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INDOOR AIR QUALITY: THE NEXT GREAT PUBLIC HEALTH CHALLENGE

White paper

By Juan Cambeiro and Brian Potter

Introduction

From the colonial period through the early twentieth century, America regularly experienced large urban fires that destroyed thousands of buildings. The 1866 Great Fire of Portland, Maine destroyed an estimated 1,800 buildings and left about 10,000 people homeless. The 1871 Great Chicago Fire destroyed more than 17,000 buildings, left about 100,000 people homeless, and killed about 300 people. At the time, these conflagrations were thought to be unfortunate but inevitable, caused by the existence of the city itself. Large numbers of buildings in close proximity created the conditions for large fires — in the words of Erik Larson, "the city was a tinderbox waiting to be set alight."

But thanks to the work of forward-thinking fire protection experts, policymakers, and others who emphasized fire prevention and control, building construction and infrastructure changed to dramatically reduce the risk of large, urban fires. Cities adopted building codes which restricted the use of flammable materials in tall buildings, and set safety standards for electrical systems. New buildings incorporated fire-safety features such as fire doors, fire escapes, automatic sprinklers, and fire alarms in their designs.

This increased focus on fire safety eliminated the large urban fires that were formerly common in the US. The last major urban fire in the US was the Great Baltimore Fire of 1904, and over the past 100 years, the risk of fire death in the US has fallen by roughly 90%. Today, virtually all buildings are required by code to use fire-resistant materials and design. Most buildings incorporate fire safety features such as smoke detectors, automatic fire sprinklers, fire alarms, fire extinguishers, and occupancy limits. As a result, while urban fires still occur, they are almost always contained to their room or floor of origin. By changing the way we build our buildings and infrastructure, a significant threat to public health and safety has been greatly reduced.

Today, we're experiencing another public health crisis largely caused by our built environment — more specifically, the air within that environment. Poorly ventilated spaces and low quality indoor air are largely behind the spread of indoor infections, and cause high concentrations of pollutants such as CO2 which have a variety of negative health effects.

In the same way that stricter building codes and other built environment changes ended large urban fires, targeted changes in indoor air requirements could prevent future pandemics, reduce seasonal infections, and improve public health.

The health implications of indoor air

Humans spend 90% of their time indoors, more than some whale species spend underwater. Because most of the air we breathe is indoors, the quality of indoor air significantly affects our health.

Indoor air quality is largely defined by the concentration of contaminants within it. The greater the concentration of contaminants, the lower the quality of the air. A variety of air contaminants can affect health.

Airborne viruses and infectious agents

COVID-19, caused by the SARS-CoV-2 virus, has highlighted the role that indoor air plays in the spread of infectious pathogens (disease-causing organisms). COVID-19 spreads primarily indoors, and most severe COVID-19 outbreaks occurred in situations where people were spending large amounts of time in poorly ventilated spaces.

More generally, pathogens that can be transmitted person-to-person tend to do so indoors. This is true for all types of pathogens, from those that cause pandemics, to more common ones such as seasonal influenza. We have moderate evidence that pathogenic bacteria and fungi are mostly transmitted indoors, and extensive evidence that respiratory viruses are. Bioaerosols — airborne particles that contain biological materials — rarely infect people outdoors, and our hunter-gatherer ancestors, who largely lived outdoors, were not afflicted by the vast majority of the transmissible pathogens we now deal with. 10,000 years ago, it would have been far more difficult for a coronavirus to transmit among humans than it is today.

Whenever we breathe, talk, cough, or sneeze, we emit small particles (called aerosols) into the environment. When we're sick, pathogens will hitch a ride on these particles, and can infect anyone that inhales them. Prior to COVID-19, it was thought that most pathogens spread via large-diameter aerosol "droplets" which fell out of the air quickly, but more recent studies convincingly show that smaller aerosols, which can stay aloft for many minutes or hours, are an important vector of infection — and inhalation of aerosols is likely the main method by which respiratory viruses are transmitted.

Outdoors, these aerosols can quickly become diluted, or inactivated by UV radiation in sunlight. Viruses, which seem poised to cause most future pandemics, are particularly ill-suited to surviving outdoors. Viruses require a host to replicate and cannot survive for long on their own. Indoors, however, infectious aerosols will accumulate in the air, increasing the likelihood of disease transmission.

Carbon dioxide

Indoor air quality is also impacted by the concentration of carbon dioxide (CO_2). CO_2 is a byproduct of human respiration, and its concentration increases in poorly ventilated spaces. High levels of CO_2 can lead to a range of negative health effects, including headaches, drowsiness, and impaired cognitive function. Recent research highlights the importance of addressing CO_2 levels in indoor environments. Harvard researchers found that cognitive function scores were 61% higher in indoor spaces with increased ventilation compared to a conventional building environment.

These results replicate in academic contexts — for instance, a 2022 study finds that a "one standard deviation increase in the school-term average daily peak of CO_2 leads to a 0.11 standard deviation decrease in subsequent test scores." The relevant ventilation improvements cost somewhere in the range of ~$10/student per year. Low-cost wins in education are rare: this is less than 0.1% of the average annual expenditure per student in public schools. By focusing on proper ventilation and maintaining lower CO_2 levels, we can improve the health, productivity, and overall well-being of building occupants.

Particulates and other pollutants

Another critical aspect of indoor air quality is the presence of particulate matter and other pollutants, such as volatile organic compounds (VOCs). Particulate matter can be generated from various sources, including cooking, smoking, cleaning, and outdoor pollution infiltrating indoor spaces. Long-term exposure to particulate matter and other pollutants can contribute to respiratory issues, cardiovascular diseases, and even cancer. High concentrations of indoor pollutants caused by inadequate ventilation are thought to cause "Sick Building Syndrome," where long periods spent indoors cause a variety of symptoms including headaches, fatigue, dizziness, and nausea. Sick Building Syndrome began to appear in the 1970s, as buildings were built increasingly airtight due to energy efficiency concerns without commensurate changes to their ventilation systems.

Improving indoor air quality by reducing particulate matter and other pollutants can lead to numerous health benefits, such as the amelioration of asthma and allergy symptoms. For example, the use of air filters leads to improvements in respiratory symptoms and issues for children with bronchial hyperresponsiveness, asthma, or allergic rhinitis.

