

Real-world challenges and opportunities for improving indoor air quality (IAQ)

Brent Stephens, PhD

Professor and Department Chair

Arthur W. Hill Endowed Chair in Sustainability

Department of Civil, Architectural, and Environmental Engineering

Illinois Institute of Technology, Chicago, IL USA

ILLINOIS TECH

**Civil, Architectural, and
Environmental Engineering**

The Built Environment Research Group

advancing energy, environmental, and sustainability
research within the built environment
at Illinois Institute of Technology



web www.built-envi.com email brent@iit.edu



Brent Stephens



Mohammad Heidarinejad

www.built-envi.com

Main research areas – Energy and air quality in buildings

- Fate, transport, and control of indoor pollutants
- Building science measurements and methods
- Air cleaning and filtration (in-duct and standalone)
- Air quality exposure and health impact assessment
- Building energy efficiency measures
- Simulation/optimization for building energy conservation
- Microbiology of the built environment

Field measurements



Core Facilities



Large chamber



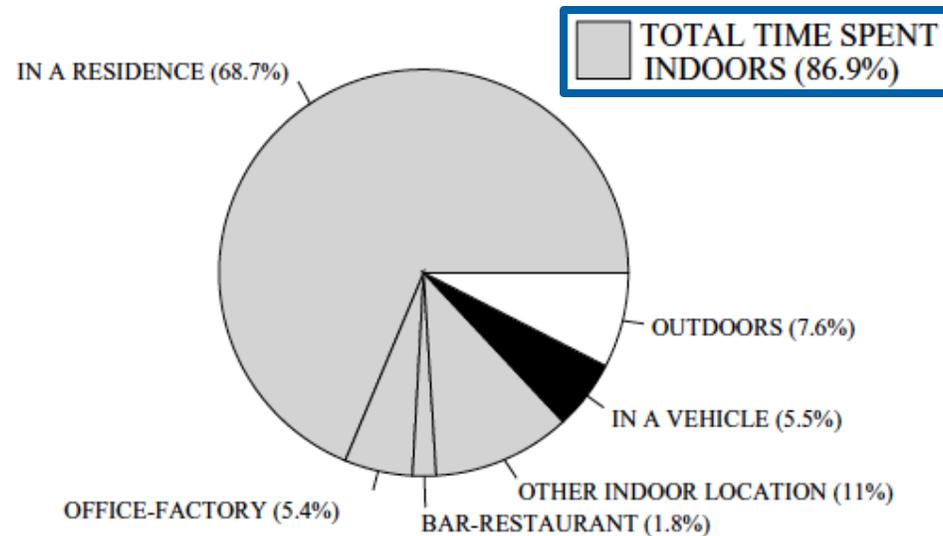
BERG Lab

Indoor air quality (IAQ) and health



NHAPS - Nation, Percentage Time Spent

Total n = 9,196

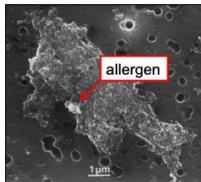


Klepeis et al. 2001 *J Exp Anal Environ Epidem*

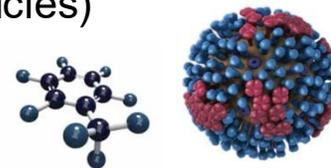
Americans spend almost 90% of their time indoors

– Almost 70% at home

There are many indoor & outdoor sources of indoor pollutants Logue et al. 2011 *Indoor Air*



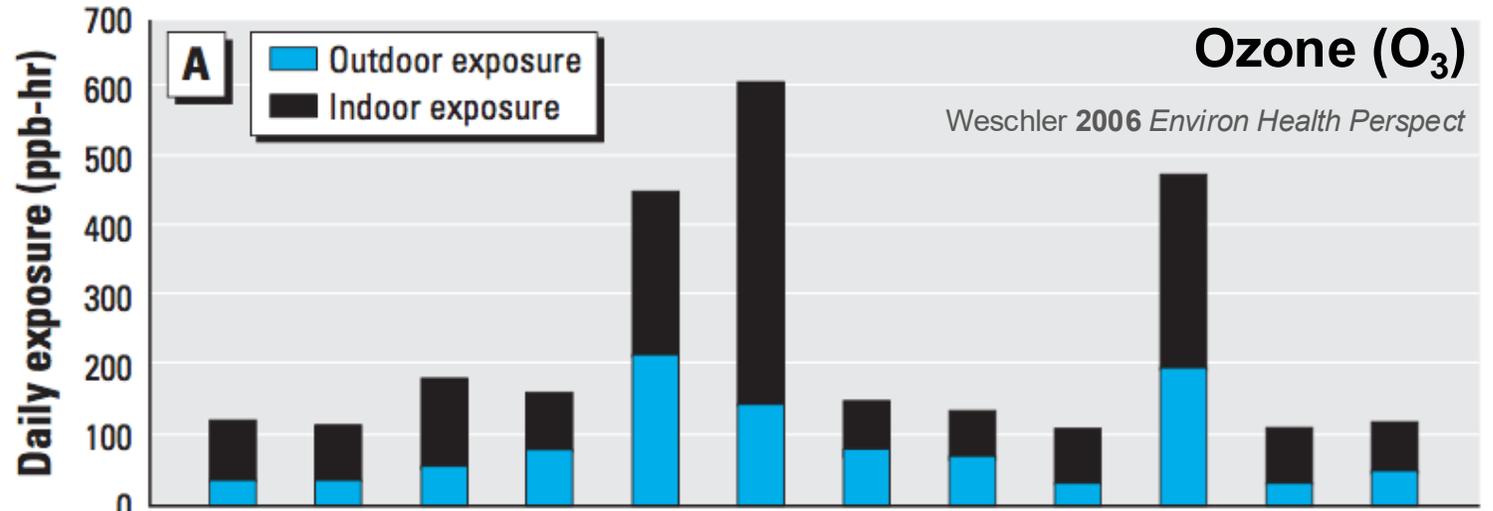
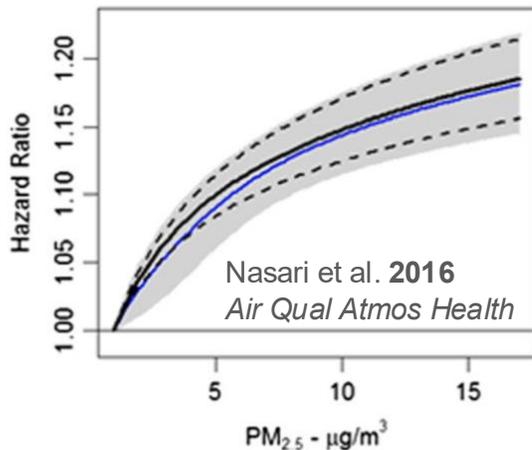
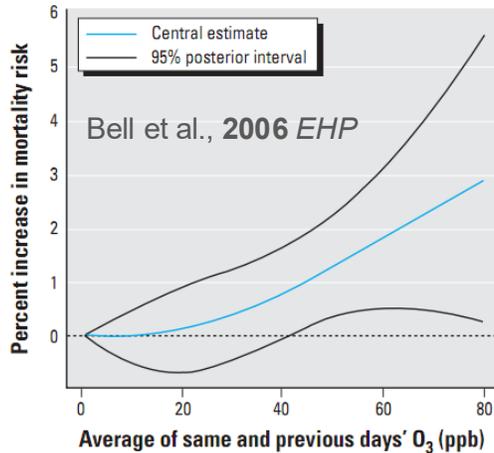
- Particulate matter (PM, including biological particles)
- Organic gases (e.g., VOCs, aldehydes)
- Inorganic gases (e.g., NO_x, CO, O₃)



