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Mandating indoor air quality for public buildings

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Abstract

Air pollutants are routinely monitored and controlled in outdoor air to protect public health, but this is not the case for indoor air – the air that we breathe most of the time. Routine monitoring of indoor pollutants is rare. A lasting transformation in indoor air quality is only possible if health-protecting indoor air performance standards for public spaces where the majority of the population spends a significant fraction of the day working, studying, spending leisure time, are developed, legislated and enforced. For indoor air performance-based standards to be enforceable, the concentration of indoor pollutants and/or their proxies must be monitored in public spaces, which so far has presented technological, scientific, and legislative challenges; however, we are now in a strong position to address many of these challenges. This paper proposes a way forward to this global issue using a new approach that allows key risks to be addressed with a minimum of monitored parameters to make indoor air quality standards possible on technological, social, and political levels.

Keywords: indoor air; indoor air monitoring; health-based standards; indoor space legislation.

Introduction

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, wellbeing, 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)[1] 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.

Challenges

1. 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

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[1] $PM_{2.5}$ and PM_{10}: are particles less than 2.5 and 10 micrometres, respectively. For regulatory purposes, based on health studies linking particle size to adverse health effects they are usually measured in terms of mass concentration. Note: the correct analytical definition of $PM_{2.5}$ and PM_{10} differs slightly.

NO_2 is nitrogen dioxide, SO_2 is sulphur dioxide, CO is carbon monoxide, and O_3 is ozone.

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.

2. 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.

3. 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).

4. 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.

5. *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.

Table 1. Proposed parameter levels. Values may be adjusted to reflect local circumstances and priorities. (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.

	Level	**Averaging time or setpoint**
$PM_{2.5}$, µg/m³	15(i)	1-hour
CO_2, ppm	800 (absolute value)(ii)	threshold
	350 (delta)(iii)	threshold
CO, mg/m³	100(iv)	15 minutes(iv)
	35(iv)	1 hour(iv)
	10 (iv)	8 hours(iv)
Ventilation (L/s/person)	14(v)	When the space is occupied

1. *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.

2. *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.

3. *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.

4. *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 $\mu g/m^3$ 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.

5. 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 wellbeing, and also save money.

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Supplementary Information

Table S1. The key elements of the approach we propose to develop IAQ standards that can be enforced and legislated.

This is what we need to do:

- Consider the feasibility of monitoring pollutants or proxies, using existing monitoring methods, including low-cost sensors for specific pollutants, and requiring unambiguous interpretation of the results.
- Based on the above, select a minimum number of pollutants and/or parameters that are proxies for other pollutants; source proxies, or proxies for conditions that result in elevated levels of pollutants of health concern.
- Establish and regularly review threshold levels of pollutants or proxies, adherence to which will result in desired overall lowering of health risks, and exceedance of which will result in a specific action.
- Provide R&D funding and/or direct government support to develop the required monitoring and mitigation strategies/technologies.

Table S2. Key aspects we propose as part of the development of laws for a 'healthy' IAQ. However, laws, and the processes for developing them, will vary between jurisdictions, according to their legal systems.

- *International scientific standards* that define IAQ and identify the means of measuring it, as presented here, is an important starting point for laws regulating IAQ.
- *Legislation that expressly includes laws for a 'healthy' IAQ*. However, laws, and processes from developing them. Will vary between jurisdictions, according to their legal system and an example of this is The Model State Indoor Air Quality Act proposed for the US (*1*).
- *Whether to include reference to international scientific standards in legislation* as a means of measuring IAQ for monitoring and enforcement. These standards may be adopted in existing or new national legislation and can assist in relieving the regulatory burden on individual states, allowing them to focus on broader objectives and referring to standards for any technical specifications.
- *Whether to include IAQ within the scope of existing legislation or whether to introduce new IAQ-specific legislation.* Even if IAQ is to be included within legislation, this does not necessarily mean that entirely new legislation will be required. It is possible that IAQ could be addressed by including it within existing laws, for example, by amending existing public health legislation or environmental protection legislation to include provisions that expressly address IAQ.
- *Whether legislation is to be at a national or state level and whether coordination is required between different levels of government*. 52% of surveyed countries shared responsibility for AQS between different levels of government (*2*).
- *The scope of the laws relating to IAQ*. Of particular importance is the issue of which indoor spaces are regulated. For example, there would be a need to clarify whether the laws would apply to IAQ in schools, businesses, and workplaces (*2*).
- *Requirements for monitoring and* enforcement *of IAQ* (*2*).