The costs of low quality indoor air are high

As with urban fires, the costs of low quality indoor air caused by our buildings are high. In the U.S., the COVID-19 pandemic caused excess deaths of over 1.3 million as of April 2023 and has cost $16 trillion – far higher than every large urban fire in US history combined. We have had to extensively use non-pharmaceutical interventions like closing schools and restaurants to mitigate the spread of COVID-19 — and we paid a very high financial, psychological, and educational attainment cost to do so. And yet, on the scale of potential damage from pandemics, the COVID-19 pandemic was comparatively mild; the death rate was relatively low, and effective vaccines were developed in record time. As of April 2023, COVID-19 has killed on the order of 23 million people, or less than 0.3% of the global population. By comparison, the Spanish Flu in 1918 is estimated to have killed between

1 and 5% of the global population. Future pandemics could potentially be far worse than COVID-19.

And high costs from airborne infectious diseases aren't limited to pandemics. The costs of influenza and other respiratory infections (such as the common cold) are estimated to be more than $100 billion dollars a year in medical costs and lost work, or roughly 0.6% of US GDP. An analysis on the costs of airborne infections in the UK (including both seasonal and pandemic infections) likewise estimated that costs were approximately 1% of GDP annually.

Current building codes and standards have limited effect on indoor air quality

While many air quality regulations exist, they almost always focus on **outdoor** air quality. The Clean Air Act sets national ambient (ie: outdoor) air quality standards and regulates the levels of hazardous air pollutants. There is no equivalent "Indoor Clean Air Act" that establishes indoor air quality (IAQ) standards. The only legally enforceable federal indoor air standards limits are set by the Occupational Safety and Health Administration (OSHA) for exposure to pollutants — not pathogens — at workplaces. And even these regulations, by OSHA's admission, are outdated and inadequate.

State level building codes do have requirements for indoor air quality, but do not address pathogen transmission or CO2 concentration. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the predominant standard-setting organization for ventilation standards for most indoor spaces. Buildings in the US largely follow ASHRAE 62.1 and 62.2, Ventilation and Acceptable Indoor Air Quality standards (for commercial and residential buildings respectively). According to ASHRAE, its standards specify minimum ventilation rates that yield an IAQ acceptable to human occupants. "Acceptable" IAQ is defined as "air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."

These "known contaminants" in question are almost entirely bioeffluents, pollutants, or toxic chemicals, for which legally enforceable limits have been set by OSHA. The survey measurement of "dissatisfaction" does not account for infectious disease transmission — for example, occupants are not asked about frequency/duration of cold- or flu-like symptoms since they started frequenting a space. "Dissatisfaction" is largely measured via assessment of thermal comfort. The newest 2022 standards do acknowledge that achieving acceptable IAQ requires more than simply meeting minimum ventilation requirements, but they do not emphasize infection control.

At the time of this paper's publication, there were no existing infection control standards from ASHRAE or other organizations specifically targeting public buildings. However, ASHRAE had announced its imminent publication of the Control of Infectious Aerosols (241) standard. This groundbreaking standard is designed to significantly reduce occupant exposure to airborne pathogens and promote healthier indoor environments. It establishes minimum, technology-neutral requirements that are based on scientific evidence. These requirements focus on achieving a target equivalent clean airflow rate through a combination of ventilation, filtration, and disinfection. The standard also includes comprehensive testing and safety requirements for air cleaning technologies to ensure they effectively meet the airflow target. Furthermore, it introduces the concept of an infection risk management mode, which enhances controls during periods of elevated risk, such as pandemics. This is similar to how fire control measures are activated during fires. The publication of this standard represents a significant step forward in the field of indoor air quality control.

Air quality standards that do exist only apply at the time of construction

What's more, indoor air standards such as 62.1 and 62.2 are design standards – they stipulate what ventilation performance should be achieved at the time of construction. In practice, buildings often have ventilation rates and measures of air quality that are substantially below design requirements.

CO2 concentration, for instance, should be below 1000 parts per million (ppm) in a building meeting ASHRAE ventilation standards, a standard studies suggest buildings regularly exceed. A review article finds that many classrooms often exceed 2000 or even 3000 ppm. Measurements of office buildings likewise routinely find that ventilation rates are below recommended ventilation rates. An estimate in the UK based on interviews with experts concluded that 50% of buildings had an ineffective or inadequate ventilation system. These low ventilation rates are exacerbated by the fact that commercial buildings often turn off their HVAC systems in the evening, even if people are still in the building.

Strategies for improving indoor air quality

Indoor air quality is a function of the level of contaminants present in the air. By removing these contaminants from the air, the quality of air can be improved.

There are, broadly, three strategies for accomplishing this:

- **Ventilation** - Removing contaminated air from indoors, and replacing it with outdoor air without contaminants. Ventilation can reduce infectious aerosols, CO2, and other contaminants.

- **Filtration** - Filtering out contaminants from the air. This can reduce infectious aerosols and particulates, but generally not CO2.
- **Disinfection** - Killing or otherwise inactivating pathogens in the air directly. The most promising technology for disinfection is **UV light**. Disinfection can remove infectious aerosols but doesn't impact CO2 or other contaminants.

All three of these methods are currently practiced in some fashion in US buildings. By changing where and how they're used, indoor air quality could be greatly improved.

Ventilation

All buildings have some sort of ventilation system – a method for replacing and recycling the air within a space. Most buildings in the US have a mechanical ventilation system, an air handling unit that replaces the air in an indoor space. This might be air from outside the building or recirculated air from elsewhere in the building. The air handler usually will be part of a Heating, Ventilation, and Air Conditioning (HVAC) system that heats and/or cools the air.

Ventilation requirements are commonly measured in air changes per hour (ACH), though there are different metrics available (see appendix). The more the air changes in a given space, the faster contaminant concentration drops. An ACH of 10 will reduce contaminant concentration by 99.9% in a matter of minutes. An ACH of 2, on the other hand, will take hours.

There are several possible ways to reduce contaminant concentration by increasing ventilation. The first is to increase the outdoor air fraction, or the ratio of outdoor air to total supply air in a ventilation system. By replacing indoor air with outdoor air, the concentration of contaminants in the indoor space is diluted. Therefore, increasing the outdoor air fraction can effectively reduce the exposure risk for occupants, as long as the outdoor air quality is acceptable and the ventilation system is properly maintained.

The other method for reducing contaminant concentration by way of ventilation is to increase the ventilation rate. Required ventilation rates vary based on factors such as type of building and occupant density, but will typically be between 1 and 4 ACH. An increase in ACH from 2 (typical for offices) to 6 would cause contaminant concentration to fall by 99.9% in 69 minutes instead of 207 minutes.

