World Health Organization
REGIONAL OFFICE FOR Europe

Measures to reduce risks for children's health from combined exposure to multiple chemicals in indoor air in public settings for children

with a focus on schools, kindergartens and day-care centres

Supplementary publication
to the screening tool
for assessment of health risks
from combined exposure to
multiple chemicals in indoor air
in public settings for children

Abstract

This publication closes the series of publications on assessment of children's health risks from exposure to multiple chemicals in indoor air in schools, kindergartens and day-care centres. It provides a selection of evidence-informed risk-reduction measures that can be considered for implementation in public settings for children at the local level based on the results of health risk assessments. The publication is intended for public health professionals, teachers, administrators of public settings for children, and other specialists responsible for creating healthy environments in places where children learn and play.

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CONTENTS

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ABBREVIATIONS

CO	carbon monoxide
CO_2	carbon dioxide
DIY	do-it-yourself
EU	European Union
HI	hazard index
HVAC	heating, ventilation and air conditioning
IAQRiskCalculator	indoor air quality risk calculator (a software)
InAirQ	the study *Transnational Adaptation Actions for Integrated Indoor Air Quality Management*
I/O ratio	indoor/outdoor ratio
NO_2	nitrogen dioxide
Oxy-VOCs	oxygenated volatile organic compounds
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter
PODIadj	adjusted point of departure index
ppm	parts per million
PVC	polyvinyl chloride
SINPHONIE	Schools Indoor Pollution and Health Observatory Network in Europe
VOC	volatile organic compound

1. INTRODUCTION

Good indoor air quality is essential for the healthy development of children, and thus the creation of safe and health-promoting indoor environments, with clean air being of the utmost importance. As children spend a large amount of time in public settings, the indoor air quality in these buildings has come into focus.

The indoor air quality in educational settings for children can be influenced by many factors, including the presence of indoor sources of air pollutants, building maintenance practices, outdoor air quality, the infiltration rate of outdoor pollutants, occupancy, and occupant behaviours, etc. A number of studies focusing on the most commonly detected air pollutants in European preschools and schools and their co-occurrence have highlighted a potential relationship between co-occurring multi-pollutant exposures and adverse health outcomes *(1–4)*.

To promote a transition from risk-assessment models based on exposure to individual chemicals to more realistic evaluations considering combined exposures to multiple chemicals co-existing in indoor air, the WHO European Centre for Environment and Health of the WHO Regional Office for Europe developed a screening tool for the assessment of health risks from combined exposure to multiple chemicals in indoor air in public settings for children (IAQRiskCalculator). The screening tool also allows for the identification of chemicals that contribute most substantially to health risks (*5).*

If the risk of co-exposures to chemical pollutants is unacceptable, public health professionals and experts responsible for promoting indoor air quality are expected to consider the implementation of risk-reduction measures. Risk-reduction approaches are well known and, depending on a given situation, vary from measures to reduce outdoor air pollution to responsible design, construction, and maintenance of educational buildings.

For example, in the Schools Indoor Pollution and Health Observatory in Europe (SINPHONIE) project, based on the results of monitoring campaigns carried out in 115 schools in 23 European countries, a wide range of risk-reduction measures were suggested to improve the quality of indoor air in different locations of the school buildings, such as classrooms, laboratories, gymnasiums, lunch rooms and dressing rooms *(6).*

The purpose of this paper, developed as a supplementary publication to the screening tool, is to support decisions on measures for reducing indoor air pollution with chemicals that pose the greatest health risks, and to cut down on or eliminate the sources of these chemicals. It provides a selection of evidence-informed risk-reduction measures that can be considered for implementation in schools, kindergartens and other public settings for children at the local level in response to the results of health risk assessments.

The information on chemical pollutants, their sources and mitigation techniques is continuously growing. The risk-reduction measures summarized in this paper are based on recently published reviews on determinants of indoor air quality and effective measures that can be considered for improving it in public settings for children.

2. MAIN SOURCES OF CHEMICAL POLLUTANTS IN INDOOR AIR IN PUBLIC SETTINGS FOR CHILDREN AND MEASURES TO REDUCE EXPOSURE

A number of airborne pollutants, such as particulate matter (PM), inorganic compounds, volatile and semi-volatile organic compounds (VOCs and semi-VOCs), and aldehydes (oxy-VOCs), can pollute indoor air. VOCs, aldehydes and semi-VOCs are most often found in higher concentrations indoors than outdoors; conversely, some VOCs emitted from transport, residential heating, industry, etc. are present in higher concentrations in outdoor air.