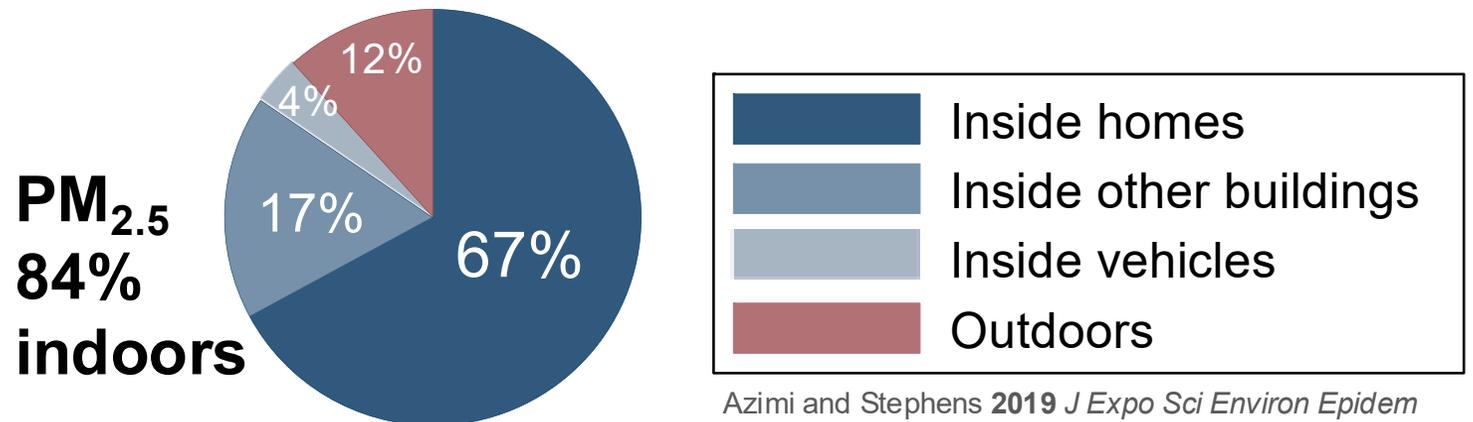
CDC; Ion Science
Ormstad, 2000 *Toxicol*
Casuccio et al., 2004 *Fuel Proc Tech*

Indoor air quality (IAQ) and **health**

Outdoor air pollution is associated with adverse health effects...



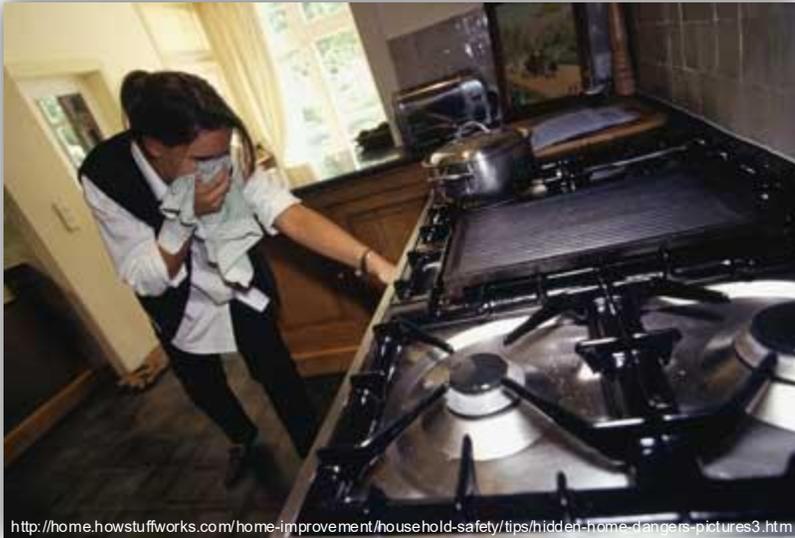
... but the majority of human exposure to many outdoor air pollutants occurs *inside buildings*



Indoor air quality (IAQ) and **health**

Cooking: major source of PM, NO_x, CO, ultrafine particles (UFPs), VOCs

- Gas emits more NO_x and UFPs
- Vented range hoods can help a lot



<http://home.howstuffworks.com/home-improvement/household-safety/tips/hidden-home-dangers-pictures3.htm>

Association between gas cooking and respiratory disease in children

Melia et al. 1977 *British Medical Journal*

Indoor Air Pollution and Asthma

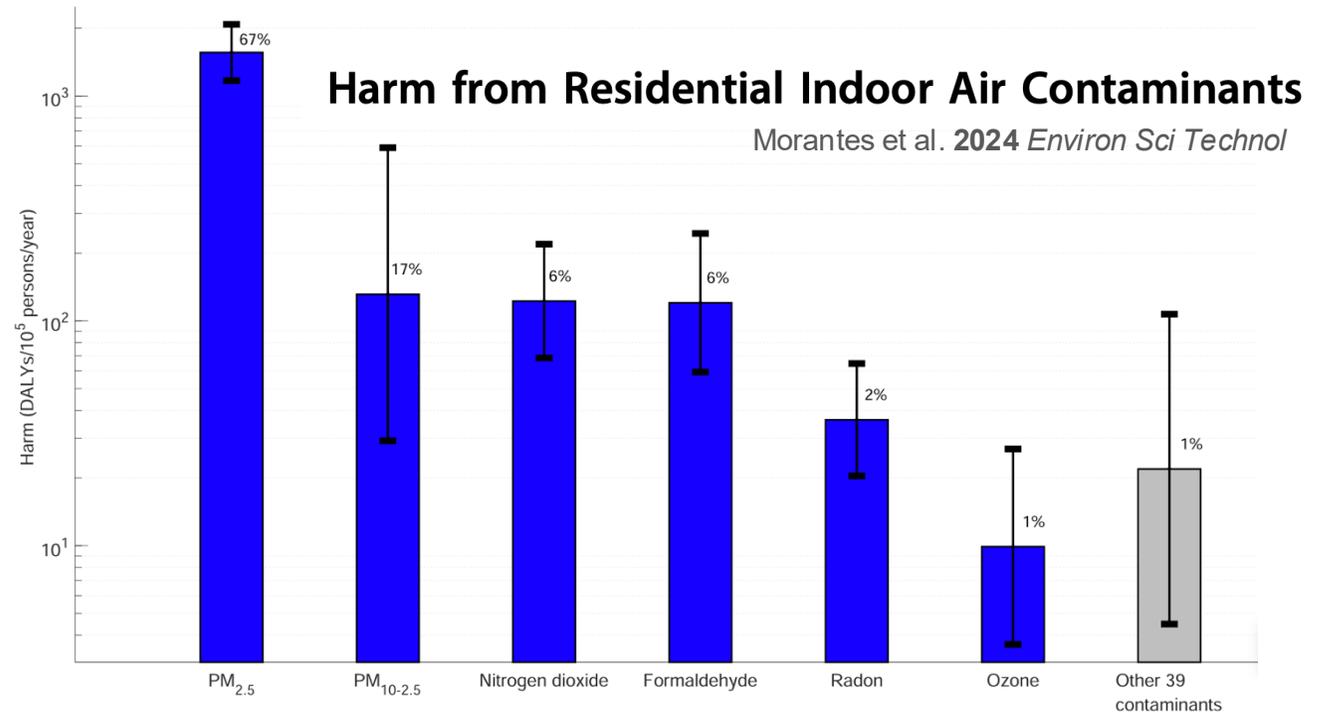
Ostro et al. 1994 *Am J Respir Crit Care Med*

Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves

Garrett et al. 1998 *Am J Respir Crit Care Med*

Meta-analysis of the effects of indoor nitrogen dioxide and gas cooking on asthma and wheeze in children

