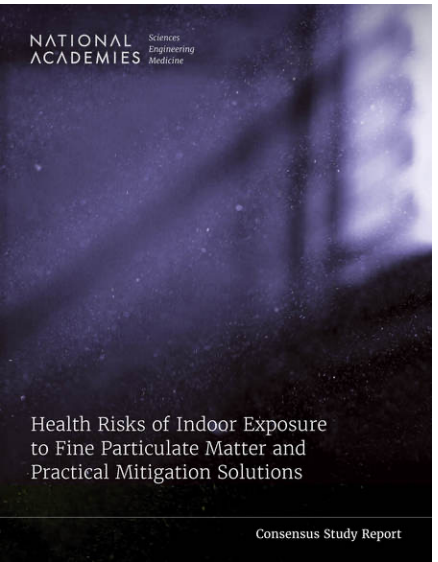
Alavy and Siegel (2019) *Sci Tech. Built Environ.*



Zhang et al. (2020) *Sci Tech Built Environ*

Important Point: Filtration Can and Does Work

- Scientific evidence
  - 55+ papers that measure a health effect associated with filtration
  - Consistent message: Filtration improves health outcomes with some variation
    - Benefit is strongest in locations with high ambient fine PM
    - Almost all are short-term studies
    - Context is often not measured



https://nap.nationalacademies.org/catalog/27341/health-risks-of-indoor-exposure-to-fine-particulate-matter-and-practical-mitigation-solutions

"The very big picture of this literature is that there is clear evidence that air cleaning is an effective mitigation measure for fine PM. However, there is also considerable variation in findings between studies and within studies for multiple health outcomes."

Energy Use of Filters

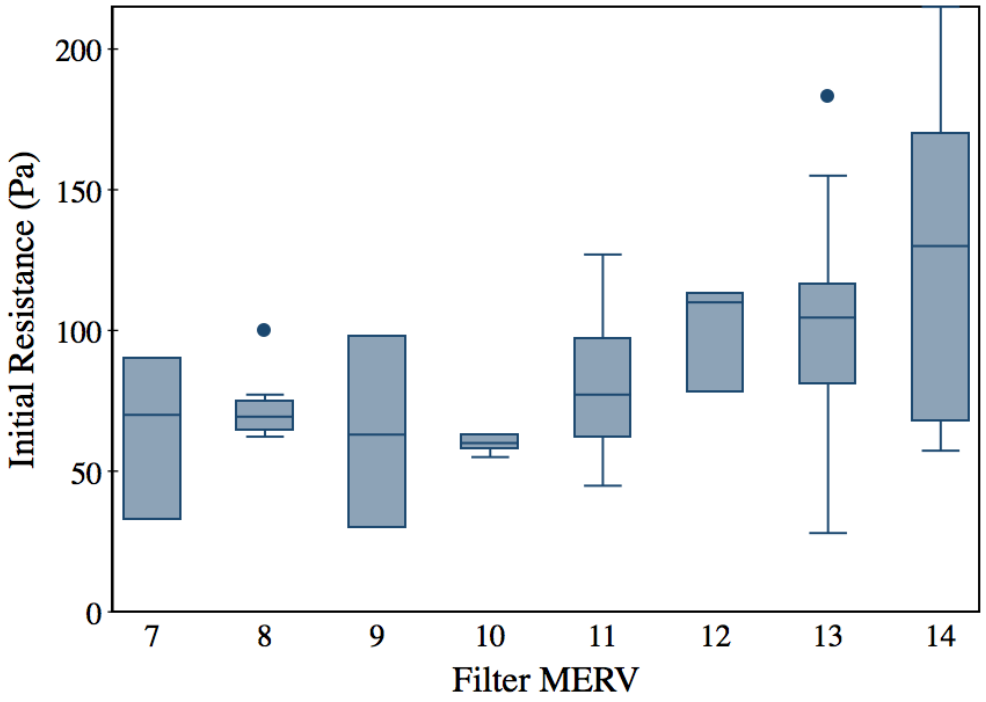
- Logical Process: Better filter = higher pressure drop = more fan energy