For example, benzene is usually reported to be primarily of outdoor origin (from vehicle exhaust), as there are restrictions on its inclusion in solvents and adhesives for indoor use. Benzene's indoor/outdoor concentration ratio (I/O ratio) has been found to be between 0.5 and 2 in most investigations of indoor air quality in children's settings *(7,8).*

Some studies of indoor air quality revealed that contributions from sources within school classrooms are often even greater than those from outdoor sources *(9).* Some chemicals, such as ethylbenzene, toluene, xylenes and formaldehyde, can originate from both indoor and outdoor sources *(8).*

An I/O ratio greater than 1 shows the presence of an indoor source. A mixture of indoor and outdoor sources can be assumed for an I/O ratio between 1 and 4, and the presence of predominantly indoor sources can be suspected when I/O ratios are higher than 5 *(8).* A significant correlation between indoor and outdoor concentrations suggests a considerable contribution of outdoor sources, while significant differences along with an I/O ratio above 1 indicate contributions mainly from indoor sources.

Several kinds of risk-reduction measures can be put in place to minimize indoor air pollution by chemicals of both indoor and outdoor origins, including:

- legislative (regulating emissions from products, land planning, setting limits and thresholds);
- engineering (establishing construction standards, ventilation techniques, building regulations for ventilation);
- administrative/organizational (regulating density of occupants/number of children per m^2, working hours, duration of breaks, ventilation habits, cleaning customs, number of pupils in a class and organization of breaks).

Generally, no single measure is sufficient in itself for the desired improvement of indoor air quality. A complex approach that includes mitigation measures adapted to local conditions is required.

2.1. Measures to reduce health risks attributable to chemicals mainly from outdoor sources

2.1.1. Sources of outdoor air pollution

Indoor air quality can be strongly influenced by outdoor air pollution. The main outdoor sources of indoor pollutants are heavy-traffic roads, parking lots and petrol stations in the vicinity of buildings; residential heating and power generation; and industrial emissions, waste incineration and agricultural activities, including those within greater distances *(10).*

Besides the proximity of pollutant sources and meteorological conditions, other factors that affect the penetration of outdoor pollutants into buildings include urban form and surrounding buildings; landscapes and green barriers; ventilation techniques and habits; and infiltration rates through cracks and leaks in the building envelope.

Differences have been observed in the concentration of pollutants of outdoor origin in public settings for children located at different levels of a given building due to construction characteristics, distribution of pollutants emitted from road traffic, etc. Furthermore, pollutants have been found in higher concentrations in classrooms facing a street than in those facing a schoolyard or other green area *(11, 12).* Car queuing on school premises also increases concentrations of outdoor pollutants during drop-off and pick-up hours *(13).*

2.1.2. Airborne chemicals originating mainly from outdoor sources

A wide range of air pollutants are emitted from outdoor sources, both natural and anthropogenic. Vehicular traffic is the main source of nitrogen dioxide (NO_2) and has a considerable influence on the ambient concentrations of other air pollutants such as PM, carbon monoxide (CO), benzene, ethylbenzene, toluene, xylenes and polycyclic aromatic hydrocarbons (PAHs). As a consequence, traffic-related emissions influence the indoor air quality in buildings *(9,14–16).*

Solid-fuel burning, including within homes, is still a major issue in many Member States. It can significantly contribute to total emissions of noxious air pollutants, including PM and PAHs, especially in the case of waste burning *(16–20).* Forest fires can also be sources of these pollutants.

A wide range of chemicals can be emitted by industries; the type and intensity of local industrial activities determine the range and the concentration of chemicals released into outdoor air. Besides the pollutants emitted directly by combustion sources (primary pollutants), some chemicals (for example, formaldehyde) are formed in the air (secondary pollutants) through complex processes involving gaseous precursors originating from combustion sources, agriculture, other anthropogenic processes and natural processes such as biogenic emissions *(21).*

2.1.3. Risk-reduction measures targeting chemicals originating from outdoor sources

As outdoor air pollution is an important determinant of indoor air quality, actions must be taken to control the air quality surrounding buildings in line with standards and guidelines *(21,22).* In this context, national and local authorities can decisively intervene at the level of urban planning and controlling emissions from different activities (for example, industrial emissions).

The consideration of proximity to heavy-traffic roads, industrial sites and other major sources of emissions should be mandatory in planning the locations of new public buildings for children, as should specific measures to reduce air pollution around the buildings.

2.1.3.1. Regulation of traffic around buildings

Actions to promote changes in mode of commuting to schools, kindergartens and day-care centres can lead to decreases of air pollution around the buildings. These include prioritizing active travel *(23)*, regulating traffic in drop-off zones, adopting one-way traffic and creating clean air zones around schools, with road closures as a long-term intervention *(24).*

Whenever possible, efforts should be taken to avoid traffic-generating establishments and events in the vicinity of buildings. Vehicular emissions can also be decreased by not allowing school buses or the cars of parents/caregivers to idle. Anti-idling policies as well as relocating drop-off/pick-up points and parking places away from school entrances and windows can be beneficial *(13).*

