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DOI
10.1126/science.adl0677

Publication date
2024

Document Version
Final published version

Published in
Science

POLICY FORUM

PUBLIC HEALTH

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If some countries lead by example, standards may increasingly become normalized

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People living in urban and industrialized societies, which are expanding globally, spend more than 90% of their time in the indoor environment, breathing indoor air (IA). Despite decades of research and advocacy, most countries do not have legislated indoor air quality (IAQ) performance standards for public spaces that address concentration levels of IA pollutants (*1*). Few building codes address operation, maintenance, and retrofitting, and most do not focus on airborne disease transmission. But the COVID-19 pandemic has made all levels of society, from community members to decision-makers, realize the importance of IAQ for human health, well-being, productivity, and learning. We propose that IAQ standards be mandatory for public spaces. Although enforcement of IAQ performance standards in homes is not possible, homes must be designed and equipped so that they could meet the standards.

For the past two decades, scientists have called for national IAQ standards and laws to be established (*2*), but so far, little action has been taken. The approach to IA contrasts sharply with outdoor air, for which quality is regulated and monitored and compliance with regulations is enforced. The World Health Organization (WHO) Global Air Quality Guidelines (AQG) published in 2021 provide recommendations for concentration levels of six pollutants and their averaging times ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3) and apply to both outdoor air and IA (*3*).

In cases for which IAQ standard and guideline values were established by national or association working groups, the outcomes were inconsistent; often the criteria for the same parameter differed by orders of magnitude. The reasons cited for limited progress include different criteria in the selection of the critical study, in the starting point, and in the derivation procedure; the complex political, social, and legislative situation regarding IAQ; the lack of an open, systematic, and harmonized approach (*4*); and that establishing an IAQ standard is always the result of a compromise between scientific knowledge and political will (*5*). Because of the heterogenous landscape of approaches needed, such barriers remain intact despite the considerable IAQ research and evidence base developed over the past decades.

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CHALLENGES

Source contributions

IA pollution originates from sources indoors (including humans) and outdoors and from chemical reactions between pollutants in IA (*6*). Compliance with IAQ standards (that refer to the concentrations of indoor pollutants) would require controlling indoor emission sources (such as combustion, building products, and cleaning products) and minimizing the entry of outdoor pollutants indoors (for example, by filtering or treating outdoor air to remove particles and chemical compounds and reducing penetration of pollutants through the building envelope).

During respiration, humans emit (in addition to CO_2) particles that contain viruses and bacteria. Most respiratory infections are acquired indoors, through inhalation of virus-laden airborne particles (*7*). However, there are no exposure-response relationships for respiratory pathogen concentrations in IA, nor are there technologies available to routinely monitor such pathogens in buildings in real time. We cannot control human respiratory emissions in the same way that we control emissions from other sources.

Monitoring

We cannot use the well-established approach that is used to measure outdoor air quality to monitor IAQ. We cannot rely on a monitoring network (in only selected indoor public spaces) because every space is different and is used differently, and we cannot use modeling to predict pollution concentration in one space by using the concentrations measured in other spaces. Compliance monitors are too costly and complex to deploy in all indoor spaces to monitor for all six pollutants included in the WHO AQG (*3*). However, there are environmental parameters that can already be monitored in each room of each building, such as temperature and relative humidity. The feasibility of monitoring IAQ parameters in buildings depends on the size, cost, robustness, and silent operation of the sensor or monitor; calibration; and ease of interpreting data. But routine, real-time monitoring of indoor pathogens is currently infeasible. In the absence of information on the concentration of pathogens in IA, the question is which proxy parameter or pollutant should be the basis for legislation that targets airborne infection transmission.

Legislation

Legislation comprises the system of rules—or statutes—created and enforced by the government of a jurisdiction. Guidelines, on the other hand, are less formal, not mandatory, and generally not enforceable unless adopted in legislation. Standards, also generally unenforceable unless they are adopted in legislation, are typically voluntary in nature and can set out requirements with respect to design, operation, and performance. They may be adopted in legislation and thus made enforceable by law.

