INDAIRPOLLNET
IMPROVING INDOOR AIR QUALITY

WORKING GROUP 6

Blueprint for indoor air chemistry characterisation campaign

Policy Recommendations to improve Indoor Air Quality

COST Action 17136 Indoor Air Pollution Network

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The network

INDAIRPOLLNET (INDoor AIR POLLution NETwork) is a network of experts on indoor air, working together to solve issues related to indoor air quality and planning an optimal way of studying indoor air pollution and its effects on health of the occupants. The overarching aim of this network is to define a blueprint for the optimal indoor air chemical characterisation campaign, which is relevant for the buildings we use and for the way that we use them.

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INDAIRPOLLNET: Policy Recommendations to improve indoor air quality

1. Introduction

In developed countries we spend 90% of our time indoors, whether in our homes, at work, or commuting between the two. This means that our exposure to air pollutants happens mainly indoors, whether those pollutants are generated indoors (e.g. through cooking (nitrogen oxides (NO_X), particulate matter (PM), volatile organic compounds (VOCs)) cleaning (VOCs, chlorinated compounds, ammonia), emissions from building and furnishing materials (VOCs, semi-VOCs) or from ingress of traffic emissions (mainly NO_X, ozone (O_3) and PM) and other air pollutants from outdoors. As well as these direct emissions, chemical and physical interactions between these air pollutants indoors can produce an even wider range of chemical species, some of which (e.g. formaldehyde) are far more harmful to health than the parent emissions from which they derive (Weschler and Carslaw, 2018). Despite all of these facts, there is currently no regulation for indoor air pollutant levels aside from the occupational environment.

Looking to the future, electrification of the vehicle fleet will cause outdoor air pollutant levels to decline. Moreover, the impacts of climate change are likely to drive energy efficiency measures that tend to make buildings even more airtight. Considering construction, usage, renovation and demolition, buildings in the European Union cause about 40% of the energy consumption and 36% of the greenhouse gas emissions (European Commission 2020). Both energy efficiency measures in the built environment and changes in ambient air quality levels mean that exposure to air pollution indoors will become even more important in terms of our overall exposure levels. Making buildings more airtight also has implications for the spread of microorganisms including mould (an issue in ~15% of European homes, Norback et al., 2017), bacteria, as well as for viruses (like the transmission of a disease as seen during the ongoing Covid-19 pandemic).

INDAIRPOLLNET (INDoor AIR POLLution NETwork: https://indairpollnet.eu/) is a European COST Action of more than 200 scientists. Through this network, we have defined the knowledge gaps and challenges for indoor air, highlighted the processes and pollutants that should be evaluated, the instruments that should be used to do so and the building parameters that must be considered. Based on our work, this document provides pointers for implementing European policy to improve indoor air quality (IAQ) for all building users.

2. Building types

Deciding which buildings to regulate depends on the time people spend in the building, their vulnerability and whether high air pollutant concentrations or intensive breathing is expected, which will increase the intake dose. Based on the INDAIRPOLLNET project, we defined five types of buildings where policy could be considered, based on these factors: i) Residential Buildings; ii) Office Buildings; iii) Educational Facilities; iv) Health Care Facilities; and v) Sport Facilities.

For all buildings, location, layout and construction, ventilation, materials and occupancy rates are critical. Ventilation and infiltration play an important role either by contributing to the reduction of chemical compounds emitted indoors, or by allowing outdoor air pollutants to enter buildings. Occupancy impacts activities in a particular microenvironment, and affects e.g. indoor carbon dioxide (CO_2) and other pollutant levels.

There are also specific sources for particular building types. For **residential buildings**, building and furnishing materials, along with cleaning products, contribute to high levels of indoor air pollution under some circumstances. Better labelling of these products (e.g. a traffic light system such as used for fat content of foods), would help consumers to choose products according to their composition. Cooking can also produce high levels of pollutants, but these can be mediated by switching to electric/induction hobs and cookers and more efficient use of extractor fans.

In **office buildings**, building materials, furniture, and cleaning substances are important sources of indoor air pollution, whilst in **educational facilities**, furniture, paint, chalk, detergents and the stirring up of soil dust, are the most important sources. Sources of organic matter include skin flakes and cotton fibres. Science classrooms (often without fume hoods) need special attention in terms of IAQ. For **health care facilities**, cleaning products, detergents, disinfectants and sterilisers, anaesthetic gases, and laboratory or pharmaceutical products are specific sources of indoor air pollution. Finally, for **sports facilities**, IAQ is highly dependent on the type of activity, but the enhanced breathing rates during physical activity mean that inhaled doses can be high.