2.1.3.2. Creation of green areas around buildings

Green infrastructure (areas of trees and shrubs) around buildings may reduce exposure to outdoor air pollutants *(25, 26, 27).* Green barriers between outdoor sources of pollutants and premises for children are also commonly effective for reducing local outdoor air pollution *(13).* Greenness within and surrounding school boundaries and higher numbers of trees around school buildings have been associated with lower concentration of NO_2 and other traffic-related air pollutants and reducing noise level *(28,29).*

Furthermore, greening of schoolyards and surrounding areas is a viable intervention for improving children's socio-emotional status and health via increasing physical activity and willingness to cycle/walk to and from school *(30).* In fact, a recent study demonstrated that the characteristics of the environment surrounding schools, namely the presence of green spaces and species richness, can reduce risks of developing respiratory diseases among school-age children *(31).*

The suitability of plants (tolerance, growth size, species, etc.) should be considered during the design of green barriers. Inappropriately planted trees and shrubs can inhibit the dispersion of pollutants, namely those generated at ground level, and some plant species can release allergenic pollen and biogenic VOCs that can present other risks to health. Small, stiff and complex-leafed plants are more effective, and evergreen species offer the advantage of filtering air throughout the year *(32)*.

In settings for children located within deep street canyons (where the street is flanked by tall buildings on either side), only green walls and low-level shrubs and hedges can be planted. In shallow street canyons (where the buildings on either side of the street are lower), less densely planted small trees may also be considered. In open-road environments, green barriers should be created at the immediate roadside, where leaf coverage runs from the ground to a minimum height of about 2 m (for example, a row of trees above a continuous hedge) *(32).* More complex and less managed green barriers have a higher capacity for air cleaning and climate-regulating ecosystem services *(33,34).*

2.1.3.3. Improvement/optimization of ventilation

In buildings with only natural ventilation, ventilation methods should be optimized to reduce occupants' exposure to outdoor pollutants. For example, classrooms can feature windows that open and close automatically based on sensors that monitor the most harmful outdoor pollutants *(35)*. If such techniques are not available, ventilation habits should be changed according to the expected level of outdoor air pollution.

In buildings located in polluted urban areas, windows should not be opened during rush hours in the mornings or afternoons, or during drop-off and pick-up periods; however, classrooms must be adequately ventilated prior the arrival of students and during each break. A late start (for example, 9:00 a.m.) in schools can alter the timing of ventilation periods so they do not correspond to rush-hour traffic *(36).* Windows facing less polluted areas are preferable for ventilation, taking into consideration local prevailing wind directions if possible.

Ventilation with unfiltered air (that is, natural ventilation or mechanical ventilation with extraction fans only) should only be used in areas with low outdoor air pollution *(37).* When air quality standards are not respected, the use of mechanical ventilation systems with certified filters and air cleaning capabilities is preferable.

In educational premises located in polluted industrial or urban areas, tightening the building envelope and insulating windows together with installing proper heating, ventilation and air conditioning (HVAC) systems can prevent the infiltration of outdoor air pollutants into indoor air. The HVAC systems used for ventilation should be properly designed, maintained and regularly inspected by qualified staff, and should comply with energy-efficiency requirements.

Guidelines for the proper design and operation of ventilation systems should always be respected *(38).* Outdoor air intakes should be located as far as possible from outdoor sources of pollutants such as parking lots, smoking areas, exhaust air effluents and chimneys.

In summary, as a general principle/approach for pollutants mainly of outdoor origin, effective mitigation measures aim at reducing pollution of ambient air surrounding schools and kindergartens, or at minimizing its penetration into indoor environments by, for example, creating green barriers and/or changing ventilation methods, including by filtering inflowing air.

2.2. Measures to reduce the health risk attributable to chemicals mainly from indoor sources

2.2.1. Chemicals originating mainly from indoor sources

A wide range of airborne chemicals can be emitted from multiple sources inside educational buildings due to construction, renovation, operation and maintenance, as well as from materials used for educational purposes and during certain activities.

2.2.1.1. Continuous emissions

The common groups of chemicals in indoor air in educational settings for children are aldehydes, VOCs (aromatic hydrocarbons, esters, terpenes and chlorinated hydrocarbons) and semi-VOCs (brominated flame retardants, PAHs, perfluorinated compounds, phthalates) *(3).* Aldehydes and VOCs are of high concern due to their ubiquitous presence and their significant impact on human health. These compounds are emitted from multiple indoor sources.

The most investigated chemical pollutants that are widely present in school environments and significantly affect children's health are formaldehyde, benzene, ethylbenzene, toluene, xylenes, naphthalene, styrene, limonene and α-pinene. A re-analysis of the data of the Europe-wide SINPHONIE project showed that 29%, 19% and 11% of schoolchildren were co-exposed to elevated concentrations (> median value) to 2, 3 and 4 VOCs known to be harmful for health, respectively *(39).* Most of these compounds are usually found at higher concentrations indoors than outdoors *(40).*

Furniture, floor/wall/ceiling coverings, carpets, curtains and sun blinds, window frames, plastics, resins, glues, and painted or varnished equipment can all continuously release chemicals over a long period of time, from weeks to years. The chemicals emitted by these products and the emission rates depend on the materials applied and other factors. The potential indoor sources of commonly detected chemicals are summarized in Annex 1 (Table A.1).