1. Pollutants not currently considered for IAQ standards

Pollutants included in the WHO AQG 2021 (3)

Ozone (O_3) is a secondary pollutant, formed in the outdoor air by chemical reactions of primary pollutants (NO_x and VOC) in the presence of sunlight. Indoor sources include printers and some ozone-producing devices sold as "air cleaners." Indoor sources of O_3 precursors, in particular personal care products, cleaning products, paints, and adhesives are important (*4*), but need UV radiation to form O_3. Ozone is reduced indoors by reactions with indoor surfaces, human surfaces, and gaseous pollutants, so O_3 concentrations are typically lower indoors than outdoors (*5*). However, various reactions with ozone take place indoors. This happens, for example, with terpenes in the gas phase and on surfaces, leading to potentially harmful byproducts (*6*), or in direct interaction with human skin (*7*). Low-cost O_3 sensors are less reliable than those for CO_2 and PM. Moreover, ozone sensors are sensitive to interfering gases such as NO_2 and vice versa (see below). Therefore, routine O_3 monitoring should be given less priority than other pollutants. Indoor ozone sources should be controlled or eliminated, while modified filters in HVAC systems can destroy O_3 in the outdoor air supply before it reaches indoor locations rather than their emissions measured.

NO_2 is a combustion product and although low-cost NO_2 sensors have been used for various research and application projects, they have a limitation that makes them less suitable for routine monitoring: the output data require complex interpretation due to interference of some other gaseous pollutants in the air (*8, 9*). The advanced data analysis required (*10*) is currently an inhibitor for large-scale regulatory use.

SO_2 in the air originates predominantly from burning of sulphur rich fossil fuels in power plants and industrial process (also aviation). In the last few decades significant progress has been achieved in reducing or eliminating sulphur in fuels. Monitoring of SO_2 indoors is not considered a priority because of its decreasing concentration outdoors, the absence of sources, and the limitations in sensor technologies for routine indoor monitoring.

Other pollutants included in the WHO IAQG 2021 (3)

This list includes organic compounds (benzene, formaldehyde, naphthalene, polycyclic aromatic hydrocarbons, trichloroethylene, and tetrachloroethylene) and radon, but none of them can be routinely monitored in all indoor settings on a day-to-day basis. For this reason, while some of these pollutants are included as guideline values and regulations of several countries, they are monitored periodically (usually as part of a survey) or voluntarily (*11*) but not routinely, and are often part of source control criteria for the classification of low-emission construction and consumer products.

The use of online devices that non-specifically monitor organic compounds in room air is not recommended for measurement and assessment reasons. In the case of sum values, the respective result strongly depends on the method. At least seven different definitions are known for the term TVOC (total volatile organic compounds) alone, based on different measurement and calculation procedures (*12*). Guideline values exist for specific organic substances, but these are based on short-term sampling and are unsuitable for continuous indoor monitoring.

Radon testing and mitigation are recommended for regions where soil emissions of radon are significant because the distribution of radium (which decays to radon) in the soil varies greatly from region to region [e.g., (*13*)]. National radiation protection authorities provide detailed radon maps. Protection against radon should be regulated in national radiation protection laws. Based on reference values, laws should provide for measures to protect the health of people in areas with high radon levels. An important measure is compliance monitoring, usually periodic, which will inform control measures according to national standards.

Dampness and Mould WHO 2009 (14)

Relative humidity and/or moisture is an important measurement (and proxy), and it is central to the source terms for mold and allergens (such as dust mites). It has impacts on indoor chemistry that are not fully understood.

Microbial pollution is an important factor in indoor air pollution, and many species of bacteria and fungi, especially filamentous fungi (mold), grow indoors under moist conditions. The scientific evidence about health problems associated with building moisture and biological agents is reviewed in WHO 2009 (*14*). The most important effects were found to be increased prevalence of respiratory symptoms, allergies, asthma and disturbances of the immunological system. Information on the conditions that determine the presence of mold and measures to control its growth indoors are also summarized. Adverse health effects are most effectively avoided by preventing or minimizing persistent dampness and microbial growth on interior surfaces and in building structures.