Lin et al. 2013 *Int J Epidemiol*



Gas stove pollution causes 12.7% of childhood asthma, study finds

The Washington Post
Democracy Dies in Darkness

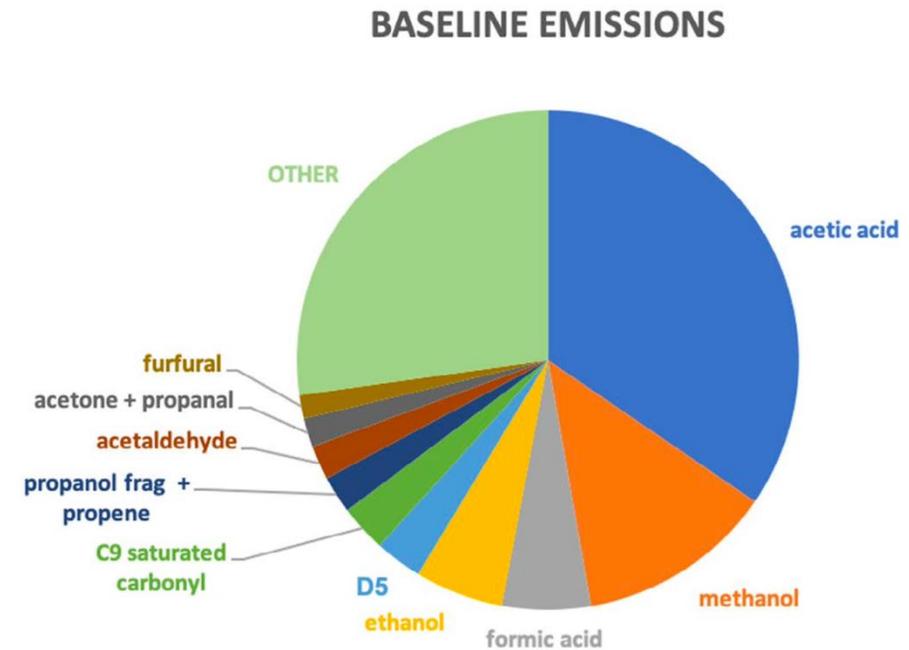
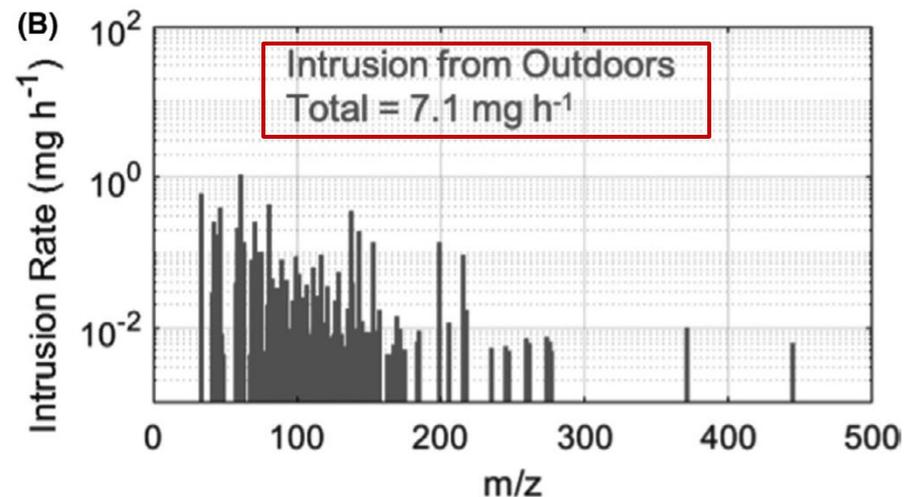
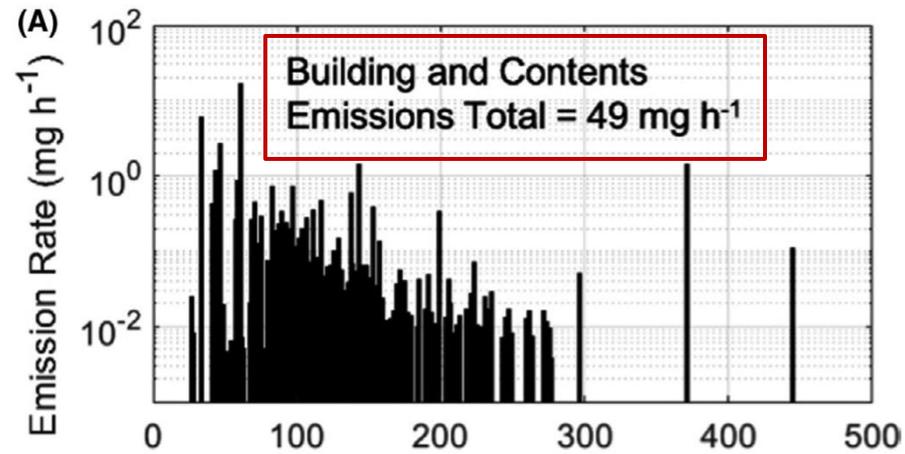
<https://www.washingtonpost.com/politics/2023/01/06/gas-stove-pollution-causes-127-childhood-asthma-study-finds/>

Indoor air quality (IAQ) and health

VOCs

Volatile organic compound emissions during HOMEChem

Arata et al. 2021 *Indoor Air*



Major VOC sources:

- Building materials
- Occupants and personal products
- Activities (cleaning, cooking, etc.)
- Indoor chemistry

Indoor air quality (IAQ) and health

VOCs



Association of domestic exposure to volatile organic compounds with asthma in young children

Rumchev et al. 2004 *Thorax*

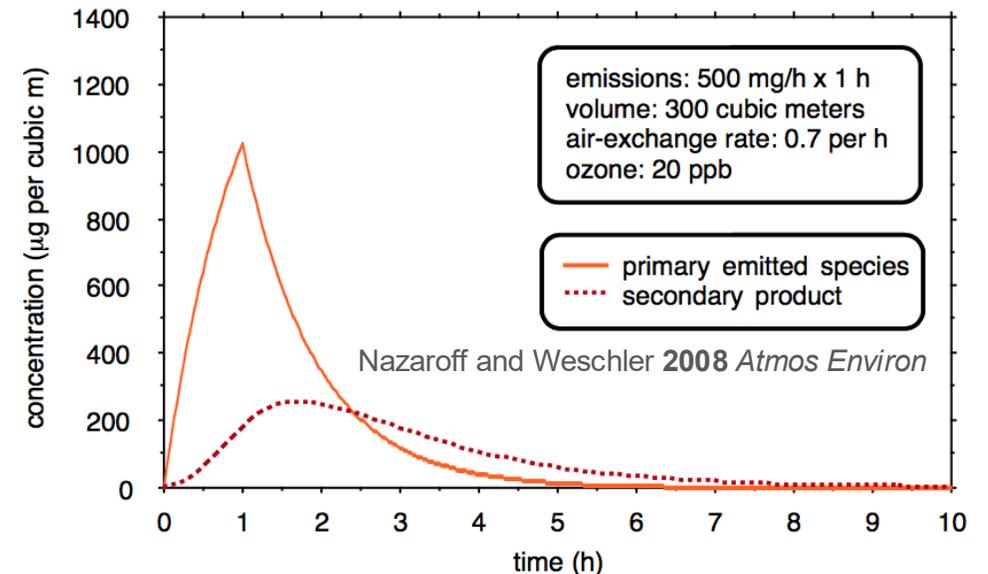
Cancer Risk Disparities between Hispanic and Non-Hispanic White Populations: The Role of Exposure to Indoor Air Pollution

Hun et al. 2009 *Environ Health Perspect*

Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments

Allen et al. 2016 *Environ Health Perspect*

Primary & secondary VOCs + ultrafine particles



Frequent use of chemical household products is associated with persistent wheezing in pre-school age children

Sherriff et al. 2005 *Thorax*

The Use of Household Cleaning Sprays and Adult Asthma

Zock et al. 2007 *Am J Respir Crit Care Med*

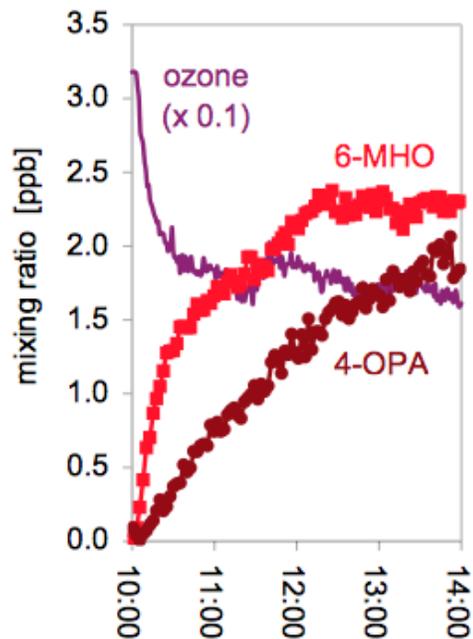
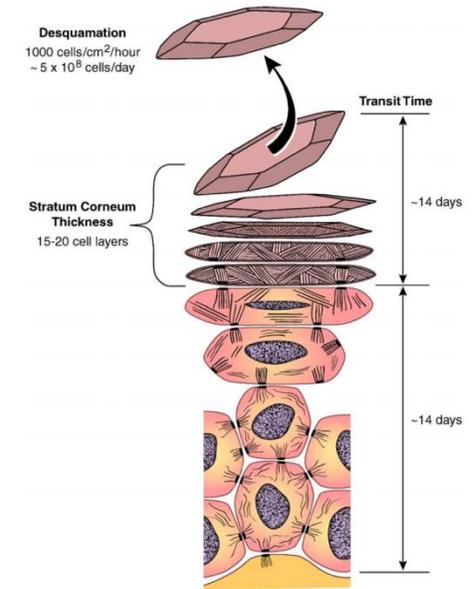
Indoor air quality (IAQ) and health



Epidermal desquamation

Milstone 2004 *J Dermatol Sci*

We shed our entire outer layer of skin every 2-4 weeks



Ozone + skin oils → VOCs + ultrafine particles (UFPs)

**Reactions of ozone with human skin lipids:
Sources of carbonyls, dicarbonyls,
and hydroxycarbonyls in indoor air**

Wisthaler and Weschler 2010 *Proc Nat Acad Sci*

**Ozone Reaction Products Associated with
Biomarkers of Cardiorespiratory Pathophysiology**

He et al. 2023 *Am J Resp Crit Care Med*

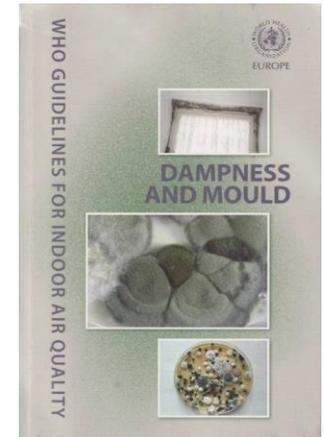
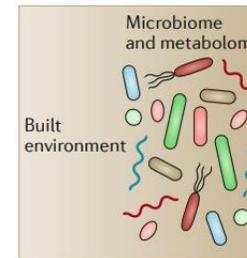
Indoor air quality (IAQ) and **health**

Dampness and mold

- **Causal** connection with exacerbation of asthma in children and “**dampness**” in buildings
 - “Do you see or smell mold or water damage?”