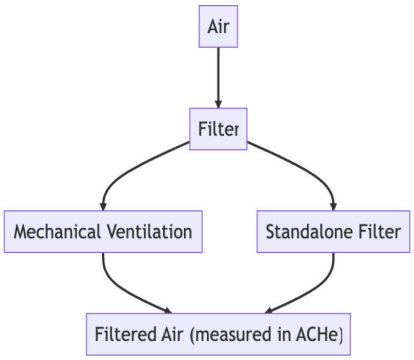
Improving ventilation has limits. Outside air brought in needs to be heated or warmed to the indoor temperature, so increasing outdoor air fraction increases the energy used to heat or cool a space. Increasing ventilation rates has similar effects. This expense can be reduced by using energy recovery systems, though these also may be costly to install and difficult to retrofit into older buildings.

Ventilation also assumes that the air will mix completely and uniformly throughout the indoor space, and that the contaminant concentration will fall proportionally with the ventilation rate. However, this may not be true in reality, as variations in airflow patterns, temperature gradients, occupant density, and emission sources create uneven distribution of contaminants. For example, if air does not circulate well in stagnant zones, or if infected people exhale more aerosols than others in some areas, ventilation may not effectively reduce the exposure risk for all occupants. Therefore, ventilation should be combined with other strategies such as filtration or disinfection to ensure adequate removal of infectious aerosols from all parts of the indoor space.

There are also practical limits to how much ventilation can be increased. Mechanical equipment can only handle so many air changes, and the exponential nature of pathogen concentration models means that increases in pathogen reduction are increasingly difficult. Very high levels of ventilation may also be uncomfortable for occupants.

Filtration

Filtration removes contaminants from the air using a filter, either as part of the mechanical system or via a separate, standalone filter. Filtration can be measured in effective air changes per hour (ACHe): how many air changes would be required to get the same level of contaminant removal.



Filtration proved very successful during the COVID-19 pandemic. A particularly salient success story is that of the Corsi-Rosenthal box, a do-it-yourself air purifier made with four or five MERV 13 air filters and a box fan. The filters are arranged in a cube shape around the fan, forming a sealed system that forces all the air to pass through the filters. Corsi-Rosenthal boxes can be built with materials available at most hardware stores for less than $100, roughly **10 times cheaper** than commercial air filters.

Most standard filters used in building mechanical systems are designed to remove large particles such as dust, pollen, and mold spores that can affect indoor air quality and occupant

comfort. More specifically, ASHRAE 62.1 and 62.2 typically require HVAC systems to use a MERV-8 filter, which filters out most particles greater than 3 microns in size. However, most pathogens and infectious aerosols are much smaller than these particles and can pass through these filters easily. To filter out pathogens, these filters would need to be replaced with high-efficiency particulate air (HEPA) filters or similar types that can remove very small particles. HEPA filters have been shown to be effective in capturing airborne viruses such as influenza and COVID-19. However, there are challenges with using HEPA filters in building mechanical systems. The HVAC system may not be designed to push air through the denser filter material, which can reduce airflow and increase energy consumption. HEPA filters also require more frequent maintenance and replacement than standard filters.

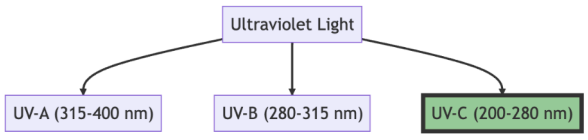
Filtration has some synergies with increased ventilation — the more air gets cycled through the mechanical system, the more air will be filtered. However, mechanical-system mounted filtration does not complement using 100% outside air, since contaminated air goes immediately outside rather than through the filter (though filtering may be necessary to remove contaminants from the outside air, particularly in areas of high air pollution).

Filtration in general has the same limits as ventilation, for the same reasons — its effectiveness is a function of how much of the air in a building is forced through the filter, and how quickly. As with ventilation, there are practical limits on how much air can be forced through a filter. Filtration also assumes that the air in the indoor space is well-mixed and homogeneous, which may not be true in reality.

Disinfection

Disinfection kills or otherwise inactivates pathogens in the air directly. As with filtration, disinfection can be measured in effective air changes per hour.

Ultraviolet (UV) light is the most widely used and promising method of disinfection, although a variety of methods exist. UV light is a type of electromagnetic radiation that has a shorter wavelength and higher energy than visible light. It can be divided into three categories based on the wavelength range: UV-A (315 to 400 nm), UV-B (280 to 315 nm), and UV-C (200 to 280 nm). UV-C is the most germicidal type of UV light, as it can damage the DNA and RNA of microorganisms, preventing them from replicating or infecting other cells. UV-C can inactivate a wide range of pathogens, including bacteria, viruses, and fungi.



UV light is currently used for pathogen disinfection in limited cases: mostly in specific healthcare settings, such as TB wards, though it is seeing some limited use in public places. Because most UV light exposure is harmful to humans, UV light disinfection systems must be designed to prevent human exposure. The two main ways that UV is currently used are in-duct UV and upper room UV.

With in-duct UV, UV lights mounted in mechanical ducts disinfect the air as it passes by. In-duct UV installation is complex and not seen as especially promising compared to alternatives. With upper room UV, UV lights are installed near the ceiling — with shields to prevent occupants from being exposed to the light. Air near the ceiling will be exposed to the UV light and disinfected. As with filtration and ventilation, this technique relies on the air sufficiently mixing to be effective. Upper room UV used to achieve dozens of ACHe.

A novel technology, known as far-UVC, could prove far more effective at disinfection. Whereas conventional upper-room UVC has a wavelength range of 254 nm, far-UVC has a wavelength range of 200-230 nm, and cannot penetrate beyond the outer layer of dead skin cells or the tear layer of the eye. As a result, it can inactivate airborne and surface pathogens without harming human tissues. Far-UVC has been demonstrated to be effective against a wide range of pathogens in laboratory studies, including bacteria (such as Staphylococcus aureus), fungi (such as Aspergillus niger), and viruses (such as influenza A virus and COVID-19). One study showed that continuous far-UVC exposure in occupied public locations within the current regulatory limits (~3 mJ/cm 2 / hour) would result in ~90% viral inactivation in ~8 minutes, 95% in ~11 minutes, 99% in ~16 minutes and 99.9% inactivation in ~25 minutes – an ACHe of over 15. However, the amount of disinfection achieved can be much higher under looser limits: “at a room ventilation rate of 3 air-changes-per-hour (ACH), with 5 filtered-sources the steady-state pathogen load was reduced by 98.4% providing an additional 184 equivalent air changes (ACHe).” Far-UVC is especially effective when combined with ventilation, because it can reduce the required air exchange rate and energy consumption while maintaining a high level of pathogen inactivation.