3. Policy recommendations

As stated above indoor exposure to air pollutants can account for a significant proportion of the total daily exposure, and the implementation of IAQ standards will help to reduce this exposure and to define when mitigation measures are required. Such measures must consider the need to ventilate indoor spaces to (i) reduce indoor pollutant concentrations and (ii) reduce the transmission of air pathogens indoors (e.g. Covid-19) that can have relevant health effects. However, ventilation in outdoor air pollution hotspots might increase indoor air pollution. Thus, the IAQ policy challenges are in this case how to obtain adequate ventilation whilst maintaining acceptable IAQ. Finally, because building types vary (e.g. homes, offices, restaurants) the policy approaches will necessarily be different.

In the following sections, we consider how and where IAQ standards should be implemented, which pollutants to include in IAQ standards, how we approach this implementation for private residential buildings and public buildings and finally, strategies to abate indoor air pollution.

3.1. How and where IAQ standards should be implemented

Validated standard measurement methods for monitoring some long-lived pollutants (e.g. NO_X, O_3 and PM) in indoor and outdoor environments are already established on a European level (EN 14211:2012; ISO 13964:1998; EN 12341:2014). For short-lived pollutants, measurements in ambient air have been discussed in the context of potential future standardisation activities (Nehr et al., 2016a; Nehr et al., 2016b). Short-lived oxidants can react indoors to form highly oxygenated organic compounds and particulate matter with known adverse health effects (Dockery et al., 1993; Donaldson et al., 2003; Van Berlo et al., 2012). However, most of the focus around air pollution exposure and research, remains on outdoor air pollutants.

To date, there are no standardised methods available for real-time, continuous indoor measurements of NO_X, nitrous acid, O_3, and VOCs, or for short-lived oxidants like the hydroxyl radical (OH), the hydroperoxy radical (HO_2), organic peroxy radicals (RO_2), nitrate radicals (NO_3), and reactive oxygen species (ROS). Sophisticated techniques to determine concentrations of these species are commonly used in field measurement campaigns for the investigation of tropospheric photochemistry (Nehr et al., 2016a; Nehr et al., 2016b; Dockery et al., 1993; Donaldson et al., 2003; Van Berlo et al., 2012; Heard, 2006; Brown, 2003; Fuchs et al., 2011). Applying these methods indoors where possible (e.g. Farmer et al., 2019), has provided a deeper insight into indoor air chemistry and its relation to human health.

Any standardisation methods related to IAQ must be adaptable: products (e.g. for cleaning) and technologies (e.g. air cleaning devices) and their resulting emissions are constantly evolving (Salthammer, 2020). Currently available ISO Standards focus on discontinuous target-screening for characterising IAQ. Conventional target-screening comprises a defined set of analytical parameters with specifically optimised analytical procedures, to ensure an interference-free measurement of the target substance with high sensitivity. However, this analytical approach might miss emerging pollutants. Emerging pollutants are not currently included in routine monitoring programs, but may be candidates for future regulation, depending on research on their toxicity, potential health effects, and prevalence.

Non target-screening permits the simultaneous analysis of hundreds of analytes, allowing unknown or untargeted substances to be measured. This approach provides a large quantity of analytical information in a short time period. However, non-target-screening is subject to detection sensitivities that can be very different for each group of substances, potentially resulting in lower sensitivity compared to target-screening (Schlabach, 2013). Future ISO Standards for the assessment of IAQ will need to consider these factors accordingly.

Although two state-of-the-art field measurement campaigns have now been held indoors in the US, buildings are highly heterogeneous regarding, e.g., building materials, construction, occupancy and room use. Given such intensive field measurement campaigns can only be performed at a limited number of sites, it can often be challenging to compare results between them.

One approach could be to define the scientific objectives, to categorise the indoor environment type, and to determine the minimum number of investigated rooms (buildings), so that harmonised data bases can be created and compared. International Standards could help to develop tools for the systematic categorisation of indoor environments and to ensure that measurement strategies are implemented consistently and that data sets are comparable.

The use of box models for the prediction of expected air pollutant levels in buildings represents a complementary approach. Data obtained in indoor field measurement campaigns can enable model evaluation (e.g. Mendez et al., 2016a; Mendez et al., 2016b, Carslaw et al., 2017). A consistent database originating from indoor field measurements would be highly beneficial in this respect. Future ISO Standards therefore need to cover IAQ modelling including model quality objectives, definition of quality indicators, and emission factors as well as emission inventories.