- **No causality, but sufficient epidemiological evidence of increased:**

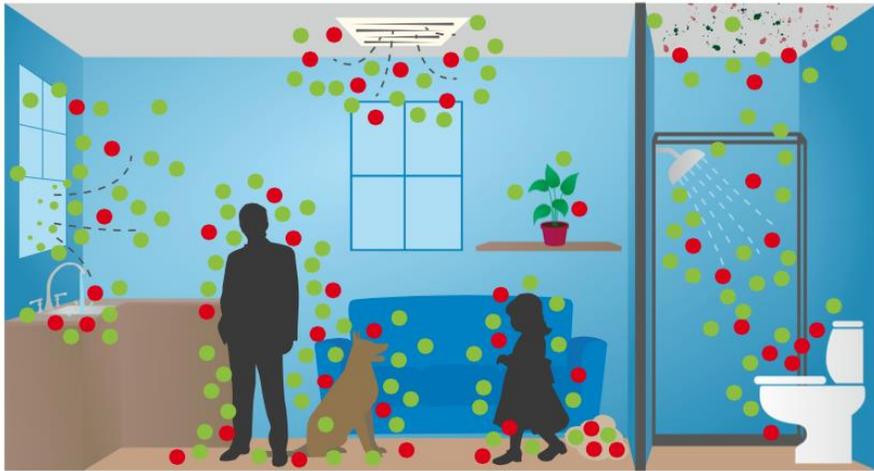
- Upper respiratory tract symptoms (coughing, wheezing, etc.)
- Respiratory infections
- Development of asthma
- Bronchitis
- Allergic rhinitis



- Interestingly, **no associations** between **quantifiable microbial measures** and respiratory health effects (some suggestive associations)
 - Moisture damage → Toxin release (e.g., microbial VOCs) from fungi (mold)?

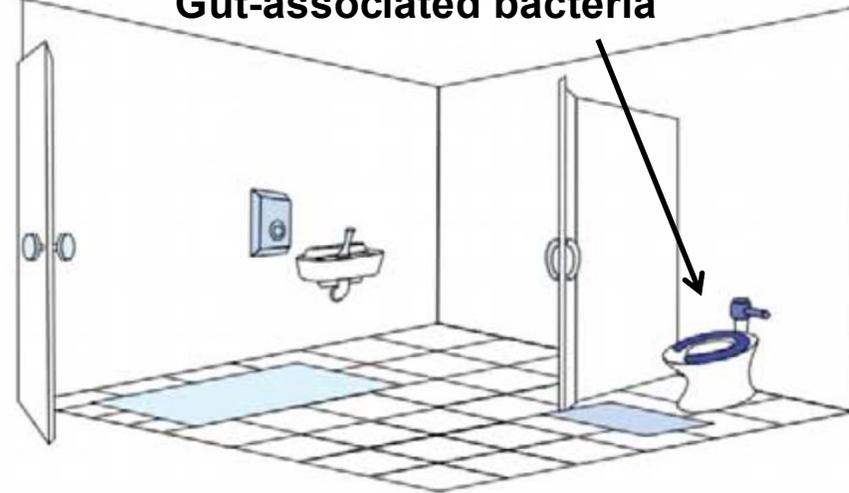
Indoor air quality (IAQ) and **health**

Indoor microbiome



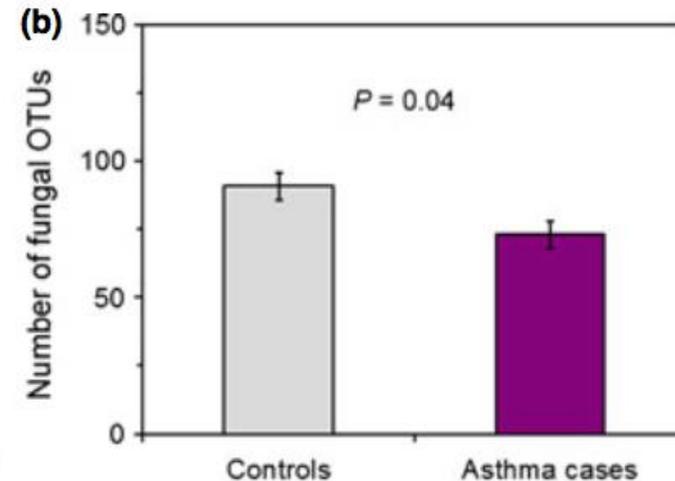
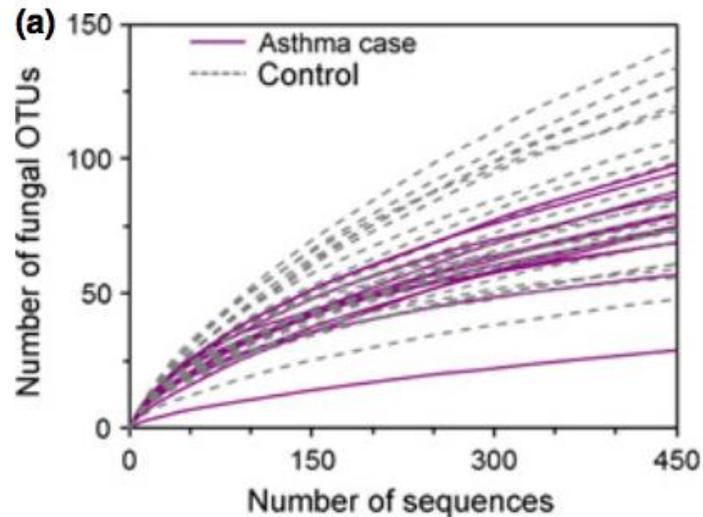
Prussin and Marr 2015 *Microbiome*

Gut-associated bacteria



Flores et al. 2011 *PLoS ONE*

Exposure to microbial diversity (i.e., the **'right' microbes** and the **'right' time**) may be **beneficial** for health?



Dannemiller et al. 2014 *Indoor Air*

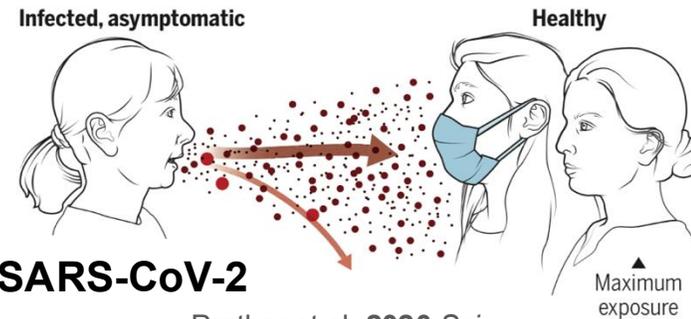
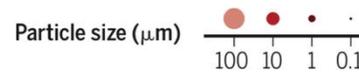
Indoor air quality (IAQ) and **health**



Infectious disease transmission

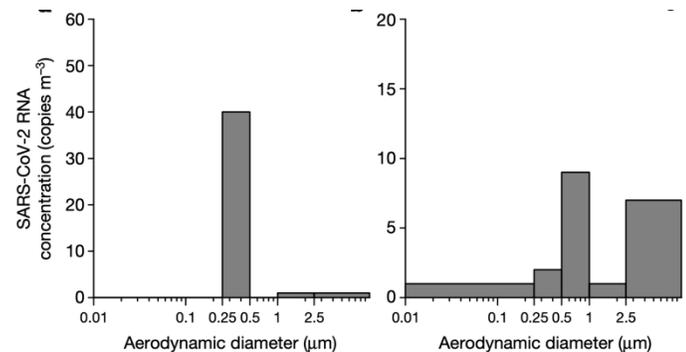
Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