How large are the potential benefits from improving indoor air quality, and how much would it cost?

Indoor infections largely take place in a small number of densely occupied buildings. An analysis produced for the UK Royal Academy of Engineering estimated that more than 50% of airborne infections occur in just 5% buildings by floor area. Infections are most likely to occur in high-occupancy buildings such as airports, schools, theaters, gyms, churches, and exhibition halls. These buildings often have poor

ventilation, around one to two air changes per hour. A 2017 study of recently constructed US schools found an average ACH of 2. A 1989 study of US office buildings found similar results, with every building studied having fewer than 2 ACH, and most having fewer than 1. The UK analysis estimated that in buildings with poor ventilation (equivalent to one to two air changes per hour), increasing ventilation to six air changes per hour reduced the spread of airborne-transmitted diseases by 30-50%. By targeting the highest-occupancy buildings most likely to cause infection, and bringing their ventilation (or effective ventilation) up to 6 air changes per hour, indoor infections overall could plausibly be reduced by roughly 17%, and reduced CO2 concentration could yield increases in productivity.

Airborne infections plausibly cost the US $100 billion a year in deaths, medical costs, and lost productivity. A 17% decrease in infections would save nearly $20 billion a year in lives saved, medical costs avoided, and improved productivity: five to six times the cost to implement the improvements, even without any advancements in filtration or UV disinfection technology.

Decreased cognitive performance caused by elevated levels of CO2 plausibly reduces productivity by 1-10% in buildings with poor ventilation. Macomber and Allen estimate that if increased cognitive performance translated directly to increased revenue, the benefits of increasing ventilation to twice the ASHRAE recommended value would be 75 times higher than the additional costs of energy required.

Policy Recommendations

Deficiencies in indoor air quality can roughly be broken down into three areas. One, standards need to be created or updated which target the health aspects of indoor air quality. Two, standards then need to be implemented in actual buildings, both new construction and existing buildings. Three, better technologies for removing contaminants from the air should be developed.

Create better standards for indoor air quality

As we've noted, current air quality standards in the US fail to consider many aspects of occupant health. Thus, the first step is to update or create a standard that would better target the health aspects of indoor air quality.

Such a standard could take a variety of forms (see appendix), but for wide deployment it will likely need to be government enforced or incentivized. The most straightforward way would be to update ASHRAE 62.1 and 62.2 to have more stringent ACH requirements, either by incorporating or being complemented by ASHRAE Standard 241P: Control for Infectious Aerosols. High occupancy buildings such as airports, train stations, and gyms should target an ACH of 5, a recently-specified CDC target which would reduce contaminant concentration and significantly reduce the likelihood of indoor pathogen spread while remaining with existing mechanical equipment and filtration systems. As air quality technology improves, this level could potentially be raised, and the requirements could be implemented in more buildings (such as commercial buildings).

In addition, because building mechanical system performance often degrades over time, building jurisdictions should require regular "commissioning" of mechanical systems every 3 years, similar to the inspections that other safety systems (such as fire sprinklers) require.

Summary:

Require ACH of 5 for all high occupancy buildings in ASHRAE 62.1 and 62.2

Jurisdictions should require regular commissioning of mechanical systems for high-occupancy buildings

Implement standard into public buildings

Because most model building codes already reference 62.1 and 62.2, jurisdictions may naturally adopt the updated requirements when they update their building codes, typically every 3 to 6 years. However, provisions that jurisdictions perceive to add building costs may be removed before the code gets adopted. And waiting for code update cycles stretches out the time before these interventions are deployed in the built environment. Therefore, the federal government should offer incentives for jurisdictions that adopt the updated versions of ASHRAE 62.1 and 62.2, as well as the new 241 standard. These incentives could be targeted based on the expected savings and increased productivity, and thus could potentially be cost neutral (or even negative).

Because existing buildings outnumber new buildings roughly 100 to 1, it takes a very long time for updated requirements to make their way into a large fraction of the building stock. Jurisdictions should thus also adopt 241 and updated 62.1 and 62.2 requirements not just for new buildings, but for existing buildings. A reasonable timeline should be provided for compliance, and federal government incentives should be offered here as well.

Summary:

Government should offer incentives for jurisdictions to adopt updated 62.1 and 62.2 requirements, as well as the new 241 standard

Jurisdictions should encourage air quality requirements of 241 and new versions of 62.1 and 62.2 to apply to existing buildings as well as new buildings

Fund research into Far-UVC safety and efficacy

A crucial step towards improving indoor air quality and preventing pathogen transmission is funding research into innovative technologies like far-UVC light. To start, more

human studies outside the laboratory — especially large-scale epidemiological studies — are needed to evaluate real-world efficacy.

While large-scale trials are needed to evaluate far-UVC's impact, standards must allow for its safe and effective use. Guidelines should take an evidence-based approach, incorporating the latest UVC safety and efficacy research to accommodate innovative technologies.

Standards like ASHRAE Standard 241 risk inhibiting far-UVC devices, even if they pose little health risk and can significantly reduce infections. ASHRAE Standard 241's safety procedure should be replaced with Standard 62.1's procedure, which sets exposure limits based on epidemiologically-informed concentrations.

Alongside trials, supporting the development of more affordable, easily-manufactured, and more effective far-UVC devices such as far-UVC LEDs and second harmonic generation devices is critical. Funding these next-generation devices will improve their lifetime, efficiency, safety, and output. To accelerate their development, a successful multi-pronged approach will require understanding device defects, improving device encapsulation,conducting new materials research for filters, and developing improved validation methods.

It's also important to invest in public education about the benefits and limitations of far-UVC light. Policymakers need to clearly communicate how far-UVC light works, why it is safe for human exposure, and address any concerns that may arise from the public or stakeholders about its use.

Fostering international collaboration can align global research efforts and promote the sharing of best practices on far-UVC light. Policymakers should engage with other countries exploring this technology to exchange knowledge and experiences, as well as support the establishment of global standards for far-UVC devices to ensure their safety and effectiveness across different contexts.

Summary:

Fund research into innovative technologies like far-UVC light and conduct large-scale trials to evaluate its impact

Revise standards like ASHRAE Standard 241 to accommodate far-UVC devices, using an evidence-based approach that incorporates the latest safety and efficacy research.