Finally, it is important to mention that although there is increasing IAQ scientific knowledge, there is a lack of translation of most of this information for professional building designers, operators of buildings, and facility managers. Translating scientific knowledge into practical applications should raise the awareness of building users of exposure to indoor air pollutants. The implementation of a management system for controlling different aspects of IAQ would have enormous benefits in terms of comfort and health of the population, although such a system must also account for energy management and outdoor environmental issues.

The elaboration of a management system for controlling different aspects of IAQ was recently accomplished by ISO (ISO 16000-40:2019) and is still subject to further developments in the field of IAQ assessment and classification (ISO/FDIS 16000-41:2023). This "Indoor Air Quality Management System(IAQ-MS)" is designed to be integrated with other Management Systems like Environmental Management according to ISO 14001 or Energy Management according to ISO 50001 (ISO 14001:2015; ISO 50001:2011). Conceptually, an integrated building system ensures that the building uses energy efficiently and sustainably, whilst providing healthy IAQ for the building occupants.

3.2. Which pollutants should be considered in IAQ standards

The core idea behind indoor air pollution standards is to set a level whereby prolonged use of an indoor space under normal conditions[1] should be safe for human health. The sources of pollutants found indoors are numerous, as explained in the Introduction. Indoor air pollutants can originate from outdoors, from the building itself (the construction materials as well as fixed and mobile installations), and also be a result of the presence and activities of building occupants. It would be very challenging to regulate for all of the chemical and biological contaminants we know about currently and also to incorporate emerging pollutants.

One way forward is to combine a *general duty of care* with a *selection of exposure limits* for pollutants that are either frequently occurring or particularly dangerous. This concept is well known and tested in occupational settings[2]. To some extent it is applied currently via liability laws.

i) The *general duty of care* obliges builders, developers, owners and operators of indoor spaces to create the conditions for healthy air within their means. Known health risks must be controlled at safe levels, even if the substance, process or

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[1] Users have a certain duty to cooperate in the use of indoor spaces. This is especially true for unusual activities that can lead to high levels of pollutants, such as smoking or certain types of cooking. In such situations, users may be required either to refrain from doing so or to improve IAQ through ventilation. In normal situations, however, excessive requirements should not be imposed on users.

[2] Note that in some work environments specific biological, physical and chemical hazards may be present. Exposure to such hazards is regulated through occupational health laws and standards and thus not further discussed in this document. However, some pollution control strategies used in those settings may also be applicable when addressing common indoor environmental hazards.

installation is not specifically regulated. Building and construction material standards provide a means for the construction sector to usually fulfil their duty of care with regards to known hazards.

ii) *Exposure limits* for gaseous and aerosolized pollutants ensure that substances that frequently cause problems are taken into account as a matter of course ("ubiquitous pollutants" such as e.g. radon). In addition, some, such as CO_2, can double as indicators for ventilation efficiency, which in many cases will ensure sufficient removal of low-hazard pollutants that originate from the indoor environment.

INDAIRPOLLNET identified ~800 chemicals found in European Indoor environments. Regulating all of them would present enforcement agencies with a challenging, time-consuming and expensive task. One approach could be to review the top 100 chemicals in this list and to consider the following strategy for identifying pollutants to be regulated with specific exposure limits:

1. Include ubiquitous pollutants such as radon, CO_2, CO, NO_2, O_3, PM2.5. For these, exposure limits applicable to the general population exist already in some European countries (e.g. for radon there is a European Council Directive (2013) that covers basic safety standards for protection against exposure to ionising radiation).
2. Include high hazard substances and their precursors that are repeatedly reported to be above safe levels in European countries. As part of our work for INDAIRPOLLNET, we ranked our 800 species according to known health effects. The top six in terms of known carcinogenicity, mutagenicity etc. were benzo(alpha)pyrene, ethylene oxide, benzene, lindane, styrene and formaldehyde. For some of these, exposure limits already exist, for others, existing occupational standards would need to be adapted to permanent occupancy situations, including consideration of vulnerable groups.
3. Include additional low to moderate risk substances where their regulation is expected to reduce the burden of disease. A special edition of *Applied Spectroscopy Reviews* summarised some of the methods that can be used to make measurements indoors (https://www.tandfonline.com/toc/laps20/57/7), based on our INDAIRPOLLNET work.
4. It may also be useful to set substance class standards for those that are of low direct harm, but important precursors, e.g. "total VOC", similar to the approach for outdoor regulations to tackle outdoor smog formation. However, this requires a careful assessment of the methods to assess these precursors and their sources. While cheap methods exist to obtain approximate concentration estimates, it is much more difficult and expensive if a more refined assessment of substance classes or individual chemicals becomes necessary. An interim method could be to have screening methods (e.g. sensor-based) that can trigger a refined assessment such as source-inventories and air-sampling by complex and more expensive methods and instrumentation if a target concentration is exceeded.