Yu et al. 2004 *New Engl J Med*



SARS-CoV-2

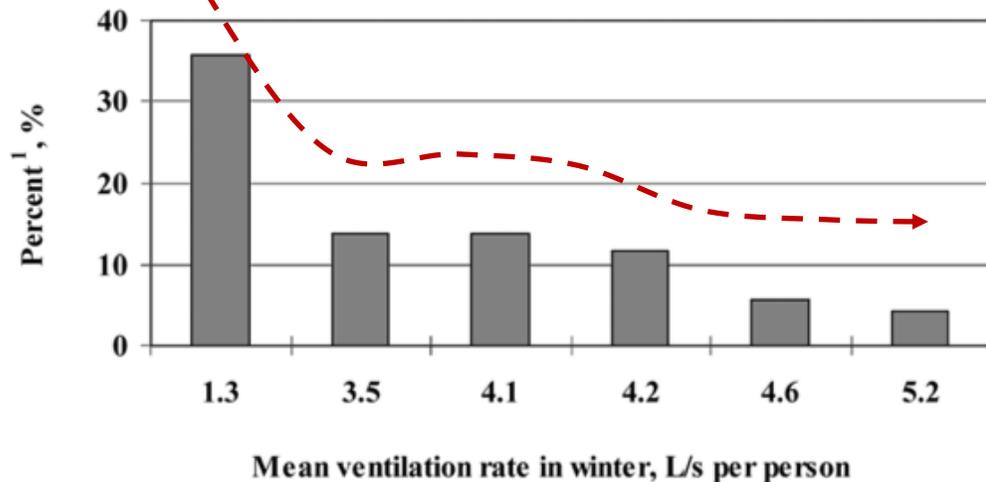
Prather et al. 2020 *Science*



Liu et al., 2020 *Nature* 582:557-560

In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

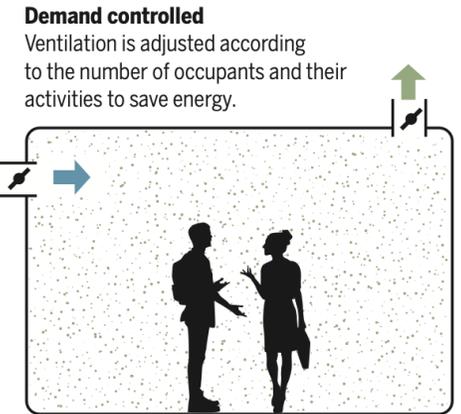
Sun et al. 2011 *PLoS ONE*



A paradigm shift to combat indoor respiratory infection

Building ventilation systems must get much better

Morawska et al., 2021 *Science* 372:689-691



Demand controlled
Ventilation is adjusted according to the number of occupants and their activities to save energy.

Indoor air quality (IAQ) and **health**

Health benefits of particle filtration

Fisk 2013 *Indoor Air*



Photo from M.S. Waring and J.A. Siegel

Air cleaners typically reduce indoor PM concentrations by ~50%

- Usually $PM_{2.5}$
- Sometimes PM_{10} or total number counts (TNC) (e.g. $<1 \mu m$)

Documented health improvements with (*mostly portable*) air cleaners include:

- Modest improvements in lung function in asthmatics
- Fewer asthma-related doctor visits
- Modest improvements in markers of cardiovascular/pulmonary function
- Few studies on *in-duct air cleaning*

EPA Guidance on air cleaners in the home:

<https://www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home>

Indoor air quality (IAQ) and **health**

- **Residential indoor air pollution** is estimated to result in **5-14%** of the annual non-communicable, non-psychiatric **disease burden** in the U.S.
 - Excludes SHS and radon
 - Descending order: PM_{2.5}, formaldehyde, acrolein, ozone, NO₂

Logue et al., *Environ. Health Perspect.* **2012**, 120, 216-222

- Cumulative lifetime **cancer risks** of **1-10** excess cases **per 10,000** people

Wallace et al., *Environ. Health Perspect.* **1991**, 95, 7-13

Sax et al., *Environ. Health Perspect.* **2006**, 114, 1558-1566

Hun et al., *Environ. Health Perspect.* **2009**, 117, 1925-1931

- Indoor air is a **dominant** environmental exposure

The costs of poor IAQ are probably high

- Health and productivity gains from better indoor environments in the U.S.
 - Fisk (2000) *Annual Reviews of Energy and Environment*
 - \$6-14 billion from reduced respiratory disease
 - \$1-4 billion from reduced allergies and asthma
 - \$10-30 billion from reduced sick building syndrome
 - \$20-160 billion from direct improvements in worker performance
- \$37-208 billion annual savings possible
 - Fisk (2002) *ASHRAE Journal*
- Improved ventilation in a manufacturing facility led to reduced sick days
 - Milton et al. (2000) *Indoor Air*
- Increased ventilation led to slight increase (5%) in productivity
 - Wargocki et al. (2000) *Indoor Air*

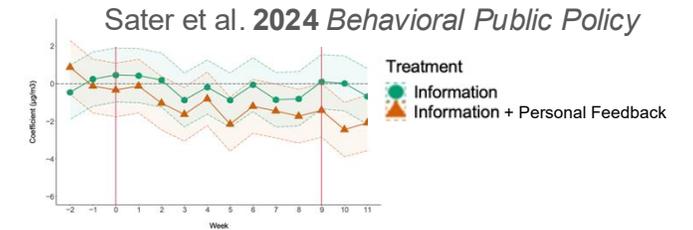
“Four principles for achieving good indoor air quality”

1. Minimize indoor emissions

Product standards, behavioral interventions



**GREENGUARD
CERTIFICATION**
FROM UL ENVIRONMENT



2. Keep buildings dry

~50% of homes and offices have visible dampness or mold
~30% of schools had plumbing or roof water problems