Most wood-based furnishings and flooring materials are bonded with urea formaldehyde resins, and thus the formaldehyde emissions of newly built products are of concern *(41).* Solid wood and wood-composite furniture coated with paints or varnishes emit formaldehyde and several VOCs, namely styrene, toluene, xylenes, ethylbenzene, dichlorobenzene and benzene *(42).*

Pressed board, plywood and particle-board floorings as well as carpet backings and fabrics may emit formaldehyde and various VOCs. Polyvinyl chloride (PVC)/vinyl flooring may continue to emit aromatic hydrocarbons (toluene, benzene, ethylbenzene, xylenes, styrene, benzaldehyde, 2-ethylhexanol, acetophenone) and semi-VOCs such as phthalates even one year after installation *(31,43).* Besides the emissions of PVC flooring or PVC overlay particle boards on their own, additional emissions can be detected if they are fixed with adhesives and glues *(44,45).* Ceiling tiles can also raise formaldehyde concentrations in classrooms *(46).*

Aldehydes in water-based paints as well as xylenes, 2-butanoxonime and other VOCs in solvent-based paints are considered points of concern. Overall, emissions from solvent-based paints are much higher *(43).* Chemical compounds commonly used as solvents in conventional paints are still contained in so-called green paints, but to a smaller degree *(47).*

2.2.1.2. Intermittent emissions

Indoor activities using paint, glue, do-it-yourself (DIY) or art products, markers, correction fluids, and electronics can increase indoor concentrations of chemicals occasionally, particularly in cases of insufficient ventilation *(48).*

Cleaning activities are among the most important sources of indoor pollutants in children's settings *(8,49).* Cleaning and disinfecting products, as well as air fresheners, usually emit several hazardous chemicals, including terpenes such as limonene and α-pinene *(50)* and formaldehyde. In addition to limonene and α-pinene, cleaning windows with products containing ammonia has been associated with increased concentrations of toluene, butylated hydroxytoluene, butanol, 1-methoxy-2-propanol, nonanal, decanal, phthalic anhydride and phenol *(31).*

The use of cleaning products in the category of waxes and polishes may also increase the concentration of benzene, ethylbenzene, m/p-xylene, tetrachloroethylene and styrene *(31)*. High exposure to terpenes may occur even when products contain essential oils as natural fragrances. Furthermore, oxidants (for example, ozone) may react with terpenes, resulting in secondary pollutants *(51)*. Some cleaning methods (for example, deep cleaning with steam) can also facilitate the emission of chemicals from certain carpets which then accumulate in indoor air when ventilation is insufficient during and after cleaning *(52).*

In schools that reported the use of indoor pesticides (to control rodents, cockroaches and/or ants), significantly higher concentrations of tetrachloroethylene, styrene and hexane were detected compared to those buildings where pesticides were not used *(31).*

2.2.1.3. Other factors influencing the emission or dilution of chemicals

In addition to continuous emissions from materials, an increase in temperature (solar radiation, floor heating, overheating) or humidity can increase emissions. Climate change and associated heat waves and heat-island phenomena in certain urban areas may induce changes in atmospheric conditions that could influence indoor air quality in different ways.

Day-care centres, kindergartens and schools are often also characterized by high occupancy and/or insufficient ventilation *(7,53–55).* Air quality can more rapidly deteriorate in classrooms with a high density of occupants, and inadequate ventilation favours the accumulation of pollutants indoors.

In countries with a cold winter, buildings that rely exclusively on natural ventilation often have high concentrations of indoor pollutants *(55).* In countries with a long hot season, the operation of wall-mounted split air conditioner units can also result in under-ventilated rooms due to keeping windows closed for thermal comfort. In many other cases, windows cannot be opened properly due to security concerns or polluted urban air *(53).* In addition, buildings have become more airtight over the years as thermal insulation has been installed for energy-saving purposes.

Carbon dioxide (CO_2) concentration, which is closely linked with occupancy rate, is commonly used as an indicator of ventilation rate in occupied rooms. Higher concentrations of CO_2 are usually associated with higher concentrations of other indoor pollutants and bioeffluents *(12,56-58).* The Transnational Adaptation Actions for Integrated Indoor Air Quality Management (InAirQ) study, which involved 64 schools throughout central Europe, found that about 80% of the schools could not manage to comply with the recommended CO_2 concentration range of up to 1000 parts per million (ppm) (which represents good air quality) *(7).* The mean CO_2 concentration observed in the schools investigated in the European SINPHONIE project was also over the value of 1000 ppm; notably, it was found to be 1581 ppm *(11,39).*