These considerations, however, are likely to produce an unrealistically large list of pollutants to check on a regular basis. The solution could be a tiered regulatory approach, whereby frequent assessment and documentation of key pollutant levels of CO_2, NO_2, and PM2.5 is mandated. These three pollutants could be seen as a proxy for occupancy effects, outdoor pollution (namely traffic) and a combination of indoor and outdoor sources respectively. Other pollutants could be assessed less frequently, such as when a new or newly renovated building is commissioned, and/or when there are health concerns or complaints. When key pollutant concentrations frequently exceed satisfactory levels, there is also the need for a more thorough evaluation of pollutant levels.

3.3. Private residential buildings

It is challenging to implement an IAQ compliance strategy for air pollutants in private residences, for privacy and cost reasons. However, actions can be implemented to:

1. Improve regulations of indoor air management (such as centralised ventilation, air conditioning) to take into account not only CO_2 concentrations, but also the air pollutants of section 3.2.
2. Carry out dissemination campaigns to explain the problem, the recommended limit values for air pollutants, and major recommendations to abate indoor pollutants and reduce outdoor infiltration of pollutants. These measures will be different in a traffic hotspot area (with high infiltration potential for soot particles and NO_2) than in a suburban and rural area (with higher problems associated with biomass burning pollutants or O_3).

3.4. Public buildings and private buildings open to the public

In indoor public spaces, a different policy approach should be implemented based on the following actions:

1. Implement specific actions to abate outdoor air pollutants around the buildings. For example, implementing traffic reduction measures and/or creating green barriers around schools, medical care centres, care homes and large office buildings. Bus stops could be shifted away from such buildings, to reduce the infiltration of air pollutants.
2. Improve regulations of indoor air management (such as centralised ventilation, air conditioning, kitchen air extraction) to consider not only CO_2 concentrations, but also the air pollutants referred to in section 3.2. These should also include filters for outdoor pollutants in mechanical ventilation.
3. Ensuring compliance with the rules of building construction, performance and maintenance of the ventilation and air conditioning systems through certification companies with frequent inspections.
4. Implementing air quality standards with the obligation for frequent concentration measurements of key pollutants, to evaluate compliance by accredited companies.
5. As for private residential buildings, carrying out dissemination campaigns to explain the problem, the recommended limit values for air pollutants, and major recommendations to abate indoor pollutants and reduce outdoor infiltration of pollutants. These measures will be different in a traffic hotspot area (with high infiltration potential for soot particles and NO_2) than in a suburban and rural area (with higher problems associated with biomass burning pollutants or O_3).

3.5 Recommendations to abate indoor air pollution and reduce risk of illness transmission - reduce emissions, increase ventilation and reduce infiltration

Reduce emissions

As **'ACTION 0'** it is important to abate emissions of indoor air pollutants: Use low emission materials (construction materials, furniture, paints, textiles, carpets, solvents, detergents); build low emitting kitchens and heating systems (switch from gas to electric/induction); avoid dust deposition and re-suspension; reduce emitting activities (use of air fresheners, incense, candles, smoking); and avoid use of instruments emitting O_3 (e.g. some laser printers and photocopiers).

Increase ventilation and reduce infiltration

The need for increased energy efficiency in closed spaces (homes, public spaces, public transport) over recent years, has led to decreased ventilation rates, in favour of a higher re-circulation of indoor air. For instance, in electric public buses and trams, fuel consumption by AC systems was reduced through recirculation of air, but the filters implemented in the AC systems meant that clean air flows were inefficient (Querol et al., 2021, Moreno et al., 2021). The SARS-CoV-2 pandemic provided evidence that ventilation (replacing indoor air with outdoor air) was needed to reduce/prevent extensive infection by respiratory viruses (Morawska et al., 2020). This ventilation is also needed to reduce the IAQ impairment caused by emissions of indoor pollutants (VOCs, NOx, CO, PM, radon, among others). On the other hand, implementing ventilation in outdoor air pollution hotspots (not only urban hotspots that are polluted with PM, UFP (ultrafine particles) and NO_2, but also in rural areas where outdoor O_3 concentrations might be high), might cause IAQ deterioration.