$$q_F = \frac{-\ln(1-\eta)}{\Delta P}$$

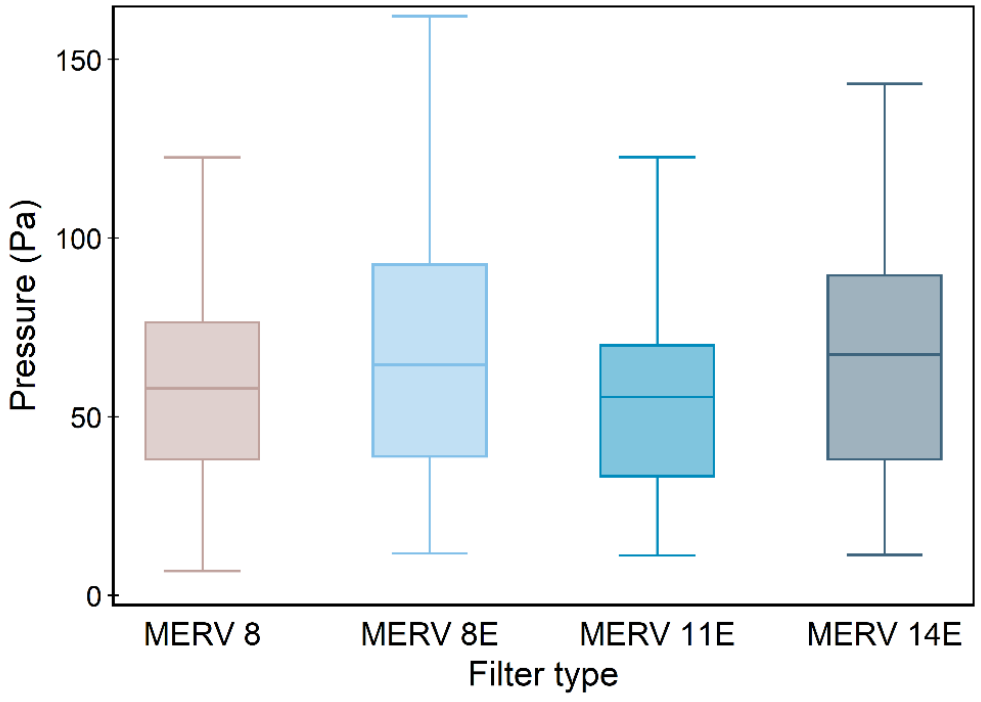
Problems:

- ΔP is a strong function of velocity
- η is a weak function of velocity and a strong function of particle size

- Velocity varies all the time and varies as filter loads
  - Depends entirely on fan and controls
  - Very different from velocities used in standard filter tests



Zaatari et al. (2014) *Bldg Environ*, Rivers and Murphy (1999) *ASHRAE RP-675*



Alavy et al. (2020) Energy Bldg.

Big Picture on Energy Use of Filters

- The energy consequences of a filter depend on
  - Fan
  - Fan controls
  - Air velocity
  - How important filter is to overall pressure drop
  - Conditioning system and sensitivity to flow
  - Pressure drop of filter
- Even in cases where filter causes an increase in fan energy
  - Fan energy is usually small (~10%) fraction of conditioning energy

Stephens et al (2010) *HVAC&R,* Zaatari et al (2014) *Bldg Environ*, Alavy et al. (2019) *Sci Tech Built Environ,* Alavy et al. (2020) *Energy Bldg,*

Miscommunication By Air Cleaner Manufacturers

- Very long history of manufacturers making claims about ”alternative” air cleaners
- Examples
  - Very low flow rates (high efficiencies)
  - Very small volume testing chambers
  - Bogus metrics
- Lawsuits
  - Sharper Image (early 2000s)
  - GPS vs. Dr. Zaatari & Bud Offerman
  - GPS vs. Elsevier

GPS Air® Files a Motion to Amend Complaint Against Elsevier, Seeking Damages in Excess of $1.8 billion

https://www.prnewswire.com/

Air Cleaning Claims

This is a suitable place to give a most earnest warning against the use of so-called secret remedies and patent medicines…. Pettenkofer (1883)

- Many types of additive technologies (ions, plasma, ozone, hydroxyl radicals, etc.)
- Central paradox for additive technologies
  1. Emitting enough into the air to make a difference and there is risk of harm
     - "Our findings suggest that negative ions, possibly along with their reaction products with the room air constituents, adversely affect health." Liu et al (2021) *Indoor Air*
  2. Not emitting enough into the air to make a difference
     - Cleaning power is small

Miscommunication by Public Health Officials

Systematically omitting indoor air quality: sub-standard guidance for shelters, group homes and long-term care in Ontario during the COVID-19 pandemic

Amy Katz, Tianyuan Li, LLana James, Jeffrey Siegel & Patricia O'Campo

Received 25 Oct 2022, Accepted 19 Sep 2023, Published online: 13 Oct 2023

Cite this article https://doi.org/10.1080/09581596.2023.2262736 Check for updates

Table 1. Selection of evidence and guidance related to the use of portable air filters in reducing transmission of airborne diseases.