<https://iaqscience.lbl.gov/dampness-and-mold>



3. Ventilate well

<https://iaqscience.lbl.gov/building-ventilation-topics>



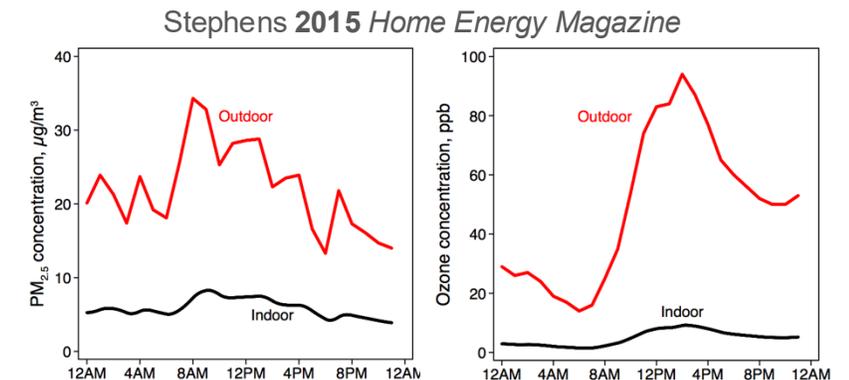
Photo: Insung Kang



Photo: Brett Singer

4. Protect against outdoor pollution

Factors: Building envelopes, window opening, mechanical ventilation



5. I also suggest a 5th principle:

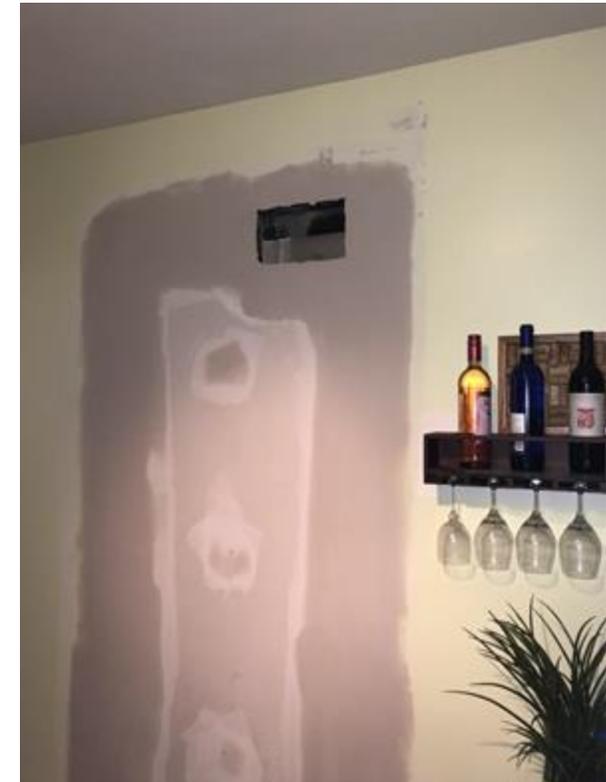
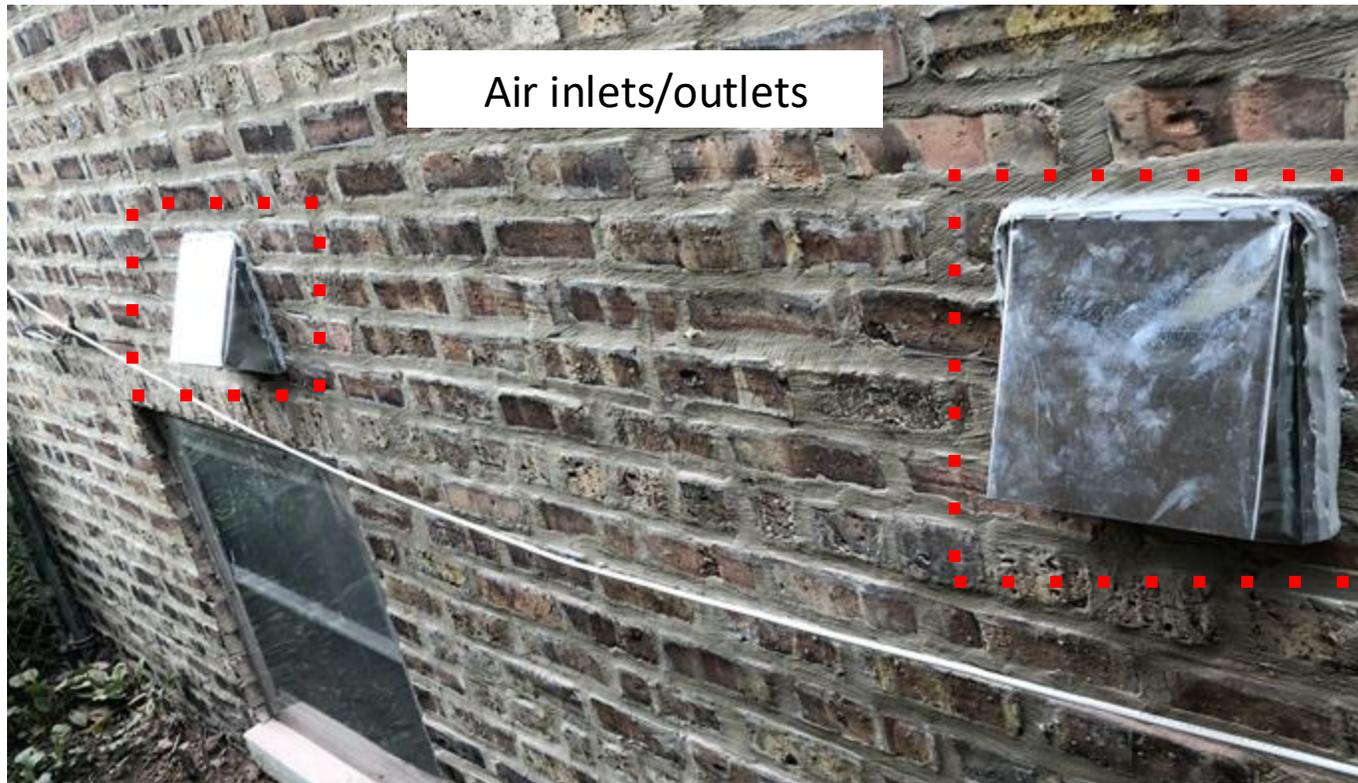
Utilize efficient air cleaning



Photo from M.S. Waring and J.A. Siegel

Practical challenges to improving IAQ

- Building stock is old, and turns over slowly
 - Investments in physical infrastructure challenging, expensive, or impossible



Practical challenges to improving IAQ

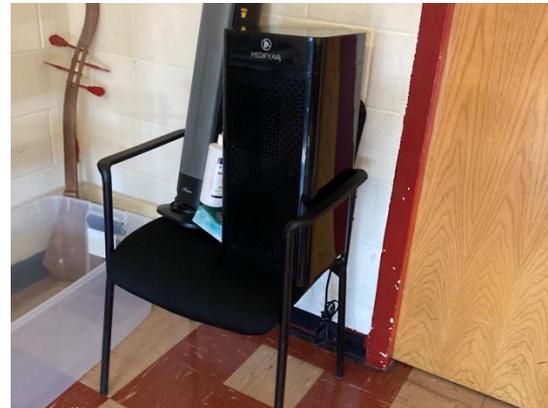
- Occupants don't always use the systems/devices they have



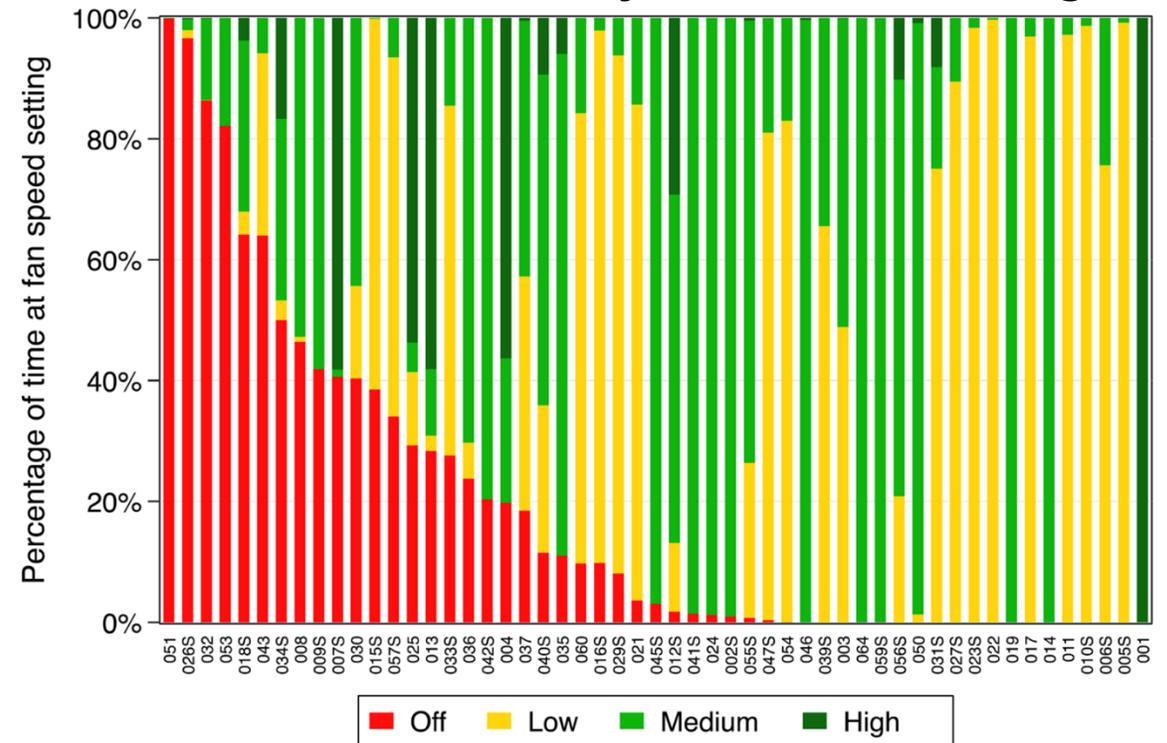
Peffer et al. 2011 *Building and Environment*

“The majority of occupants operated thermostats manually, rather than relying on their programmable features”

Meier et al. 2011 *Building and Environment*



Runtime of portable HEPA air cleaners in homes of US military Veterans in Chicago



Farhoodi et al. 2025 *Environ Sci: Processes & Impacts*

Practical challenges to improving IAQ

- Increasing ability to monitor IAQ, but a comprehensive assessment of IAQ (and health) is not trivial (and expensive)