Support the development of affordable, easily-manufactured, and effective far-UVC devices such as far-UVC LEDs and second harmonic generation devices

Invest in public education to communicate the benefits, safety, and limitations of far-UVC light, addressing any public or stakeholder concerns

Foster international collaboration to align global research efforts, promote the sharing of best practices, and support the establishment of global standards for far-UVC devices.

Conclusion

Evidence clearly demonstrates that by enhancing indoor air quality through improved ventilation, filtration, and disinfection, we can drastically curtail the impacts of airborne infections. Concurrently, these measures can boost cognitive performance and productivity. Implementing these improvements in high-occupancy buildings could result in substantial savings, with benefits potentially amounting to billions of dollars at only a fraction of the cost.

It's crucial for policymakers to consider stricter standards that call for higher air changes per hour (ACH)/equivalent air changes per hour (ACHe) in public buildings. They should also create incentives that encourage jurisdictions to adopt and enforce these standards in both new and existing structures. In addition, supporting research into promising technologies like far-UVC lighting could lead to higher effective ACH without significantly higher costs.

Addressing the deficiencies in our built environment that contribute to indoor infections and cognitive impairment is essential for improving public health, particularly considering the amount of time we spend indoors. We've seen the power of combining strategic policy changes with technological innovation in tackling large scale urban fires. We can apply these same principles to indoor air quality to potentially prevent future pandemics, seasonal infections, and their associated high costs.

Appendix

Challenges of measuring filtration effectiveness
Standard test methods and metrics for filtration technologies include:

- Efficacy of in-duct filters/air cleaners: **single-pass removal efficiency (%)**, which measures the percentage of contaminants removed or inactivated by the air cleaner in one pass. There are different rating systems for filters based on their single-pass removal efficiency,

such as MERV (Minimum Efficiency Reporting Value), ePM (Efficient Particulate Matter), HEPA (High-Efficiency Particulate Air), FPR (Filter Performance Rating), and MPR (Microparticle Performance Rating). Higher ratings indicate higher removal efficiencies. There is also a standard test method for UV in-duct efficacy, ASHRAE Standard 185.1, which measures the percentage reduction of viable microorganisms on irradiated surfaces.

- Efficacy of portable/stand-alone air cleaners: **Clean Air Delivery Rate (CADR, ft^3/min)**, which measures the volume of clean air delivered by an air cleaner per unit time. CADR can be measured for different types of particles using different test methods, such as AHAM AC-1 for particles from 0.09-11 microns, m-CADR for microbes from AHAM AC-5. Higher CADR values indicate greater removal capacities.
- Safety: Ozone emissions, which measure the amount of ozone generated by some electronic air cleaners as a byproduct. There are different standards for ozone emissions, such as **UL 867 for low ozone (<50 ppb)** and **UL 2998 for near-zero ozone (<5 ppb)**. Byproduct formation, which measures the amount and type of other harmful substances generated by some additive filtration technologies as a result of their chemical reactions. There is currently no standard test method or metric for byproduct formation.

It may be more difficult to assess the validity of non-standardized tests and metrics, such as those provided by manufacturers, without independent verification or peer-review.

To interpret performance data for filtration technologies effectively, it is important to understand how they are measured and what they mean for pathogen control. Some key points to consider are:

- **Single-pass removal efficiency (%)**: This metric indicates how well an air cleaner removes or inactivates contaminants in one pass but does not account for how many times the air passes through the air cleaner in a given time period or space. Therefore, it is necessary to know the airflow rate through the air cleaner and the volume of the space where it is used to calculate the air changes per hour (ACH) or equivalent ventilation rate (EVR) that the air cleaner provides.
- **CADR**: This metric indicates how much clean air an air cleaner delivers per unit time, and is useful for comparing different technologies in terms of pollutant or pathogen removal. AHAM AC-1 is the most widely used test method for CADR: a mixture of smoke, dust, and pollen particles are used to measure the decay of particles in a test chamber with and without the air cleaner operating. This method is widely used for testing portable or in-room air cleaners, and AHAM's website lists about 800 products that have been tested for CAD. Typical CADR range is 50-500 cubic feet per minute (CFM). Higher CADR means greater removal. However, the units used for CADR may vary depending on the source (e.g., ft^3/min vs. m^3/h vs. L/day). If this is the case, one has to convert them to compare them.
- **Non-standardized tests and metrics**: For these tests, interpretation is required as they may not be directly comparable to standard metrics or real-life conditions. Some questions to ask are:
  - For additive air cleaning technologies:

    Were real-world additive constituent levels used? Were byproducts measured?

    For air cleaners with multiple technologies: Which technologies were active? How much did each technology contribute to removal or inactivation?

    How do chamber test results translate to standard metrics and real-life conditions?
- **Microbial inactivation test**: Measures how much an air cleaner reduces viable pathogens in a test chamber. However, microbial inactivation does not tell one how much clean air a cleaner delivers per unit time, or how effective it is under different conditions. To translate this performance data into CADR, one can use methods such as those proposed by Stephens et al. (2022) in ASHRAE Journal or tools such as ACE IT (Air Cleaner Efficacy Investigation Tool).

Existing air quality metrics

All four of the following air quality metrics are related and can be used to estimate or calculate one another. We present a brief overview here, remembering that the ultimate goal here is to measure the extent to which new infections are prevented.

- **ACH**: the number of times the total air volume in a room is completely removed and replaced by outdoor air in an hour. ACH is used to assess the extent to which mechanical ventilation systems bring fresh air into a space.
  - Requires knowing room volume and flow rate of air in cubic feet per minute (CFM)
  - American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the predominant standard-setting organization for ventilation rates based on ACH
  - Existing minimum standards for ACH vary based on building type
  - Higher is better

- **ACHe**: the equivalent of ACH for methods that clean the recirculated air in a room instead of bringing in outdoor air. This is commonly used for methods other than mechanical ventilation — namely, filtration and upper-room germicidal ultraviolet.
  - Requires knowing the steady state concentrations of some particle or pathogen type before and after the method is switched on — e.g. the concentration of Staphylococcus before and after a UVC lamp or air purifier is turned on
  - Usually used to toward meeting minimum standards for ACH as specified by ASHRAE
  - Higher is better
- **CFM per person**: volumetric rate of flow of air in cubic feet per minute per person. Like ACH, CFM per person is used to assess the extent to which mechanical ventilation systems bring fresh air into a space.
  - Requires knowing the volume of cubic feet of air that passes through a space with a fixed area.
  - ASHRAE is the predominant standard-setting organization for ventilation rates based on CFM
  - Higher is better
- **CADR**: volumetric rate of clean air produced per minute. CADR is used to assess the effectiveness of air purifiers.
  - Rule of thumb is CADR rating is about 2/3 of the maximum airflow in CFM.
  - CADR can also be used to estimate ACH or ACHe and vice versa: ACH or ACHe is calculated as[CADR in cubic feet/min × 60 min] divided by the room volume in cubic feet
  - CADR for air purifiers is certified by Association of Home Appliance Manufacturers (AHAM)
  - Higher is better