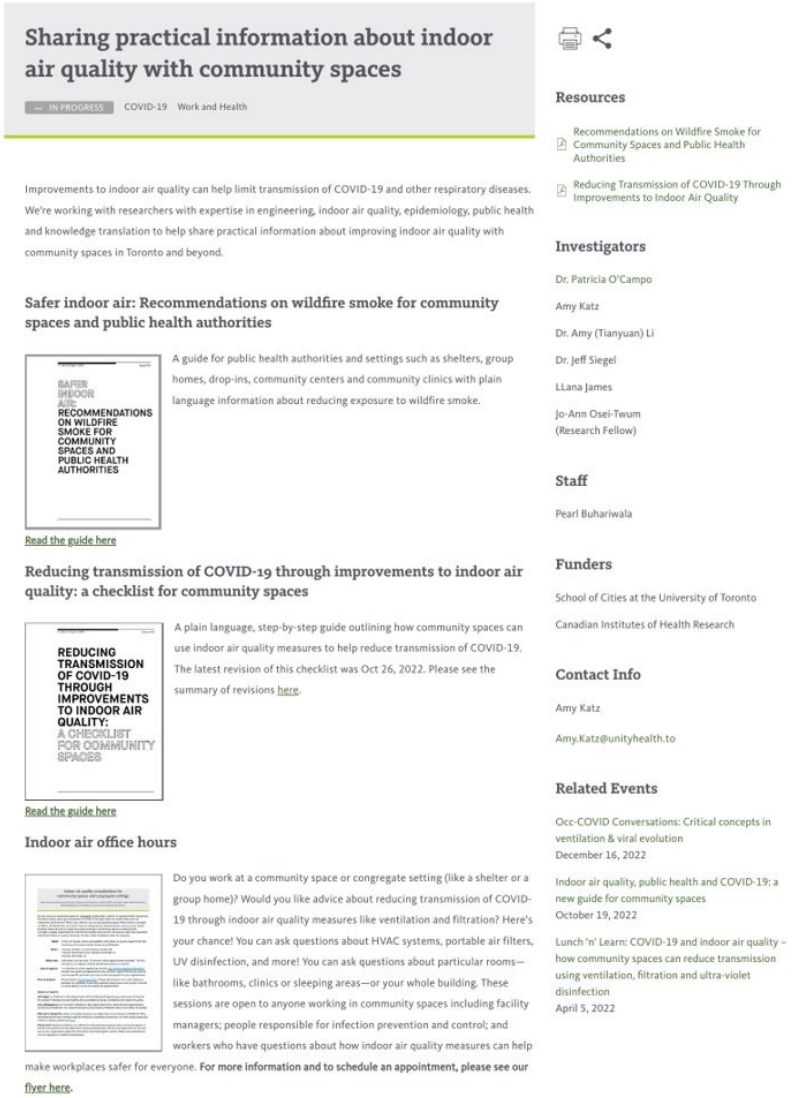
Type	Reference
Studies demonstrating that portable air filters (PAFs) remove particles that are the same size as respiratory particles from the air.	Derk et al. 2023; Fennelly et al. 2023; Buising et al. 2022; Dellweg et al. 2022; Lee et al. 2022; Coyle et al. 2021; Curtius, Granzin, and Schrod 2021; Duill et al. 2021; Lindsley et al. 2021; Boswell and Fox 2006; Miller-Leiden et al. 1996; Rutala, Weber, and Jones 1995; Offermann et al. 1985
Studies demonstrating that PAFs help to reduce transmission of COVID-19 by reducing concentrations of SARS-CoV-2 RNA copies in the air.	Morris et al. 2022; Myers et al. 2022; Thuresson et al. 2022; Ueki et al. 2022; Rodríguez et al. 2021
Studies demonstrating that portable HEPA filtration has been a standard practice in hospital infection prevention and control.	Curtis 2008; Eckmanns, Rüden, and Gastmeier 2006; Hahn et al. 2002; Davis, McCray, and Simone 1997; Loo et al. 1996; Nicas et al. 1993; Sherertz et al. 1987
Engineering guidance documents recommending the use of PAFs to reduce transmission of airborne diseases.	Centers for Disease Control and Prevention 2023; ASHRAE 2023; OSPE 2022; ASHRAE 2021
Examples of high-quality guidance for PAFs use and do-it-yourself PAFs.	Li, Katz, and Siegel 2022; CleanAirCrew 2021
Studies and guidance to aid in selecting PAFs that do not use unproven technologies or generate harmful by-products.	Siegel 2016; ASHRAE et al. 2015; Waring and Siegel 2011