In terms of formal international law, there are global treaties on transboundary air pollution, but to date, no international treaty requires or encourages adoption of ambient air quality standards (*8*). It is conceptually difficult to legislate for air quality standards in general, let alone IAQ, because air quality legislation is typically focused on a result or outcome, rather than on behavior (for example, imposing limits on pollution sources) (*8*).

Other challenges include the scope of what to regulate, how monitoring and enforcement activities are undertaken, and who has responsibility for them.

At a country level, IA legislation is hampered by the tremendous variability across jurisdictions and the particulars of each country's legal structure. "Air pollution" is not defined in air quality legislation in a substantial number of countries (*8*). This presents a challenge for the development of laws on IAQ. However, the United Nations (UN) Sustainable Development Goals provide an opportunity for global progress on IAQ (*9*).

Industry priorities

Many regulations reflect compromise between the needs for human protection and for industry opportunities, with the regulatory process involving balanced participation from groups with different priorities to reach consensus. There has not yet been sufficient coordinated support to implement IAQ regulations. The industry most closely related to IAQ is the heating, ventilation, and air conditioning (HVAC) industry, which in response to market demand has evolved to focus primarily on thermal comfort and energy efficiency; the market has not yet demanded large-scale supply of technologies to improve IAQ. Regulation could rapidly change this demand, which may or may not benefit the HVAC industry and many other building industries. There will always be some industries that do not benefit and/or will require strategic change owing to new regulations, so they would prefer the status quo. There are groups who will be forced into capital costs by regulation change (such as property owners and their associations) that must be convinced of need and value. Thus, in the pursuit of new IAQ regulation, market forces may mean that industry support is not guaranteed.

The social and political dimension

Introducing standards is complex, not only because scientific parameters may be contested or technically difficult to achieve but also because human stakeholders have different values, goals, and power, and standards may have cultural or political implications. A particular standard may be unfeasible in any given setting (for example, because it is unaffordable or blocked by powerful individuals or groups), so compromises must be made. Organizations that choose (or are required) to implement standards must go through a complex and sometimes costly process to identify, assimilate, implement, and adapt them.

ADDRESSING THE CHALLENGES

The proposed approach is based on science, technology, and specific solutions that have existed for some time and can now serve as a basis for addressing a complex interdisciplinary problem.

Proposed parameter levels

Values may be adjusted to reflect local circumstances and priorities.

	LEVEL	AVERAGING TIME OR SETPOINT
$PM_{2.5}$, µg/m^3	15$^{(i)}$	1-hour
CO_2, ppm	800 (absolute value)$^{(ii)}$	threshold
	350(delta)$^{(iii)}$	threshold
CO, mg/m^3	100$^{(iv)}$	15 minutes$^{(iv)}$
	35$^{(iv)}$	1 hour$^{(iv)}$
	10$^{(iv)}$	8 hours$^{(iv)}$
Ventilation, liters/s per person	14$^{(v)}$	When the space is occupied

(i) 24-hour level from (*3*). (ii) When 100% of air delivered to the space is outdoor air, assuming outdoor CO_2 concentration is 450 ppm; based on classroom scenario (see SM). (iii) Delta is the difference between the actual CO_2 concentration and the CO_2 concentration in the supply air. (iv) 8-hour averaging time, from (*15*). (v) Clean air supply rate in the breathing zone; see (*12*). At 25°C and 1 atm for CO 1 ppb = 1.15 µg/m^3. Threshold is the concentration level of CO_2 that must not be exceeded.

Pollutants recommended by WHO

Low-cost sensors are a viable technology to measure some of the six pollutants included in the WHO AQG; however, not all six can be realistically monitored in buildings, nor do they all need to be monitored. The two most relevant candidates for routine regulatory IAQ monitoring are $PM_{2.5}$ and CO, for which low-cost advanced sensors have demonstrated stability, durability, and robustness. Particulate matter in IA originates from indoor and outdoor sources, and exposure to $PM_{2.5}$ is among the 10 leading risks (*10*). CO arising from various natural processes is present in the atmosphere at very low concentrations, but it is incomplete combustion (indoor and outdoor) that can raise concentrations to levels harmful to humans. Indoor CO should be routinely measured in areas where outdoor CO concentrations exceed regulations and where indoor combustion takes place. In several countries, CO monitors are mandated in spaces where combustion takes place to alert to life-threatening levels of gas, but these monitors are typically not sufficiently sensitive to lower concentrations.