Innovation in indoor air quality metrics

It is worth mentioning one potential alternative approach that warrants further exploration: the path principle. There is some evidence to suggest that the most important factor to transmission in an enclosed and mechanically ventilated environment is the **path** — not the **air changes per hour**— between the contaminant source and the ventilation exhaust vent. Simulations have shown that when this path is interrupted by air streams, the contaminant is likely to migrate to other parts of the indoor space. From the path principle perspective, the worst possible situation is one in which the main exhaust area is far from the contaminant source and where the path is considerably intercepted by air streams. If the supply air is instead directed away from the path, then contaminant migration is limited. This approach thus differentiates between different types of air flow instead of treating them all equally: between those that interrupt the path between the contaminant and exhaust and those that do not.

By this view, the best ventilation system design is one that is in accord with the hypothesized path principle. Currently, room ventilation systems are designed to mix room air with supply air for the purposes of creating a uniform thermal condition. A path principle design would instead likely involve pushing contaminated air upward toward exhaust vents in the ceiling — similar to how a laboratory fume hood captures contaminants. Standards might encourage under-floor air distribution systems that consistently push air up toward exhaust vents, as opposed to mixing ventilation methods where air can either be pushed up or down depending on the part of the room.

A metric that assesses the extent to which an air ventilation system conforms with the path principle might standardize how air actually flows through a room, as opposed to the amount of air that is replaced in a given amount of time. For example, air flow in the rooms of commercial buildings might be specified to move as directly as possible toward exhaust vents. This can be a simple binary system or can have multiple levels, though the latter would likely necessitate some consistent way to measure the paths of aerosolized particles.

Current indoor air quality testing

Though nearly every building in the U.S. is designed for ASHRAE standards, these standards in practice are often not met for operating buildings. On day one a newly constructed building will almost certainly meet the minimum acceptable standards, but on day two there is no regulatory or industry body measuring performance to make sure the standards are continuously met. At the moment, most indoor air quality is tested outside of any sort of regulatory or credentialing systems.

The most common IAQ testing method by far is use of a **CO2 monitor.** Most high quality CO2 monitors cost a few hundred dollars and there are many online tools that help people make sense of the CO2 measurements — namely, for the purposes of calculating the ACH:

- When a room/space is occupied (this is the most common method): **measure steady state concentration**. Estimate the CO2 generation rate by multiplying the number of occupants in the classroom by their rate of CO2 exhalation. Estimate the target volumetric flow of outdoor air. Multiply the volume of the classroom (in cubic feet) times the target air changes per hour and divide by 60 minutes per hour. Can use steady state CO2 concentration to understand ACH — e.g. normal size classroom with 15 teenager

students, and a ventilation rate of 4 ACH should have a steady state CO2 concentration around 800 ppm.

- When room/space is first occupied, then emptied: Can **measure rate of decay of CO2 concentration** when the occupants leave to estimate how fast air from outdoors (~400 ppm) replaces the indoor volume of air as a way to determine ACH. Can do the same using dry ice instead of occupants.

However, relying on CO2 monitors alone to assess indoor air quality has several drawbacks. First of all, there is no requirement to install or use CO2 sensors in most buildings, so many indoor spaces may not have any real-time measurements of CO2 levels at all. Even if CO2 sensors are present, they may not be properly calibrated, maintained, or located to provide accurate and representative readings of the indoor environment.

CO2 can be used as a proxy for ventilation but not as a standard for it — for example, ASHRAE standards do not contain an indoor CO2 limit. Belgium is innovating in this space by rolling out a "national ventilation plan" for all commercial spaces that are open to the public. It requires that all these spaces have a CO2 meter that is clearly visible to the public and asks every building manager to keep an inventory of the CO2 measurements taken. It moreover specifies the following two recommended target values:

- **Level A**: a CO2 concentration lower than 900 ppm (parts per million). Ventilation and/or air purification must therefore be provided at a rate of at least 40 m³ per hour per person.
- **Level B**: a CO2 concentration lower than 1,200 ppm or a ventilation flow of at least 25 m³ per hour per person.

Finally, as of 2025 locations will also have indoor air quality labels that are determined by certification officers. As Belgium's ventilation plan demonstrates, use of CO2 monitors to measure IAQ has the following advantages: it is already widely used in mechanically ventilated buildings through embedded sensors as a way of controlling ventilation systems (though this monitored data usually is not accessed), of existing measurement methods it is the most well-understood by the public, it is very accessible, and it is low-cost compared to alternatives. However, measuring CO2 has two big drawbacks. It is a poor indicator for ventilation effectiveness in spaces with a low number of occupants. More importantly, it does not account for non-ventilation methods like air filtration or UVC, since these strategies remove microorganisms from the air but not CO2.

Below are indoor-specific alternatives to CO2:

- For measuring ventilation directly and accurately: use of **a balometer**, which is used for unit ventilators/central air systems. Is placed on a capture hood to measure the flow rate (in cubic feet per minute) coming into the building through the grille where air is sucked in.
- For measuring filtering of air: both of the above (CO2 monitor and balometer) only measure actual ACH as opposed to equivalent ACH — i.e., only accounts for outdoor air coming in as opposed to filtered/sterilized air. By using **clean air delivery rate [CADR] of air filtration device or CFM** (at least one is usually provided, usually the CFM) one can figure out equivalent ACH. Use CFM and room volume to figure this out.
    - Most aerosols with infectious viruses are less than 5 microns in size, so filters like PM1, PM2.5, MERV-13 are ideal
- For measuring UVC cleansing of air: this unfortunately requires **air sampling of bioaerosols**, which is costly and necessitates considerable expertise.

Unfortunately, as we've seen **there is no single easily-accessible measurement method that can account for all existing types of indoor space interventions**. The closest that one can get to this is via the indirect route of calculating air changes per hour and the effective air changes per hour provided by each of one's interventions and summing those up — but this relies on using measurements that result from external testing, rather than on measurements one can take in real-time in one's own specific space.