Li et al. In Review

Rapid response to wildfire smoke →

Checklist/plain language guidance →

Office Hours for community organizations to ask questions about reducing disease transmission/IAQ, Grant-writing consulting →



Sharing practical information about indoor air quality with community spaces

IN PROGRESS COVID-19 Work and Health

Improvements to indoor air quality can help limit transmission of COVID-19 and other respiratory diseases. We're working with researchers with expertise in engineering, indoor air quality, epidemiology, public health and knowledge translation to help share practical information about improving indoor air quality with community spaces in Toronto and beyond.

Safer indoor air: Recommendations on wildfire smoke for community spaces and public health authorities

SAFER INDOOR AIR: RECOMMENDATIONS ON WILDFIRE SMOKE FOR COMMUNITY SPACES AND PUBLIC HEALTH AUTHORITIES

A guide for public health authorities and settings such as shelters, group homes, drop-ins, community centers and community clinics with plain language information about reducing exposure to wildfire smoke.

Read the guide here

Reducing transmission of COVID-19 through improvements to indoor air quality: a checklist for community spaces

REDUCING TRANSMISSION OF COVID-19 THROUGH IMPROVEMENTS TO INDOOR AIR QUALITY: A CHECKLIST FOR COMMUNITY SPACES

A plain language, step-by-step guide outlining how community spaces can use indoor air quality measures to help reduce transmission of COVID-19. The latest revision of this checklist was Oct 26, 2022. Please see the summary of revisions here.

Read the guide here

Indoor air office hours

Do you work at a community space or congregate setting (like a shelter or a group home)? Would you like advice about reducing transmission of COVID-19 through indoor air quality measures like ventilation and filtration? Here's your chance! You can ask questions about HVAC systems, portable air filters, UV disinfection, and more! You can ask questions about particular rooms—like bathrooms, clinics or sleeping areas—or your whole building. These sessions are open to anyone working in community spaces including facility managers; people responsible for infection prevention and control; and workers who have questions about how indoor air quality measures can help make workplaces safer for everyone. **For more information and to schedule an appointment, please see our flyer here.**

Resources

Recommendations on Wildfire Smoke for Community Spaces and Public Health Authorities

Reducing Transmission of COVID-19 Through Improvements to Indoor Air Quality

Investigators

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School of Cities at the University of Toronto

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Related Events

Occ-COVID Conversations: Critical concepts in ventilation & viral evolution
December 16, 2022

Indoor air quality, public health and COVID-19: a new guide for community spaces
October 19, 2022

Lunch 'n' Learn: COVID-19 and indoor air quality – how community spaces can reduce transmission using ventilation, filtration and ultra-violet disinfection
April 5, 2022