Carbon dioxide

Currently CO_2 concentration values are not included in the WHO AQG. However, regardless of the potential harm it causes, CO_2 can serve as a proxy for occupant-emitted contaminants and pathogens and as a means to assess the ventilation rate. CO_2 sensors are readily available, inexpensive, and robust and can be used in all interiors. The advantage of using CO_2 as a proxy is that although both pathogens and CO_2 are emitted during human respiratory activities, it is much easier to link CO_2 concentrations to these activities than to model risk from the emissions of pathogens.

Ventilation

Ventilation with clean air is a key control strategy for contaminants generated indoors. The efficacy of ventilation in reducing infection risk has been demonstrated in many studies (*11*). The role of ventilation is to remove and dilute human respiratory effluents and body odors and other indoor-generated pollutants at a rate high enough relative to their production so that they do not accumulate in IA. IA is replaced (diluted) with outdoor air (assumed to be clean) or clean recirculated air. Outdoor air ventilation rates are almost always set according to criteria of hygiene and comfort (perceived air quality). Effective air distribution (ventilated air reaching the entire occupied zone and airflow not directed from one person to another) is a practical candidate for a standard. The measured ventilation rate can be used as a proxy of IAQ.

Although technologies for measuring ventilation already exist in most modern mechanically ventilated buildings, monitoring the ventilation rate in terms of clean air delivered to the space without considering the number of occupants or their activities is not sufficient to ensure adequate IAQ. One way to assess the quality of ventilation is to concurrently measure the CO_2 concentration: If it rises above an accepted threshold relative to the outside concentration or concentration in the recirculated air brought into the room, the ventilation is inadequate.

Suggested numerical levels

Below, we provide justification for proposed numerical levels and their averaging times for the pollutants and the parameters discussed above (see the table). Actual levels adopted by countries and jurisdictions will differ, reflecting local circumstances and competing priorities.

$PM_{2.5}$ concentration. It is proposed that the WHO AQG 24 hours, 15 µg/m^3 level be considered as the basis for IAQ standards, but with a 1-hour averaging time because 24 hours is much longer than people typically spend in public places or, for that matter, that public spaces are occupied. This is a compromise between the realistic occupancy of and exposure in public spaces and the need for rigor in the derivation of the health-based value.

Using the WHO AQG value for 24-hour exposure for 1-hour exposure is a conservative approach that considers each environment as though it were the only one where people spend all their time.

CO_2 concentration. To decide on a level that would adequately control the risk of infection in public spaces, a scenario of exposure must be defined and then a risk assessment model be applied. We propose a scenario of a classroom with one infected student [see supplementary materials (SM)]. A ventilation rate of 14 liter/s per person, keeping CO_2 concentrations at or below the standard level proposed in the table, would ensure that the reproduction number R_e < 1 even for respiratory pathogens with high transmissibility, such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) Delta and Omicron variants and measles. The recommended level of 800 parts per million is within an already relatively narrow range of values of the CO_2 levels recommended by different organizations and countries (see SM). This approach takes outdoor concentration as a baseline. However, not only are outdoor concentrations continually increasing because of emissions to the atmosphere that outweigh removal, which must be taken into account in the formation of the standard, there are also variations between locations, and at individual locations there are diurnal and annual variations. Therefore, jurisdictions should consider local CO_2 baseline levels when setting levels.

In indoor environments where the supplied ventilation air is a mixture of outdoor air and recirculated air, the CO_2 concentration can be high, but the risk of infection may be low provided that the supplied ventilation air is sufficient. This is because the recirculated air is often filtered, and most of the pathogens are removed before it reenters the space; however, gaseous pollutants, such as CO_2, are not removed by this process. The actual (absolute) CO_2 concentration in the space and the difference between the actual CO_2 concentration and the CO_2 concentration in the air delivered to the space (outdoor air delivered with natural ventilation or air delivered by mechanical ventilation systems) are assumed as a proxy for ventilation.