In summary, the challenges for improving IAQ are:

1. To reach ventilation rates that are adequate to reduce the risk of transmission of respiratory viruses and reduce indoor pollution caused by indoor emissions of pollutants.
2. Maintain energy efficiency while implementing adequate ventilation rates.
3. Avoid infiltration of outdoor pollutants caused by ventilation considering two different scenarios:
   a. Pollution hotspots in cities, where outdoor air used for ventilation should be treated to filter PM, UFP and to absorb VOCs, NOx, and depending on the climate of the region, also O_3.
   b. Pollution hotspots of O_3, especially rural areas receiving the impact of the pollution plumes of populated and industrialised areas, where O_3 has a key role if infiltrated in indoor air; thus, absorption of O_3 before ventilation should be implemented, together with PM traps. If high O_3 levels infiltrate indoors, as a powerful oxidant, it reacts with indoor VOCs and might induce high levels of formaldehyde and UFP.
4. Where ventilation is not possible air cleaners using HEPA filters can be implemented.

INDAIRPOLLNET published a guide for ventilation of public spaces that suggests strategies to follow to reduce the transmission of respiratory viruses and the improvement of IAQ that addresses these challenges. Figure 1 summarises this strategy.

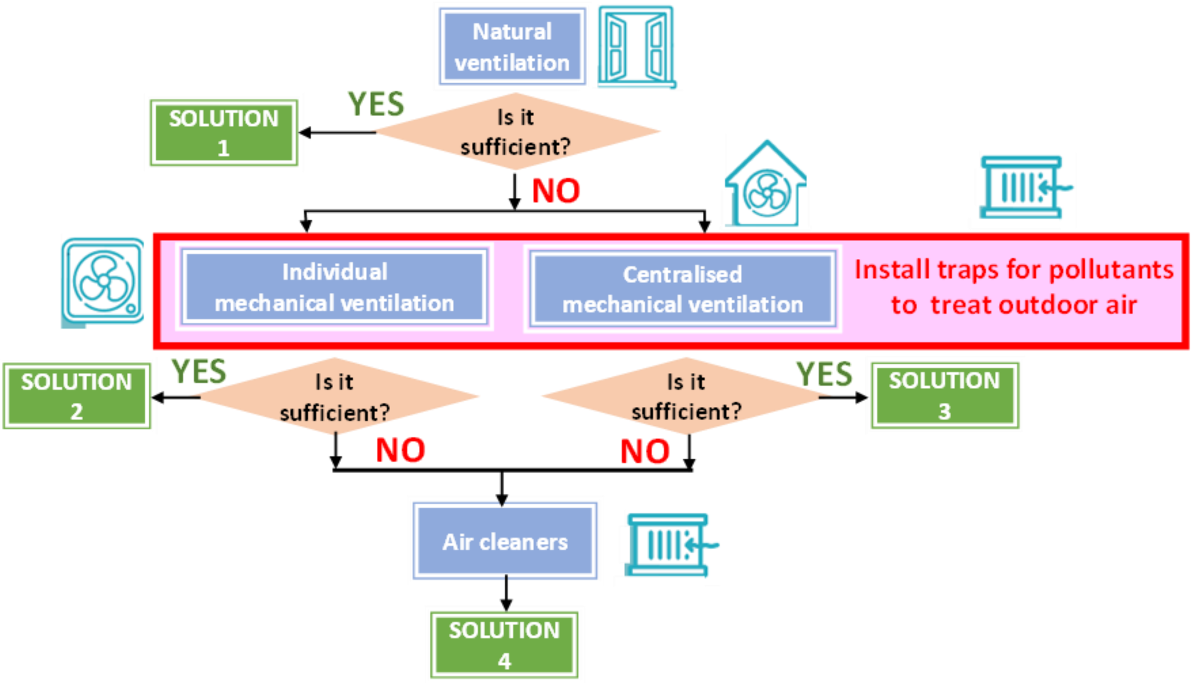

Figure 1. Strategies to improve indoor air quality and reduce the transmission of respiratory pathogens.

Thus the following solutions for ventilation could be adopted:

SOLUTION 1: When possible use natural ventilation, especially cross ventilation (windows and doors open on opposite sides). This reduces energy consumption.

SOLUTION 2: If natural ventilation is insufficient, extra ventilation can generally be achieved using individual exhaust fans or outdoor air supply + exhaust systems with sufficient airflows.

SOLUTION 3: If centralised mechanical ventilation systems are available, outside air supply should be prioritised, recirculation of indoor air should be minimised, and filters in the air recirculation flow should be upgraded to be as efficient as possible. If the building is surrounded by high outdoor pollution, PM, NOx, VOCs and O_3 should be removed from the outdoor air flow used for ventilation.

SOLUTION 4: If none of the above is possible or sufficient, the indoor air must be cleaned with air cleaners equipped with high efficiency (HEPA) filters (or other type of filters with vary high volume exchanges per hour) and traps for pollutants considering the specificities of the area (for example: NOx traps if there is a combustion source).

The final solution can be a combination of options, for example, natural ventilation with additional air cleaning.

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