2. Monitoring of particulate matter

There are comprehensive and critical review articles available on particulate matter monitoring using low-cost sensors (LCS). However, we highlight the two most important challenges of low-cost particulate matter monitors incorporating optical particle sensors, which are calibration and overestimation of concentrations at times when water particles are present in the air (e.g., fog, steam).

Overall, significant progress has been reported in the development of new methods for outdoor LCS $PM_{2.5}$ calibration (*15-18*). In one of the applications (*16*), the correction factors developed by the study reduced the root mean square error of the raw data from 8 to 3 $\mu g\ m^{-3}$, with an average FRM or FEM concentration of 9 $\mu g\ m\ m^{-3}$. Importantly, this correction equation, along with proposed data cleaning criteria, has been applied to PurpleAir $PM_{2.5}$ measurements across the US on the AirNow Fire and Smoke Map (*15, 17, 18*). Submicron particles have not yet been included in regulatory monitoring, nor are exposure–response relationships available for them. Therefore, we do not consider them in the context of IAQ standards. To date, no simple method has been developed to account for this overestimation as a function of other environmental parameters such as temperature and relative humidity. This problem could be addressed in the same way as in regulatory instruments, by heating the inlet, but this would significantly increase the cost and complexity of the monitors, making them unfeasible for this application. Therefore, the suggested solution is to discard the data for relative humidity conditions above 75% (when water droplets may be present in the air) (*19*). However, this problem does not affect indoor air measurements under most conditions, as relative humidity is typically below 75%.

3. The scenario considered in the risk assessment model

We propose a scenario of a 1-h class with a seated infected student who emits infectious particles through oral breathing for 80% of the time, and speaking for 20% of time, while the exposed susceptible subjects are seated and silent students.

This scenario is a typical classroom setting, and among many types of public buildings with human exposure, schools are considered a particular priority because of the high probability of infections in the classroom (large numbers of children sharing the same indoor environment for many hours), the vulnerability of children, and the impact of infectious children transferring the infections to families and the community.

To calculate the values in Table 1, we considered a classroom, assuming that susceptible individuals remained in the microenvironment for the same amount of time (1 hour) as the infected individual (SARS-CoV-2 Delta variant) (*20*). The scenario consisted of a 150 m^3 classroom (total area of 50 m^2, populated with 25 students + 1 teacher with 2 m^2/student) in which a seated infected student emitted infectious particles through 80% oral respiration and 20% phonation, while the exposed susceptible students were seated (not wearing personal protective equipment). No exceptional events such as coughing or sneezing were considered in the evaluation of the infectious particle emission rate of the infected person. In addition, ventilation of 14 L/s/person (corresponding to approximately 9 ACH) was assumed.

Once all boundary conditions were defined for a prospective assessment of the long-range airborne transmission, we used the AIRC tool (*21*) to estimate the individual probability of infection and to verify whether the event reproduction number (R_e) was maintained below 1.

The infection risk was 2.9%, confirming that with a gathering of 25 students, the condition $R_e<1$ was met (R_e continued to stay below 1 until the maximum speaking value of 40%).

In the scenario considered, based on the CO_2 mass balance given by Mahyuddin and Awbi (*22*) and considering an emission rate per student of 0.005 L/s (*23*), a CO_2 value in the steady-state condition lower than 800 ppm was obtained, with a background CO_2 of 450 ppm. Consequently, a CO_2 threshold value for this scenario could be 800 ppm (350 ppm as an increase over the outdoor value). For more infectious variants (e.g., the SARS-CoV-2 Omicron variant), the ventilation rate would have to be increased, and the related CO_2 concentration reduced, to remain at the same infection risk as for the scenario considered. In that case, extra facilities such as local (recirculating) air cleaners could be introduced to limit the need for higher ventilation rates. Such an increment in the ventilation rate is not normally feasible in existing buildings.