Innovation in air quality testing

A potentially promising avenue is real-time instruments for indoor bioaerosol measurements that use some version of a viable particle counter approach. These use a biofluorescent particle counting technique for particle sizing, counting and differentiating between viable and non-viable bioaerosols. At the moment, costs run in the hundreds of thousands of dollars, with estimated costs of tens of thousands of dollars per year for continued calibration and maintenance. The technique is primarily used in sensitive manufacturing facilities, like pharmaceutical manufacturing facilities. Historically, this approach has not been used much — if at all — for viruses, and will need to be tested. But this may be a potentially interesting area of future innovation for driving down costs and making the technology simpler and more accessible.

Another way to measure bioaerosols directly is to use sequencing techniques on samples collected from HVAC condensate, the water that forms when warm air passes over a cold coil in an air conditioning system. It can contain traces of microorganisms that were present in the air. By sequencing the DNA or RNA of these microorganisms, one can identify what types of pathogens are circulating in indoor air. This method has been used to detect bacteria and fungi in HVAC systems, but it could also be applied to viruses.

However, sequencing HVAC condensate has some limitations. It requires specialized equipment and trained personnel to collect and analyze the samples.Moreover, it does not provide information on how many viable particles are present in the air or how infectious they are.

A possible solution to these challenges is to develop a PCR test that can be performed on-site without needing someone to run it. PCR stands for polymerase chain reaction, a technique that amplifies a specific segment of DNA or RNA from a sample. It is commonly used to diagnose COVID-19 and other diseases by detecting viral genetic material in nasal swabs or saliva samples. An automated PCR test for HVAC condensate could potentially detect viral particles in real-time by collecting air samples, extracting and amplifying the DNA/RNA present, and detecting the specific virus. The device would ideally have a user-friendly interface that can display the results in real time or transmit them. Such automated PCR tests **already exist**, but the size and cost of the relevant equipment makes widespread use infeasible. Moreover some technical challenges would have to be overcome, namely ensuring the device is robust enough to withstand environmental variations/contamination, optimizing extraction/amplification protocols, and selecting an appropriate range of different probes to detect relevant pathogens.

Another option is to use aerosol sampling and alarm systems that can alert occupants when bioaerosol levels exceed a certain threshold. These systems could use sensors that detect changes in particle size distribution, optical properties, or electrical charge of airborne particles as indicators of bioaerosol presence. They could also use filters or collectors that capture particles for further analysis or disposal. The advantages of using aerosol sampling and alarm systems are that they can provide real-time feedback on indoor air quality and potential health risks; they can cover large areas and multiple zones within a building; they can be integrated with ventilation systems to control airflow and filtration; and they can be customized to target specific pathogens or allergens of interest. The disadvantages of using aerosol sampling and alarm systems are that they may not be able to distinguish between viable and non-viable particles or between different types of microorganisms; they may have high false positive or negative rates due to environmental interference or sensor drift; they may require frequent calibration and maintenance; and they may be expensive and complex to install and operate.

These methods would provide more direct and timely feedback on IAQ than conventional methods such as CO2 monitoring or filtration efficiency testing. CO2 monitoring measures the concentration of carbon dioxide in indoor air as a proxy for ventilation rate and occupancy level. However, it does not account for other factors that affect IAQ such as humidity, temperature, or pollutant sources. Filtration efficiency testing measures how well an air filter removes particles from an airstream under controlled conditions. However, it does not reflect how well the filter performs in actual indoor environments where factors such as airflow rate, pressure drop, or filter loading may vary.

What is really needed is a measurement method that can account for all the IAQ indoor space interventions that exist and are turned on in a space, and which gives accurate real-time data. This is what we do for temperature — measure directly, not assessing via room volume.

Background on US building codes

Like most laws in the US, the authority for regulating building standards exists at a variety of levels, from federal all the way down to county or city requirements. The government or organization that's responsible for building code enforcement in a given area is called the Authority Having Jurisdiction (AHJ).

Most building code adoption in the US is handled at the state level, where each state will have its own building code that applies statewide. Some states, however, have no statewide building code (or only have statewide codes for certain portions of the building, such as septic requirements), and building code adoption is left entirely to local jurisdictions (cities, counties, townships, etc). In some cases a jurisdiction may not decide to adopt a building code at all, (though this is uncommon, and is typically limited to rural, unincorporated areas).

For states that do have a statewide building code, enforcement is typically handled by local jurisdictions, and in many cases local jurisdictions will add their own code requirements. The City of Decatur, for instance, has its own set of high performance building requirements that goes beyond the state building code. In most cases, the state code is a minimum requirement, but a few states allow local jurisdictions to reduce state level requirements.

Jurisdictions typically don't do the work of creating their entire building code themselves. They will instead typically start with a model code (or a series of model codes) written by a private code authoring organization, and then make modifications to it. Some major model code organizations in the US are the International Code Council (ICC), the International Association of Plumbing and Mechanical Officials (IAPMO), and the National Fire Protection Association (NFPA). These private organizations convene committees of experts to author building codes and standards designed to be adopted into law by AHJs.

Related to codes are standards. These are created by trade organizations, technical societies, standards development groups (such as ASTM and ANSI) and government agencies (such as NIST and FEMA) that define performance criteria or provide design guidelines and information for some particular aspect of the building. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), for instance, has developed standards for indoor air quality, thermal conditions for human occupancy, building energy efficiency, and many other aspects of HVAC systems. ACI has several hundred standards and guidelines covering all aspects of concrete design and placement.

Model codes typically reference various standards as a way to provide requirements without having to detail every aspect of some particular system. The International Residential Code, for instance, references several hundred different standards, test methods, and design criteria. And standards, in turn, may reference other standards and guidelines.

Potential avenues for regulatory change in the built environment

Our recommended regulatory path for improved indoor air quality is to update an existing standard (ASHRAE 62.1 and 62.2), which will then (hopefully) be incorporated into model codes (such as IBC and UBC) and/or adopted by building jurisdictions. But there are a variety of potential avenues for updating requirements for buildings, and it's worth making note of them.

There are, broadly, two potential things to consider: how the standard is structured, and the way that standard gets adopted by jurisdictions.

Standard structure

Updating indoor air quality requirements requires the creation of some relevant standard. One option would be to update an existing standard. ASHRAE produces several standards on indoor air quality (such as 62.1, 62.2, and 170) that are widely referenced and used. These could be updated with new requirements that would better prevent indoor infections. Alternatively, changes could be made to a model code directly (such as to the International Building Code).