The European standard EN 16798 1:2019 allows a CO_2 concentration of 550–1350 ppm above outdoor concentration (415 ppm with increasing trend), depending on the building. Some other national ventilation standards (for example, the United Kingdom’s Building Bulletin) *(59)* set a maximum value of 1500 ppm. The CO_2 concentration of up to 1500 ppm can therefore be considered as the acceptable limit for classrooms for moderate indoor air quality, whereas 1000 ppm is appropriate for good indoor air quality *(58).*

2.2.2. Risk-reduction measures targeting chemicals originating mainly from indoor sources

2.2.2.1. Source control

The most effective mitigation measures are those that focus on the elimination of indoor sources of harmful pollutants. Minimizing the use of chemicals leads to reduced pollution and chemical waste, reduced costs and increased safety. This includes measures for using smaller quantities of chemicals (for example, chemicals used in school science laboratories, for ground maintenance and for DIY projects, as well as other products to which intermittent increases in indoor air pollution can be attributed) and replacing them with greener substitutes, if possible. The use of low-emitting products will reduce continuous emissions into indoor air.

Refurbishment: materials and timing

Over the past decades, several certification systems for low-emission materials have been introduced. Various mandatory and state organizations test and certify low-emission materials. For construction, decoration, renovation and furnishing products (for example, vinyl floor and composite wood boards, adhesives, varnishes, paints, synthesized resins, carpets, curtains, shadings), certified and labelled alternatives with no or low emissions of VOCs and semi-VOCs are strongly recommended for use in public settings for children.

Management and staff should be aware of information on emissions prior to purchasing new materials and products, or when accepting material donations for renovation or redecoration. The European Union (EU) Ecolabel covers a wide range of product groups (textiles, coverings, furniture, paints and varnishes, lubricants, cleaning products, etc.), whose manufacturing and use ensures the protection of human health and the environment. More information on the EU Ecolabel can be found on the dedicated website of the European Commission.[1] Several other labelling systems are Blue Angel, AgBB, Nordic Swan, EMICODE, M1, ANSES, Ü-mark, Danish Indoor Climate Label, Byggvarudeklaration, Natureplus, and Umweltzeichen.

Floor, wall and ceiling coverings should be chosen with particular caution due to their large emitting surface. Solvent-free, low-emission adhesives are preferable for both hard and flexible floor/wall/ceiling coverings. Only low-emission wall paints are recommended for use (for example, lime wash, emulsion paints).

In case of refurbishing, even materials with relatively low emissions can release several chemicals that accumulate in indoor air; thus more intensive ventilation is needed for 3–4 months after renovation, redecoration or acquisition of new furniture *(47).* Non-urgent renovations should be allowed only on longer breaks (such as the summer holiday) to permit enough time for chemicals to flush out before occupants return. If possible, indoor air quality checks should be implemented in refurbished schools, with the relevant assessment of chemicals and/or a questionnaire on health symptoms among occupants.

Furniture

Furniture products labelled low-formaldehyde or formaldehyde-free are preferable for use in public settings for children. Coatings and surface coverings should also be labelled low-emission, and unnecessary varnishes and paints should be avoided.

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[1] More information on the EU Ecolabel can be found on the dedicated website of the European Commission. See EU Ecolabel Product Catalogue: http://ec.europa.eu/ecat/.

Cleaning

Improving cleaning routines, replacing products with low-emission cleaning materials, changing cleaning methods, and opening windows during and after cleaning can decrease chemical concentrations *(60).* The period after classes should be considered as the preferential time for conducting major cleaning activities. Avoiding the use of air fresheners or other fragranced cleaning products is strongly recommended.

Equipment

Photocopiers and printers are a source of VOCs, ozone and particles when in operation *(61)*. Placing them in a separate room with proper ventilation can reduce exposure to the emitted pollutants *(28).*

Intermittent activities

Indoor activities, art lessons and/or lessons in science laboratories that involve chemicals should be carefully planned to use only necessary chemicals in small quantities, and to use greener alternatives if possible. It is preferable to install direct-exhaust air extraction in science laboratories, storage rooms, duplicating rooms and kitchens to remove pollutants before they disperse. If this is not possible, increasing ventilation rates during and after the activities are recommended.

2.2.2.2. Temperature and relative humidity control

Several test chamber experiments have proven that controlling the temperature (below 26 °C in summer) and relative humidity (40–55%) can decrease releases of harmful chemicals from materials *(62).* Equipping building facades with external shading devices can prevent solar and conductive heat gains through windows. For the same purpose, external walls can be completely or partially covered with greenery. External living walls (where plants are rooted in the ground) and green facades (where plants are rooted in vertical supports on a wall) have a cooling effect, improve air quality and decrease noise in urban street canyons *(63).*

If such installations are not possible, low-emissivity, heat-reducing window films can prevent heat gain and improve thermal comfort. Energy-efficient lighting and electrical equipment can also prevent internal heat gain. If these passive measures are insufficient in warm climatic zones, low-energy cooling technologies can be applied.