https://maphealth.ca/ventilation/

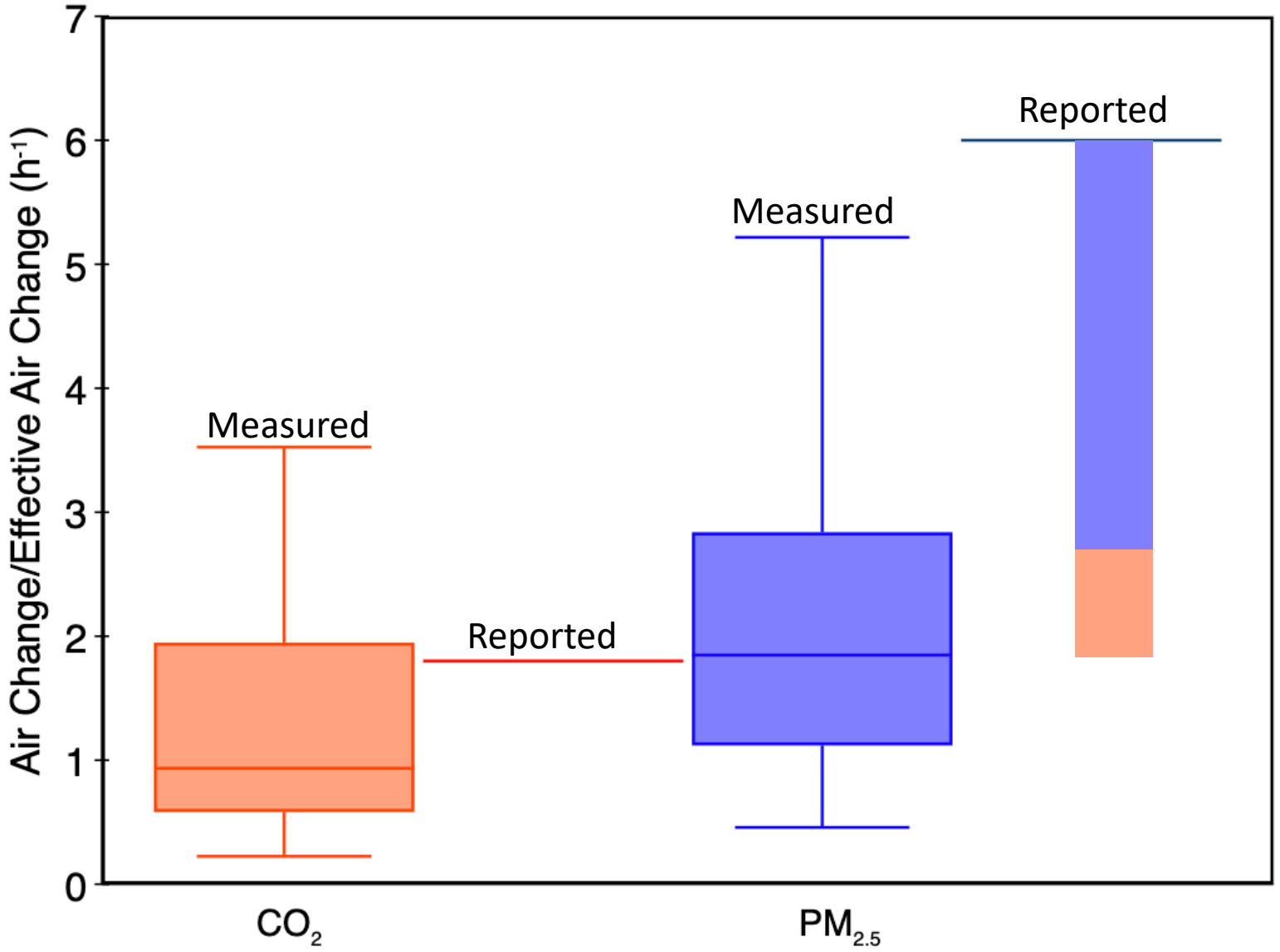
Opportunity # 1: Teach Users How to Use Filters

Install a good filter properly, make sure lots of air goes through it, change it frequently, and verify performance.

Verifying Performance

- Since context matters
  - Need a standardized approach to assess filtration/air cleaning/ventilation performance in any environment
  - Ideally: fast and cheap
    - Low-cost instrumentation
  - Need to detect byproducts (still a work in progress)
  - Role of placebo is important

Wallberg Room 130, November 11-22 2021, 121 decay periods (after filtering)