Ventilation rate. The recommended rate of 14 liters/s per person, based on (*12*), is higher than the WHO-recommended minimum ventilation rate for nonresidential settings of 10 liters/s per person (*3*), or the highest category I ventilation rate defined in the existing standard ISO 17772-1. However, it is in line with ventilation rate recommended by (*11*), based on an experimental exposure study of a cohort of school children.

Legislation

As noted in the UN-EP 2021 report, one advantage of an IAQ regulatory framework is the ability to place obligations on owners of indoor premises (*8*). This contrasts with ambient air quality, which generally relates to "unowned" air for which allocating responsibility can be more difficult (*2*). Premises that operate under extant legal frameworks (such as workplaces, schools, and hospitals) may be more amenable to regulatory control through these frameworks (*2*) to consider as part of the development of laws for IAQ (table S2).

IMPLEMENTATION OF STANDARDS

For IAQ standards to have practical value, they must be implementable; buildings must be designed, constructed, maintained, operated, or retrofitted to meet the standards, given the intended use, and must be used accordingly. This should be checked at delivery and routinely throughout the building life. Standards must establish specifications for IAQ and be technically feasible, affordable to construct and operate, and compatible with other priorities and constraints such as energy use. Several means are available for achieving IAQ that meets these objectives.

The use of natural or hybrid ventilation (natural ventilation supplemented by mechanical ventilation when necessary) when feasible can greatly reduce space conditioning energy requirements and associated operating costs. Stratified air supply (distributing air to create vertical stratification of temperature and contaminant concentrations) by using displacement ventilation or underfloor air supply and personal ventilation (supply of clean air directly to the breathing zone of each occupant) can have a positive impact. For required delivery of outdoor air, high-efficiency air-to-air energy recovery is essential and required by many energy standards.

Additional measures in support of ventilation, such as air cleaning and disinfection, can greatly reduce the need to increase outdoor air supply, which carries a substantial energy penalty. Filtration of recirculated air is an effective way to reduce concentration of, and exposure to, airborne particulate matter, allergens, and pathogens. Other air treatment technologies may help inactivate infectious airborne particles. Work is ongoing to develop consensus methods for determining the effectiveness of some of these technologies and safety measures.

The use of demand control (modulating control levels in response to need and activation of higher levels of protection) can be guided by public health data, for example, during annual influenza seasons or when a new pathogen emerges with the potential to cause an epidemic. The recently published ASHRAE Standard 241–2023 Control of Infectious Aerosols (*13*) incorporates most of the noted measures and is intended to apply during periods of elevated risk of airborne disease transmission.

Actions to address IAQ will add cost in the short term and may not be prioritized by many countries because of pressures on budgets. However, if some countries lead by example, we anticipate that IAQ standards will increasingly become normalized. Social and economic benefits in terms of public health, well-being, and productivity and performance will likely far outweigh the investment costs in achieving clean IA. Few countries realize the enormity of public health costs, but disability-adjusted life years (DALYs) attributable to IA pollution accounted for an estimated 14.1% of the total DALYs in China for the period from 2000 to 2017, and corresponding financial costs (not including the costs of IA-borne infection transmission) accounted for 3.45% of China's gross domestic product (*14*). By making IAQ standards the reality, we will improve our health and well-being, and also save money. ■

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ACKNOWLEDGMENTS

This paper was supported by the Australian Research Council (ARC) Industrial Transformation Training Centre (IC220100012) and ARC Laureate Fellowship (FL220100082). The Engineering and Physical Sciences Research Council (EPSRC) funded the CO-TRACE project (grant EP/W001411/1), UK Research and Innovation [EPSRC, Natural Environment Research Council (NERC), Australian Human Rights Commission (AHRC)] funded the RECLAIM Network Plus project (grant EP/W034034/1), and NERC funded the GreenCities project (grant NE/X002799/1).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adl0677

10.1126/science.adl0677