2.2.2.3. Ventilation

Concentrations of chemicals originating from indoor sources usually decrease immediately during ventilation periods as polluted (indoor) air is diluted with outdoor air *(37,54).* Increasing ventilation rates and reducing CO_2 concentrations in classrooms has been shown to increase pupils' performance speed and improve their test performance *(64).*

Natural ventilation strategies

In educational buildings where ventilation mainly consists of manual airing only, concentrations of indoor-generated chemicals continuously increase during occupant activities when windows are closed, and quickly decrease in ventilation periods *(65).* The optimization of natural ventilation is effective for improving indoor air quality. A ventilation strategy in public settings for children should be adapted to current concentrations of outdoor air pollution, thermal conditions and noise.

Wall-mounted split air conditioning units without additional fresh air intake should not be used in naturally ventilated children's settings, or should be used only with the simultaneous operation of CO_2 monitors. Avoidance of crowding is recommended, and rooms should provide space of at least 2 m^2 per child to prevent air stuffiness *(11,66).*

The following list presents natural ventilation strategies for improving indoor air in naturally ventilated public settings for children where outdoor pollution is low, along with additional points on their use.

- Natural ventilation can be increased with automatically opening windows connected to low-cost sensors.
- The installation of CO_2 monitors that feature a visual warning signal when CO_2 concentrations are elevated can be combined with instructions for teachers and students to open windows in response *(67).*
    - These monitors feature indicator lights that continuously show the degree of air stuffiness in the room (for example, orange when ventilation is recommended because of slightly stuffy air; red when windows and doors/windows should be opened immediately because the CO_2 concentration is above the limit of 1500 ppm; and green when doors/windows can be closed to save energy because the CO_2 concentration is low).
    - Although higher CO_2 concentrations are usually associated with the accumulation of other pollutants originating from indoor sources, this system is unable to provide direct information on the concentrations of other indoor pollutants. As such, limiting CO_2 concentration is not always enough to prevent exceedance of guideline values by other pollutants *(56).*
    - If increased concentrations of chemicals are likely (when newly installed furnishings or decorations are present; during art or DIY activities that involve the use of markers, inks, adhesives or paints, etc.), extra ventilation may be needed beyond what is indicated by CO_2 sensors.
    - Likewise, in the case of severe epidemics, the alert limit of sensors should be temporarily set at lower levels (for example, orange when CO_2 concentrations are up to 800 ppm and red when they meet or exceed 1000 ppm) *(68).*
- The ventilation rate can also be increased through the application of mitigation measures by teachers, students and collaborators.
    - Such measures include opening widely all windows on one side and the door on the other side (cross ventilation) before beginning lessons and during each break for a certain period, depending on the temperature difference between outdoor and indoor air; opening windows during and after art/DIY activities, meals and cleaning activities; leaving the door to the inner corridor open in winter; and semi-opening top-hung windows at night in the warm season.

  - Night ventilation strategies not only provide better indoor air quality in the mornings but are an effective passive-cooling method recommended for high-insulated buildings.

♦ Behaviour change among teachers and students can be encouraged through awareness-raising initiatives and educational flyers highlighting the benefits of proper ventilation on health and academic performance, and interactive tools for students to estimate CO_2 concentrations and generate ventilation plans *(55).*

  - Different variations of low-cost measures focused on behaviour change have been implemented in intervention studies *(55,69).* Although they resulted in decreases of CO_2 concentrations in participating classrooms, they were not always sufficient to lower concentrations of all indoor pollutants to below safe limits *(69).*

♦ Natural ventilation can be assisted in the warm season (when the temperature difference between inside and outside may not be great enough to provide adequate air exchange during breaks) by intermittently operating fans *(70),* solar chimneys or wind towers (*71*).

For all of the above strategies, it should be noted that increasing ventilation in areas with polluted ambient air without proper filtration and air cleaning may increase indoor concentrations of pollutants from outdoor sources and thus occupants' exposure to them.

Mechanical ventilation strategies

In cases of building renovations, the installation of a mechanical ventilation system (or hybrid ventilation system) operating on a low-energy setting enables better control of indoor air pollution via increased air exchange, particularly in settings located in polluted urban or industrial areas. Setting the ventilation system to keep the CO_2 concentration below 1200 ppm can increase the removal rate of indoor-generated pollutants *(37).*

The rate of ventilation should be established based on the actual needs and demands of occupants and not only the design parameters – that is, it should be defined and expressed as litre per second per person (l/s/person) or cubic metre per hour per person (m^3/h/person) and meet relevant guidelines and standards *(70).*

The recommended minimum ventilation rate for air quality in spaces polluted by human bioeffluents (CO_2 and water vapour) without emissions from materials is 4 l/s/person (about 15 m^3/h/person) *(38, 70)*. This fresh air supply ensures that the concentration of CO_2 metabolically produced by occupants stays below 1500 ppm, and that relative humidity stays in the normal range. In cases of higher activity rates (for example, moving, exams) or existing indoor pollutant sources, higher ventilation rates are recommended when guidelines for indoor air quality such as the WHO guidelines for indoor air quality are not met *(21)*.