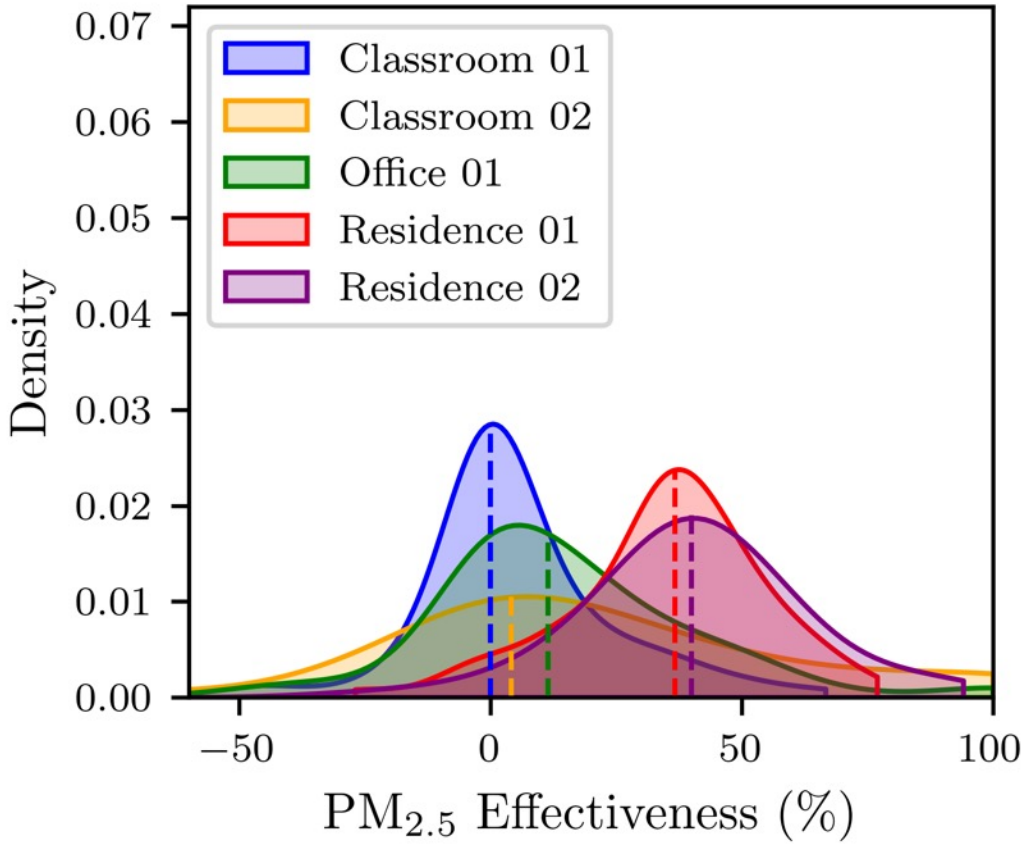


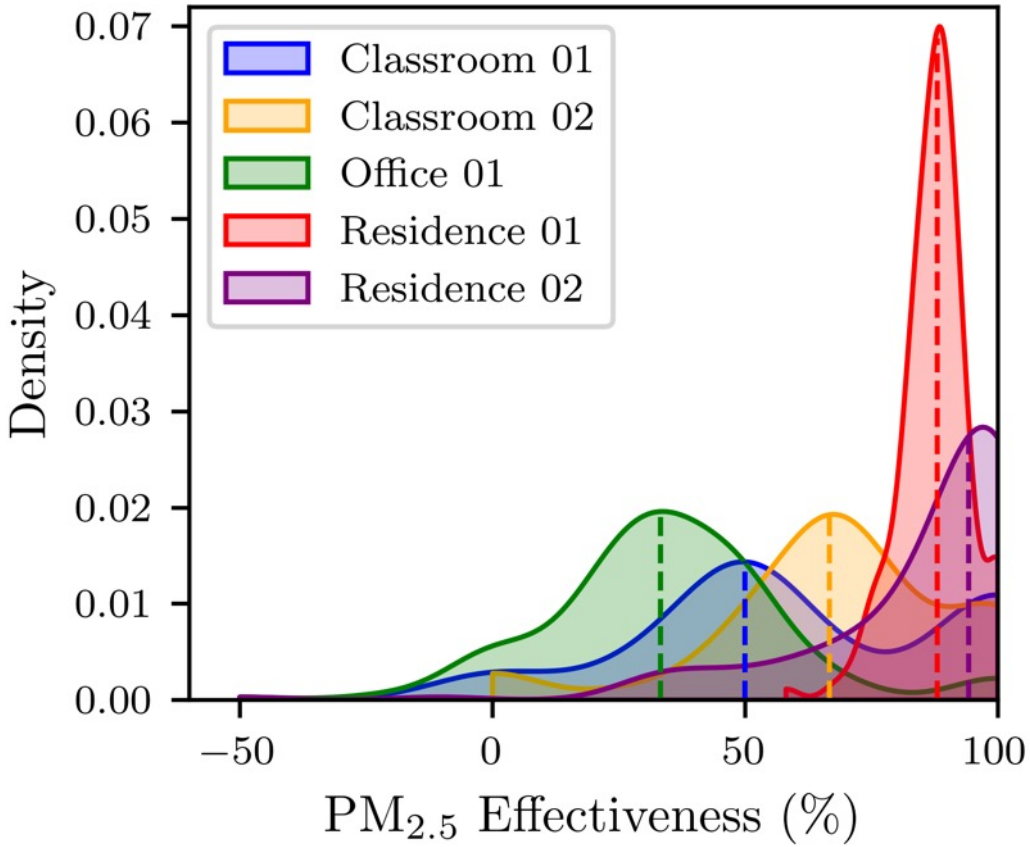
Performance gap

Du and Siegel (2023) *ES&T*

Verifying Performance #2

Air Cleaner	Placebo	Air Cleaner	Placebo



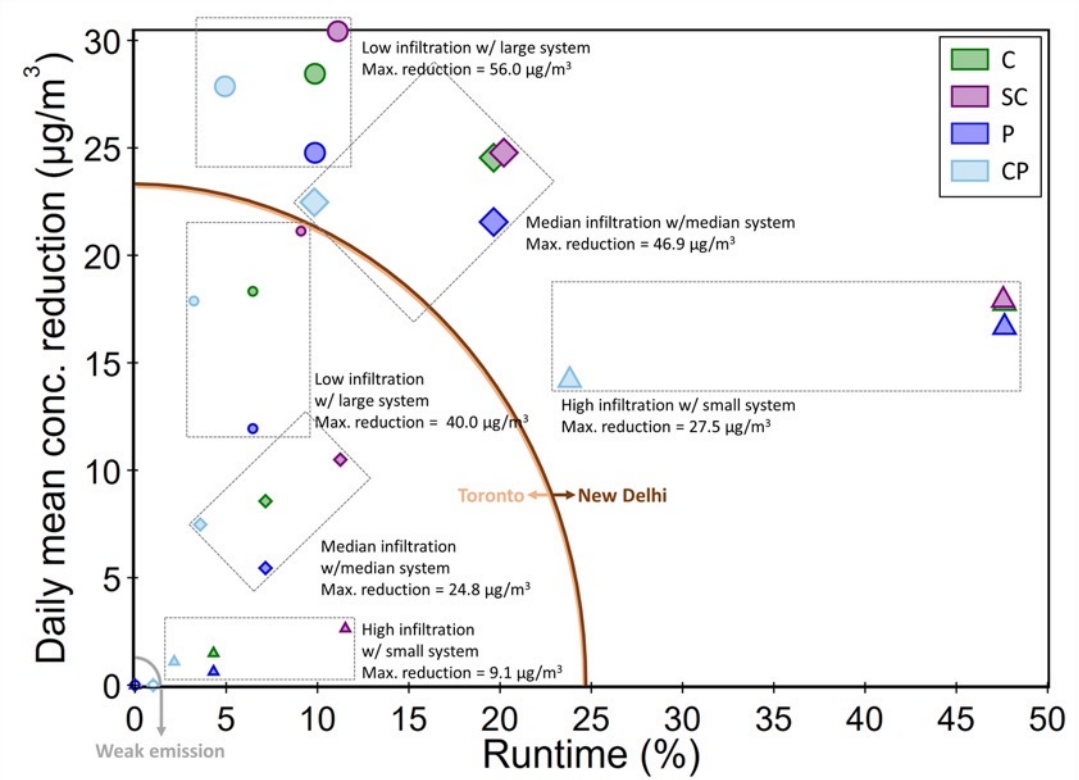


Nahian & Siegel *in review*

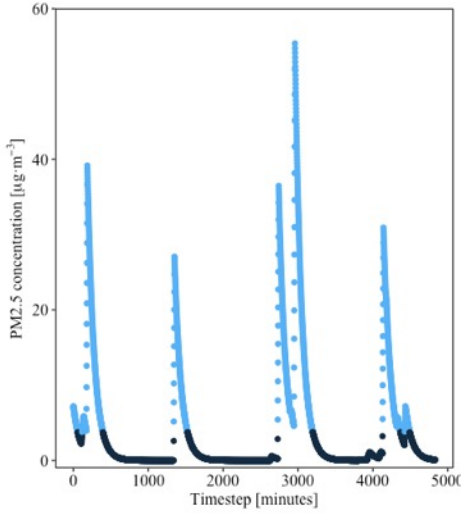
Opportunity #2: A New Acronym *HVACAC*

- We have systematically underinvested in HVAC systems
- We have both a pandemic and a climate crisis