The benefit of updating an existing code or standard is that much of the hard work of adoption has already been done. But the political barriers for making changes might be higher, as these standards and codes likely have built-in constituencies that might resist changes, particularly ones that might affect cost.

Another option would be to create a new standard or model code from scratch. This could be done by an existing standards creating organization (such as ASHRAE), or another organization (such as NIST, CDC, or the EPA).

The benefits of a new standard is increased freedom to structure it in whatever way seems best. The downsides are that it may have to "redo" work that existing standards have already done to get adopted. Additionally, standards not created using a certain process may have difficulty being adopted – for instance, some jurisdictions did not adopt LEED requirements because they weren't created using an ANSI standard (which ultimately resulted in the creation of ASHRAE standard 189.1).

There are also hybrid approaches. For instance, the development of the criteria and requirements could be performed by NIST, and then handed off to ASHRAE for incorporation into a standard.

Paths to adoption

Once a standard has been created or updated, it must be adopted by relevant jurisdictions. We can classify paths for adoption as hard or soft. Hard paths are legally mandated requirements, while soft paths incentivize adoption while not necessarily legally requiring it.

Hard paths of adoption would involve changing the building code to make indoor air quality criteria mandatory requirements. There are several possible ways this might be achieved. One option would be for jurisdictions to directly adopt an indoor air quality standard. This is how elevator safety requirements are implemented, for instance: nearly all jurisdictions have directly adopted the American Society of Mechanical Engineers (ASME) standard A17.1 Safety Code for elevators and escalators. Similarly, many jurisdictions have directly adopted the ASHRAE standard 90.1 for building energy efficiency requirements. A jurisdiction might choose to modify its building requirements directly, without referencing a standard.

Another option would be to add updated indoor air quality requirements to a model code already in use, such as the International Building code. One way of doing this would be to get the model code to reference an outside standard for indoor air quality. This is how, for instance, seismic design force requirements are implemented – the International Building Code references the ASCE 7 "minimum design loads for buildings" standard, which includes extensive methods for determining the required seismic design loads on different portions of the building.

Alternatively, the text of the requirements could be added directly to the code, or to an existing standard. ASHRAE standards 62.1, 62.1 or 170 could include the updated criteria for indoor air quality. An example of this sort of adoption working is the recent changes to the International Building Code which allow for taller timber buildings. These changes were developed by an ICC committee, and then added to the International Building Code directly.

Requirements added to an existing model code or standard can easily achieve widespread adoption. Nearly every jurisdiction in the country uses some flavor of the International Building Code, so changes made to it are likely to eventually percolate out to the states. An existing code or standard has done much of the work.

The downside of this approach is time. Existing model codes and standards update only every few years, and individual states also only update their model codes every few years, so a change might take a decade or more before it spreads to the majority of states. And that's assuming the states didn't excise the changes, which often happens. For instance, the international residential code has requirements for single family homes to have fire sprinklers, but, thanks to lobbying by the NAHB, nearly every state removes these requirements. There may be more political barriers to updating an existing code or standard. Committee members, for instance, might object to proposed changes likely to increase building costs or otherwise harm their interests.

Getting jurisdictions to adopt requirements directly is more direct, and may see initial results more quickly. It also may be more achievable. However, the large number of permitting jurisdictions in the US means that this is likely to be a slow process for large-scale adoption.

Soft requirements would incentivize the adoption of indoor air quality standards in ways other than legally mandating them.

Governments could encourage adoption by way of benefits to buildings that adopted these criteria. An example of this sort of adoption is green building standards such as LEED certification. LEED certification typically isn't mandatory, but many jurisdictions, such as Seattle, allow new buildings that achieve LEED certification to be built taller, or with more square footage, than would otherwise be allowed. In essence, the costs of achieving LEED pay for themselves in terms of better building economics.

This could also be done by large stakeholders, such as large companies or universities. An example of this is Microsoft, which **requires** its buildings to be designed and constructed to minimize carbon footprint.

Developers also might choose to willingly adopt the standard if it can be couched as a benefit that they can sell. If buildings built with higher indoor air quality standards reliably rent for more (because people value being in those buildings, or companies see higher productivity because their workers are sick less often), increased adoption will naturally follow. Mass timber construction, for instance, is more expensive than other methods of construction, but is sometimes chosen because the spaces which utilize it rent for more.

Even the act of creating a standard could potentially change the construction landscape and encourage its adoption. Creating a standard lowers the barriers for people who are interested in building to a certain level of infection safety. It also can potentially change what the "standard of care" is for design professionals, allowing the courts to be de facto agents of enforcement rather than AHJs.

The benefits of soft paths for adoption are potentially fewer political barriers and increased feasibility. Suggestions are likely to marshall less opposition than mandatory requirements, and there are fewer stakeholders that will need to weigh in. It also potentially allows for more frequent standard changes instead of being tethered to a code update cycle, which may be important in an area where understanding and available technology is rapidly changing.

The downside is that adoption will likely be less widespread than for mandatory requirements. LEED, for instance, is by far the most successful "optional" standard, but is only adopted on approximately 20% of commercial building square footage, and a much smaller proportion of total buildings, as well as many fewer residential buildings, despite having been in existence for 20 years.

There are also paths for adoption that are between hard and soft requirements. One option would be to include pandemic-resistant construction standards as an appendix to a model code or standard. Appendices are opt-in, rather than opt-out: jurisdictions have to deliberately decide to adopt them rather than deliberately decide not to adopt them. One example is the standard for legionella prevention, which was recently referenced in a code appendix for the uniform mechanical code. Updated indoor air quality criteria could be added as an appendix to ASHRAE 62.1, 62.2 or 170.

Similarly, a state may adopt a model code as a "permissive code," which local jurisdictions can choose to adopt or not. Georgia, for example, has several permissive codes that some, but not all, local jurisdictions have adopted.

The benefits and drawbacks for these methods are similar to other soft requirements: there may be fewer barriers to accomplish them (for instance, the NAHB has argued strongly against fire sprinkler requirements in the international residential code, but has few objections to including it as an appendix), but they're likely to be less widely adopted.

Another option would be to make them mandatory requirements, but in narrower domains than building code changes. For instance, any institution that receives federal funds must meet federal fire safety requirements, including having fire sprinklers. Similarly, any project that receives federal funding or approval must comply with NEPA.