4. Recommendations for CO_2 concentration levels by various bodies

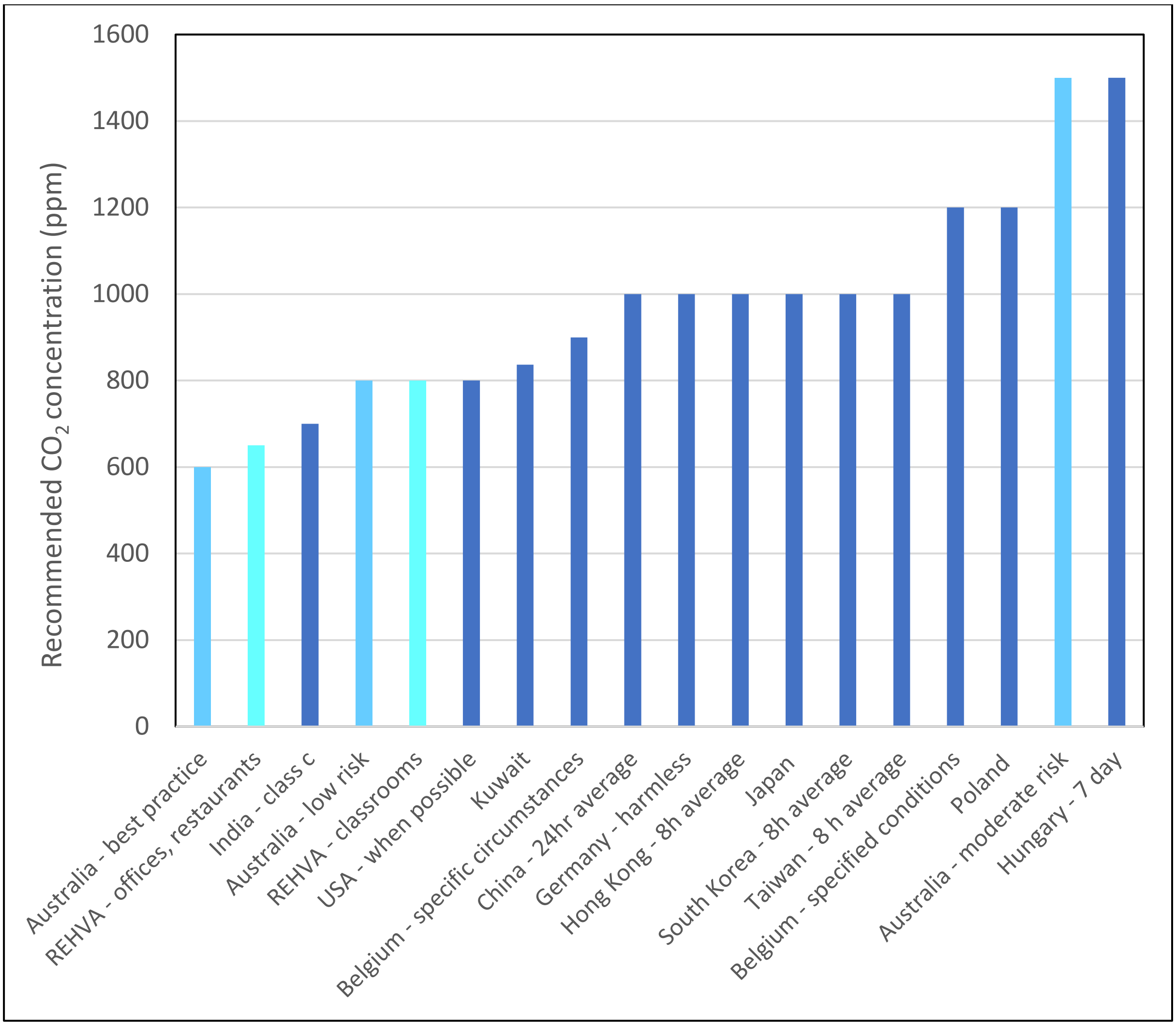

Figure S1: Summary carbon dioxide (CO_2) values recommended by various countries/organizations (*24-33*).

The Netherlands has a building decree and the so-called fresh school guidelines (*34, 35*). In the Ministry of the Interior and Kingdom Relations (*34*), for classrooms in buildings constructed or renovated after 2012: 8.5 L/s/person is obligatory. In the Netherlands Enterprise Agency (*35*), recommendations are given for schools: level A (CO_2 < 400 ppm above outdoor level; > 12 L/s/person), B (CO_2 < 550 ppm above outdoor level; > 8.5 L/s/person); and C (CO_2 < 800 ppm above outdoor level; > 6 L/s/person).

More information on IAQ Guidelines Reports are available at IEQ Guidelines (*36*).

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