Beyond the fresh air demand for removing human bioeffluents, an additional 0.2–1 l/s/m^2 air supply is needed in buildings with low-emission materials, and 0.8–2 l/s/m^2 in buildings with non-low-emission materials, according to European standard EN 16798 1:2019. Several studies propose ventilation rates higher than the minimum requirements of standards and regulations *(71).* The lowest ventilation rate at which no negative effects were reported in epidemiological studies was found to be about 6–7 l/s/person (about 22–25 m^3/h/person) *(70).*

2.2.2.4. Filtration and other removal techniques

In cases when indoor or outdoor emissions cannot be eliminated immediately, in addition to limiting them as much as possible and improving ventilation, filtration techniques may be regarded as a complementary measure for lowering levels of chemical pollutants in indoor air. As described above, properly operated HVAC systems with adequate filters and air-cleaning capabilities in buildings can remove most pollutants from both outdoor and indoor sources and decrease occupants' exposure *(71).*

In certain cases, filtration with high-performance portable air cleaners also seems to be an effective supplement to source-control and ventilation strategies *(72,73)*. Besides filtering particles, some air cleaners have gas purifier technology. Adsorbent and chemisorbent media air filters can remove certain pollutants without producing secondary emissions, albeit with a finite capacity for adsorption. However, some air cleaners may emit harmful by-products (for example, aldehydes, NO_2, CO and ozone) *(74,75).* In addition, mobile air cleaners can filter the air only in a single room or in a restricted area due to their limited performance *(74,75).* Those with higher fan speeds that could efficiently filter the air of a classroom are usually too large and noisy for educational contexts. As these devices do not provide fresh air but rather circulate the air already in the room, they should not be used in public settings for children without fresh air intake. Their use is therefore not recommended; however, they can be applied as an interim complementary solution in specific cases. In such cases, an effectiveness test under real-room conditions should be obtained from the manufacturer before purchasing the equipment.

To meet energy-saving requirements, energy-efficient means of improving indoor air quality should also be considered. Although indoor plants are known to remove some VOCs, CO_2 and PM, large numbers of plants (10–1000 plants/m^2) would be needed to control indoor air pollution *(76)*. Likewise, indoor green walls of sufficient size (> 5 m^2) with appropriate density of plants and proper lighting could be capable of removing pollutants, but only to a limited extent *(77).*

Further studies are needed to evaluate all of the pros of indoor green walls (improved air quality, positive emotional effects) as well as the cons (mould and increased moisture), and to investigate other alternative biofiltration technologies. In the case of the large-scale installation of plants, special attention should be paid to the prevention of exposure to microorganisms or excessive indoor humidity and mould *(78–80).*

Adsorption and photocatalytic oxidation with paints using catalytic nanomaterials are also new approaches for the removal of VOCs; however, they show low effectivity without airflow to carry pollutants to the reaction site. Furthermore, nanomaterials may also pose a health hazard *(81).* In some studies, paints sold with claims of purifying air were found to be ineffective *(47),* and their application can create a false sense of safety. Consequently, the use of these paints should be carefully considered and potential complications should be taken into account.

In summary, in terms of pollutants mainly of indoor origin, effective mitigation measures aim at reducing releases of pollutants through both source-control strategies and strategies to enhance the dilution/removal of pollutants by ventilation or filter absorption.

3. CASE STUDIES ON INDOOR AIR QUALITY IMPROVEMENTS

Case studies have been carried out to test the efficiency of different measures to improve indoor air quality. Some details of these documented intervention studies are summarized in Table 1.

Table 1. Intervention studies on the improvement of indoor air quality in public settings for children

Location, number of study sites	Interventions	Conclusions	References
Different districts in Switzerland 23 classrooms in the heating season	• Verbal and written instructions • Awareness-raising via a school lesson and an interactive tool for students to estimate required duration of ventilation	• Median CO_2 concentration decreased • Time to reach 1500 ppm increased	Vasella et al., 2021 *(55)*
London, United Kingdom 6 nurseries	• Application of different air filtration systems	• All the air filtration systems were successful in reducing $PM_{2.5}$ concentrations and to a lesser extent NO_2 concentrations	Greater London Authority, 2020 *(82)*
Porto district in Portugal 2 nurseries, 2 preschools and 2 primary schools	• Awareness-raising of impact of ventilation, cleaning products, art materials, etc. on indoor air quality • Promotion of behavioural changes (ventilation and cleaning methods)	• PM mass, CO_2 concentrations decreased; however, measures not always sufficient to decrease concentrations of pollutants to those considered safe for human health • Poor results in case of formaldehyde • CO, NO_2, O_3, total VOCs and radon did not present concerning situations in the studied rooms	Sá et al., 2017 *(69)*
North-eastern United States of America 18 classrooms (9 control, 9 intervention) in 3 urban elementary schools	• Application of a classroom-based commercial air cleaner with high efficiency particulate air (HEPA) filter	• Significant reductions in PM with an aerodynamic diameter of less than 2.5 μ ($PM_{2.5}$) and black carbon concentrations	Jhun et al., 2017 *(83)*

Table 1 cont.

