Mandating indoor air quality for public buildings
If some countries lead by example, standards may increasingly become normalized

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This PDF file includes:

Supplementary Text
Fig. S1
Tables S1 and S2
References

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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 μg m^{-3}, with an average FRM or FEM concentration of 9 μg 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

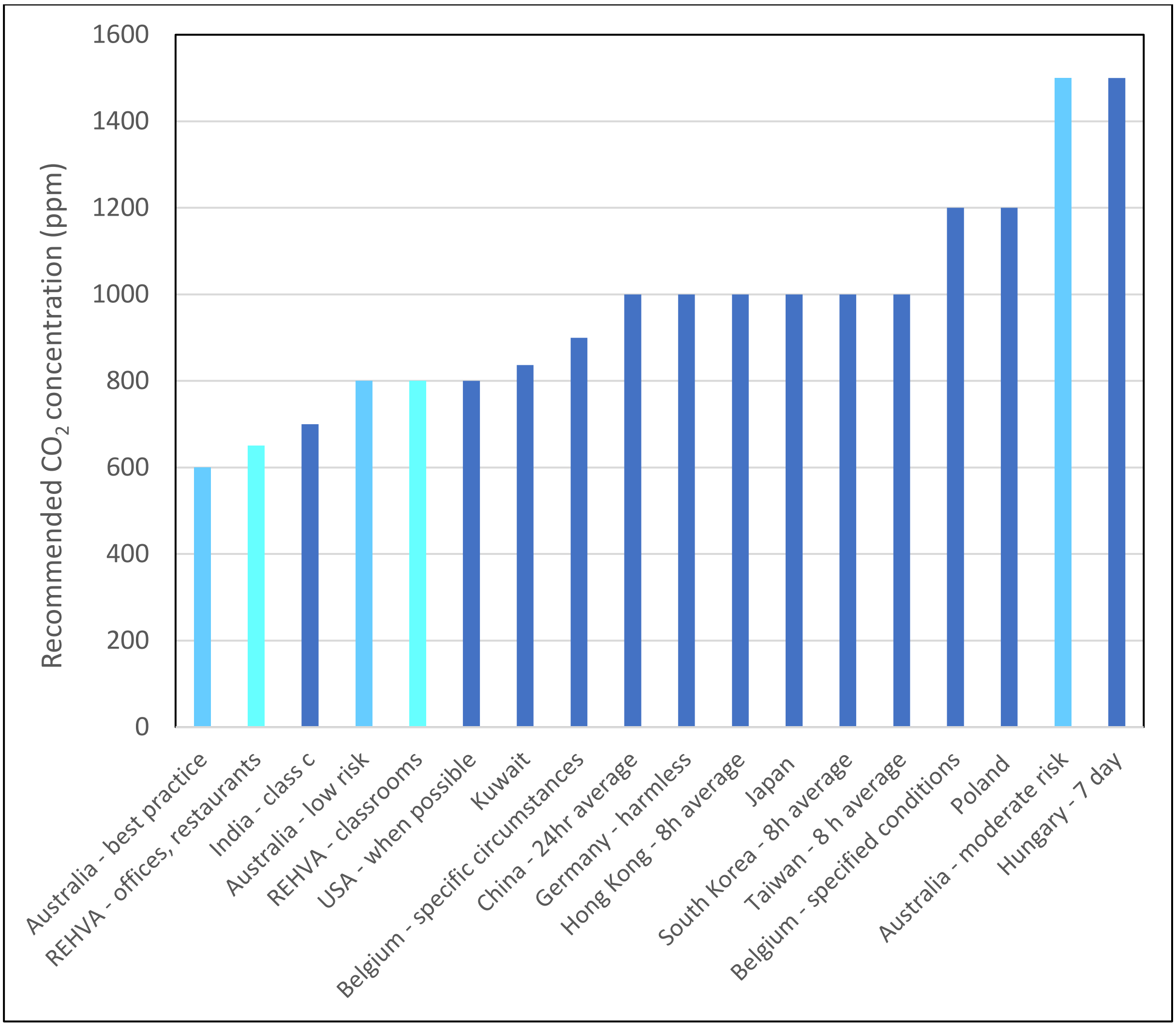

Figure S1: Summary carbon dioxide (CO_2) values recommended by various countries/organizations (*24-33*).

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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