PurplAir PA-II



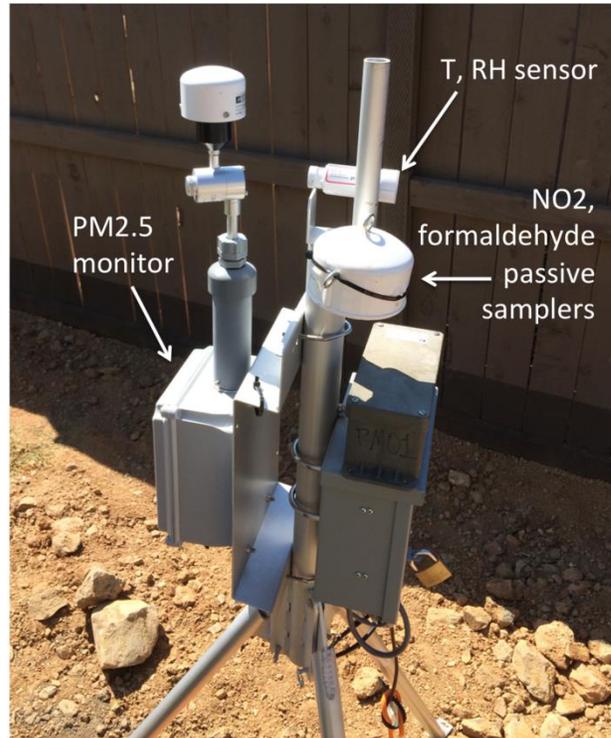
AtmoCube



Plantower PMS5003



Sensirion SPS30



Chan et al. 2020 CEC-500-2020-023



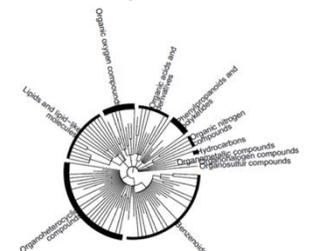
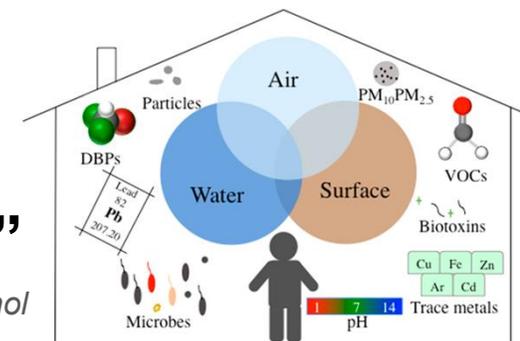
Farmer et al. 2025 Environ Sci: Processes & Impacts



<https://www.aqmd.gov/aq-spec>

Indoor "Exposome"

Dai et al., 2017 Environ Sci Technol



Stanfield et al. 2025 Environ Sci Technol 18

Practical challenges to improving IAQ

- Fragmented adoption of standards



Recommended listening:

50. IAQ Paradigms—The Next Generation
ASHRAE Journal Podcast

<https://www.ashrae.org/news/ashraejournal/ashrae-journal-podcast-episode-50>

241: Equivalent clean airflow (ECA) rates



ANSI/ASHRAE Standard 62.1-2022
(Supersedes ANSI/ASHRAE Standard 62.1-2019)
Includes ANSI/ASHRAE addenda listed in Appendix Q

Ventilation and Acceptable Indoor Air Quality

See Appendix Q for approval dates by ASHRAE and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 180 Technology Parkway, Peachtree Corners, GA 30092. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

© 2022 ASHRAE ISSN 1041-2336

PDF includes hyperlinks for convenient navigation. Click on a reference to a section, table, figure, or equation to jump to its location. Return to the previous page via the bookmark menu.



ASHRAE 62.1



ANSI/ASHRAE Standard 62.2-2022
(Supersedes ANSI/ASHRAE Standard 62.2-2019)
Includes ANSI/ASHRAE addenda listed in Appendix E

Ventilation and Acceptable Indoor Air Quality in Residential Buildings

See Appendix E for approval dates by ASHRAE and by the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 180 Technology Parkway, Peachtree Corners, GA 30092. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

© 2022 ASHRAE ISSN 1041-2336

PDF includes hyperlinks for convenient navigation. Click on a reference to a section, table, figure, or equation to jump to its location. Return to the previous page via the bookmark menu.



ASHRAE 62.2



ASHRAE Standard 241-2023

Control of Infectious Aerosols

Approved by the ASHRAE Standards Committee on June 24, 2023.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

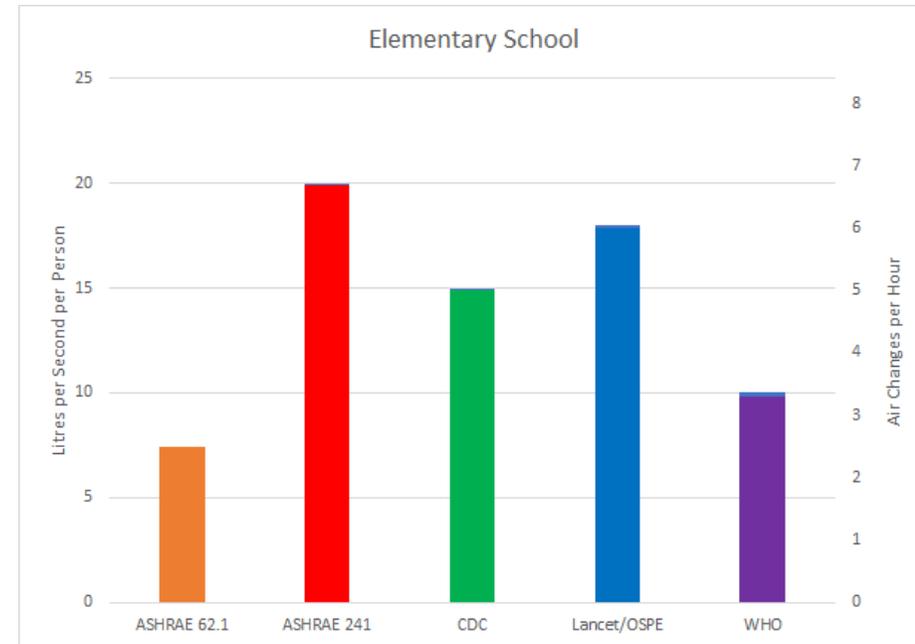
The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 180 Technology Parkway, Peachtree Corners, GA 30092. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

© 2023 ASHRAE ISSN 1041-2336

This standard includes links to online supporting files.



ASHRAE 241



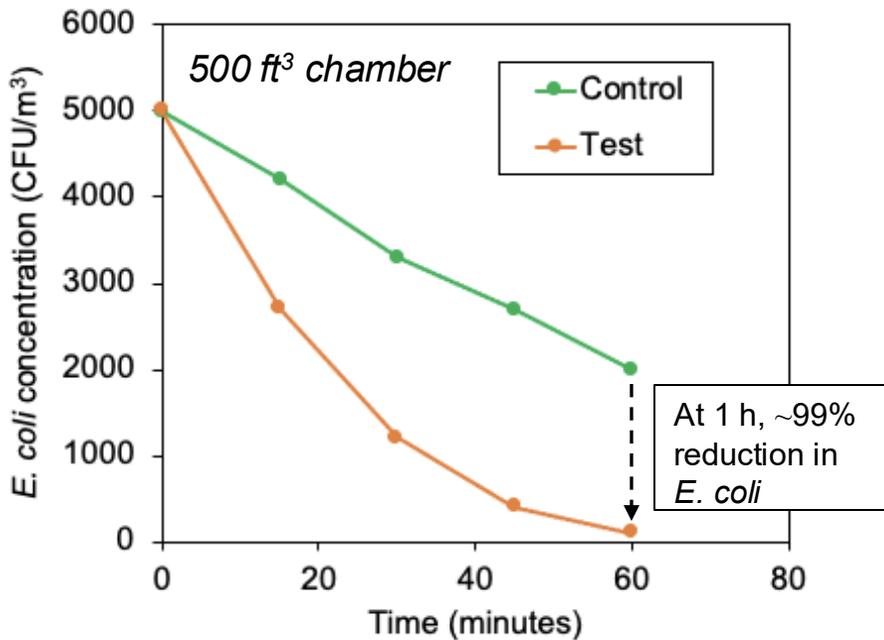
<https://itsairborne.com/ashrae-241-control-of-infectious-aerosols-part-2-equivalent-clean-airflow-rates-76a511769d4d>

Practical challenges to improving IAQ

- Standards lag the marketplace (e.g., indoor air cleaning)

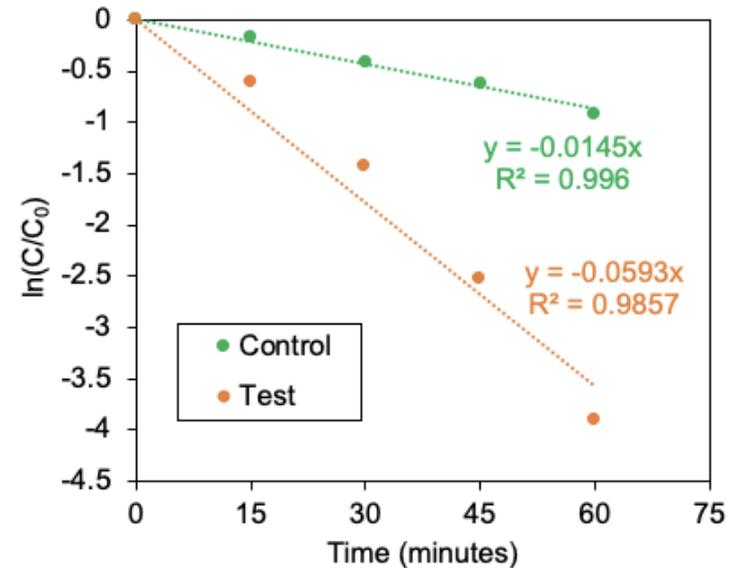
“Air Cleaner Technology A reduces viable pathogens by **99% in 60 minutes** in a test chamber”