Opportunity #3: Use Filters Better



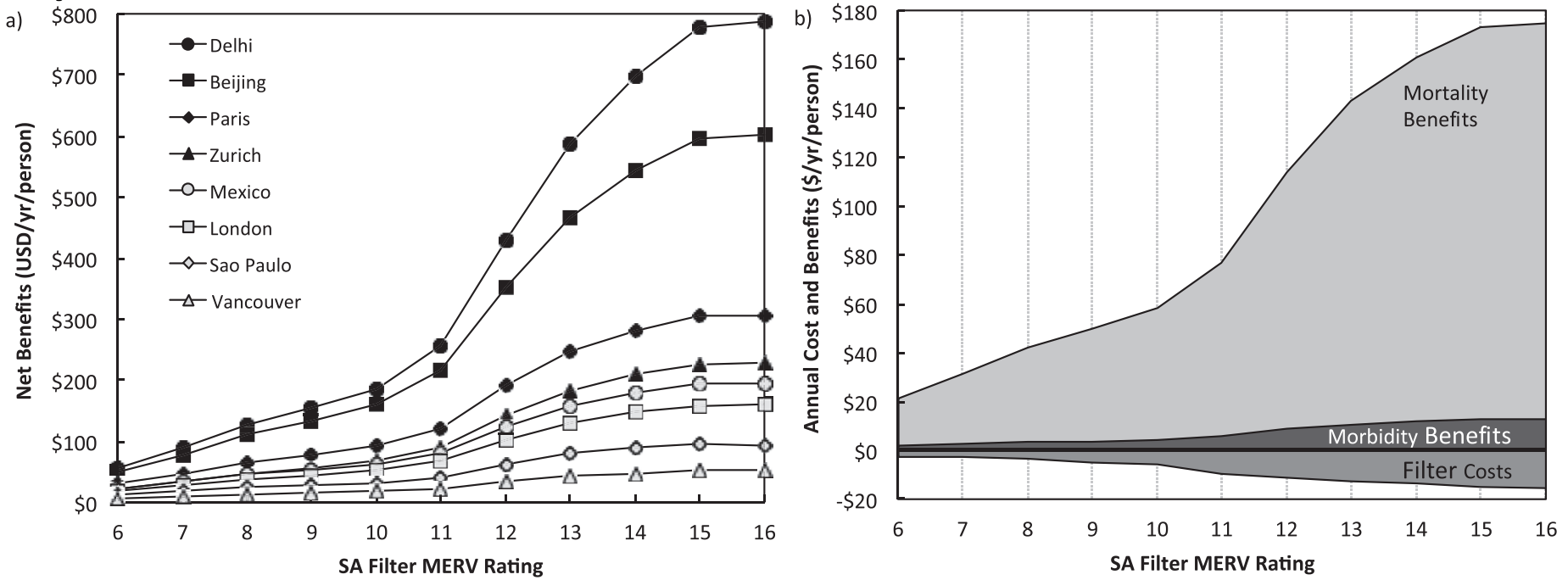
Li & Siegel (2020) *Bldg Environ*



Mendell et al. (2022) *Indoor Air*

Threshold [μg·m^{-3}]	Runtime [%]	Normalized Exposure Reduction [%]
Constant	100	100
4.0	13.6 ± 11.4	70 ± 23
8.8	8.3 ± 9.7	58 ± 29
27	4.2 ± 6.4	43 ± 30
Adaptive	*7.0 ± 6.2*	*57 ± 25*

Opportunity #4: Value the Benefits



Montgomery et al (2015) *Bldg Environ*

Vakalis et al. (2021) *Crit Rev Envrion Sci Tech*

Value New Benefits

Invest in filtration to improve cognitive function. Use benefits to pay for improvements. Chronic health outcome improvement are a "side" benefit.

- CO_2 may not be causative agent for cognitive impacts (Du et al., 2020, *Indoor Air)*
- Essential oil diffuser emissions associated with more impulsive decision-making (Du et al., 2022, *Indoor Air)*
- Air cleaners slightly appear to mitigate negative high-level cognitive impacts *In prep*
- MRI/imaging may offer a mechanistic model
  - Wide variety of information from ambient air investigations, unclear whether it translates to indoor air

Value Benefits Completely

Dec 16, 2021 by Anthony Fong

Inuit communities bracing for return of RSV in babies

https://healthydebate.ca/2021/12/topic/inuit-communities-rsv-outbreak/

- Economic costs: Medical transport, medical treatment & pharmaceutical treatment, housing families, diminished income for parents
- Social costs: Disrupted schooling and communities

Summary

- Benefits of filtration are understated/unstated
- Costs of filtration are overstated
- Filtration information and knowledge translation is imperfect, but can be overcome

- Substantial opportunity to realize benefits of filtration

Acknowledgements

- Postdocs and Students: Masih Alavy, Bowen Du, Elliott Gall, Raheleh Givehchi, Daniel Haaland, Zoe Hoskins, Alireza Mahdavi, Alex Mendell, Tianyuan (Amy) Li, Rafsan Nahian, Federico Noris, Brent Stephens, Marwa Zaatari, Yuchao Wan, Yizhi (Annabel) Zhang
- Collaborators: Arthur Chan, Richard Corsi, Miriam Diamond, Sarah Haines, Kerry Kinney, Seungjae Lee, Bill Nazaroff, Atila Novoselac, Jim Rosenthal, Marianne Touchie, ASHRAE TC 2.4 & RP1649 PMS, NASEM Fine PM/Mitigation Committee
- Funding

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