Hypothetical microbial inactivation test results



Stephens et al. April 2022 ASHRAE Journal

Fit data to a 1st-order decay model



Determine CADR from loss rates

$$CADR = V_{test}(L_{ac\ on} - L_{ac\ off})$$

$$CADR = 500\ ft^3 \times \left(0.0593 - 0.0145 \frac{1}{min} \right)$$

$$CADR = 22.4 \frac{ft^3}{min} \approx \mathbf{22\ CFM}$$

Also potential for byproduct formation from additive air cleaners:

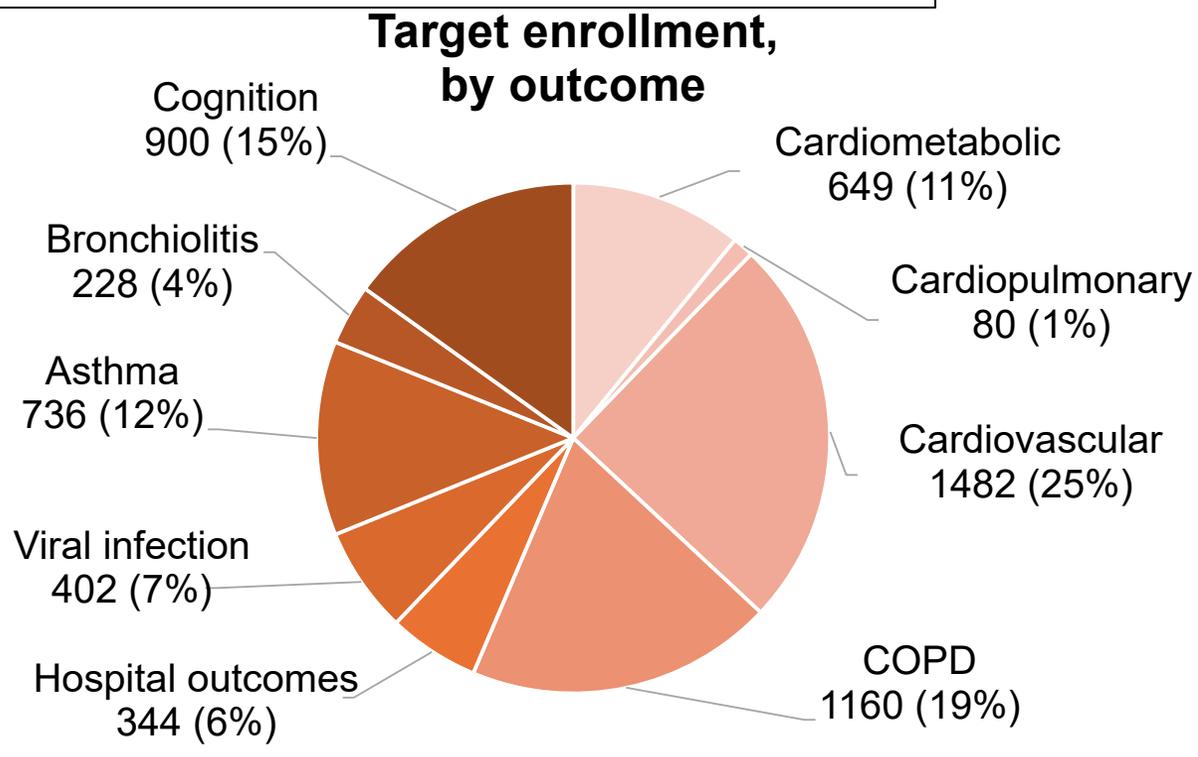
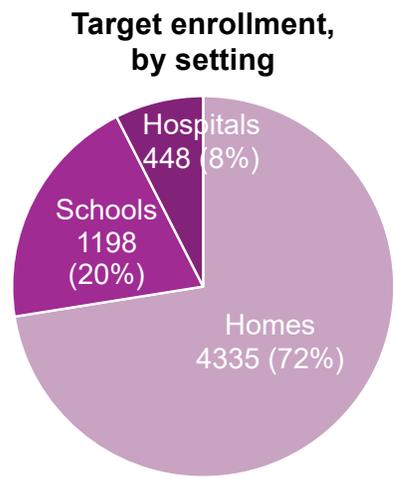
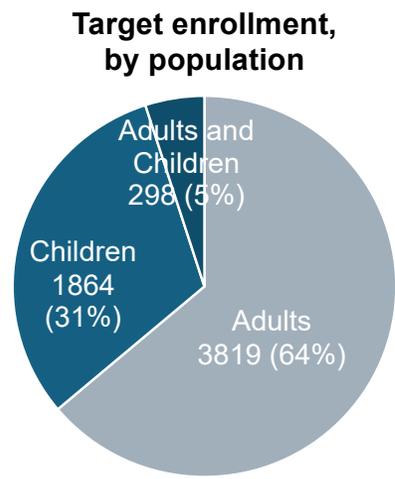
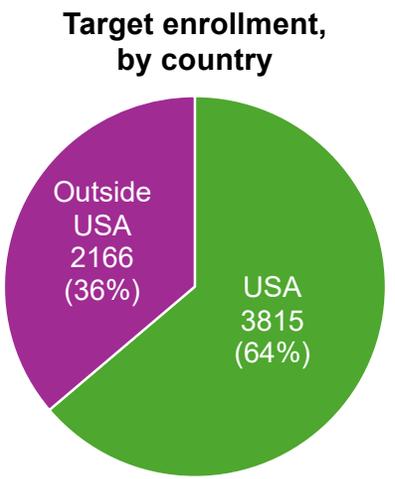
- ASTM WK81750

Zeng et al. 2022 Pollutants

Practical challenges to improving IAQ

- Increasing desire for evidence-based medicine/interventions
 - Robust investigations require interdisciplinary teams + funding

~30 registered air cleaning intervention trials are currently active*



- ~2/3 in US, ~1/3 outside US
- Planned enrollment target: **~6000 participants**



Farhoodi et al. 2025 *Environ Sci: Processes & Impacts*

* Search terms: “air clean*”, “air purif*”, “HEPA filt*”; excludes 1 planned study of box fan filters and UVGI in classrooms in Bangladesh targeting 20,000 participants

Practical challenges to improving IAQ

- The IAQ research and practitioner community is relatively small



Indoor Air Quality

<https://www.aiha.org/public-resources/air-quality>



INTERNATIONAL SOCIETY OF
INDOOR AIR QUALITY
AND CLIMATE

<https://www.isiaq.org/>



Shaping Tomorrow's Global
Built Environment Today

<https://www.ashrae.org>



IAQA | INDOOR AIR QUALITY
ASSOCIATION

<https://www.iaqa.org/>



Healthy Housing
Principles Certificate

<https://www.bpi.org/certificates/healthy-housing-principles/>

Locally:

IndoorScience

<https://indoorscience.com/>



Ian Cull, PE, CIH
Chief Science Officer

An internationally-recognized expert in indoor environmental quality. A sought-after speaker, consultant, and author with over 25 years of industry experience

icull@indoorscience.com

Acknowledgements

- **Research funding**

- US Department of Housing and Urban Development and US EPA (homes)
- University of Illinois SHIELD (schools)
- JustGiving: <https://justgiving.com/campaign/BuiltEnvironmentResearch>

- **Collaborators and students**

- IIT: Mohammad Heidarinejad, Mingyu Wang, Saeed Farhoodi, Saman Haratian, Saba Abhari, Aditya Singh, Yicheng Zeng
- Elevate: Rachel Scheu, Anna McCreery, Amanda Gramigna, Marina Beke
- Jesse Brown VA: Israel Rubinstein, Zane Elfessi, Nancy Karpen, Kaveeta Jagota
- UIC: Mehdi Torkmahalleh, Cameron Zielke, Yuan Shao, Margaret Sietsema
- IDPH: Anna Pineseault, Charles Williams, Natsumi Nemoto
- UT-Arlington: Insung Kang

- **Donations**

- Filter/air cleaner donations and discounts: Austin Air, Winix, Medify, Tex-Air Filters, AAF, Rensa
- Monitoring instrument discounts: Onset, PurpleAir