Location, number of study sites	Interventions	Conclusions	References
Ottawa, Canada 2 early-start (8:00 a.m.) classrooms and 2 late-start (9:00 a.m.) classrooms	• Adjustment of HVAC system operation: in the morning 1 hour prior to planned occupancy, then off from beginning of morning rush hour until the systems were required to be operational for occupation of the building (start of the school day)	• Significant decreases in concentrations of traffic-related pollutants (PM, benzene, toluene, ethylbenzene, and m/p-xylene) in late-start classrooms, but not in early-start classrooms.	MacNeil et al., 2016 *(36)*
Copenhagen, Denmark 1 naturally ventilated and 1 mechanically ventilated classroom during the heating season 2 naturally ventilated classrooms (with and without air conditioning) during the cooling season	• Provision of visual feedback with CO_2 sensor	• Reduced CO_2 concentrations as more windows were opened	Wargocki et al., 2015 *(67)*
North-eastern Netherlands 18 classrooms from 17 schools (12 experimental classrooms and 6 control classrooms)	• Use of specially designed and installed mechanical ventilation device	• Significant decreases in CO_2 concentrations in intervention classrooms	Rosbach et al., 2013 *(37)*
Denmark 10 classrooms in 5 schools	• Installation of electrostatic air cleaners in classrooms that were either operated or disabled (blind crossover study)	• Decreased concentration of particles in the classrooms where electrostatic air cleaners were operated • No consistent effects on performance of schoolwork, on children's perception of the classroom environment, on symptom intensity, or on air quality as perceived by the sensory panel	Wargocki et al., 2008 *(84)*
Barcelona, Spain 39 classrooms in 39 schools	• Assessment of greenness within a 50 m buffer around schools with Normalized Difference Vegetation Index derived from RapidEye images	• Higher greenness and higher number of trees within and around the schools associated with lower indoor and outdoor traffic-related pollutants, including NO_2	Dadvand et al., 2015 *(29)*

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ANNEX 1. PRACTICAL MEASURES FOR REDUCING INDOOR CONCENTRATIONS OF CHEMICALS CONTRIBUTING SUBSTANTIALLY TO HEALTH RISKS

The user-friendly IAQRiskCalculator tool was developed by the WHO Regional Office for Europe's European Centre for Environment and Health to assess combined exposures to indoor air pollutants in public settings for children. A tiered approach is applied to the risk calculation in the screening tool as follows:

- Tier 0 – calculates a hazard index (HI) as a sum of hazard quotients; chemicals are not grouped according to their adverse-effects endpoints;
- Tier 1, level 1 – calculates HIs with chemicals grouped according to the five selected adverse effects endpoints;
- Tier 1, level 2 – calculates an adjusted point of departure index (PODIadj) for the selected adverse effects of interest.

In case of a considerable health risk either in Tier 0 or in Tier 1 levels (HI > 1, PODIadj > 1), indoor air quality should be improved. The tool indicates the air pollutant(s) posing the greatest health risks, and thus specific interventions to reduce concentrations of the risk-driven chemical(s) can be selected and applied. Recommended measures for chemicals included in the screening tool are summarized in Table A.1. Potential indoor and major outdoor sources of the chemicals are also listed.

Table A.1. Summary of risk reduction measures for chemicals included in the screening tool

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Formaldehyde	• Furniture and wooden products (for example, pressed board, plywood, particle board, fibreboard furniture, flooring, panelling, doors) • Flooring materials (for example, PVC flooring with adhesive, carpet backings) • DIY products (for example, paints, wallpapers, glues, adhesives, varnishes, lacquers) • Electronic equipment (for example, photocopy machines) • Certain cleaning products and disinfectants • Cosmetics (for example, nail-polish remover) • Other consumer products (for example, new books, magazines) • Human activities (for example, smoking, cooking) • Secondary formation	• Road traffic • Certain industries • Biomass and waste burning • Photochemical reactions	**Indoor sources:** • Choose certified, eco-labelled materials with low VOC emissions for floor/wall/ceiling covering and furniture • If possible, remove high-VOC-emitting material • Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals • Undertake renovations and refurbishments in the first month of the summer holiday • Increase the ventilation rate for 3–4 months following renovations • Ventilate rooms adequately • Use a CO_2 monitor for effective natural ventilation • Place photocopiers and printers in separately ventilated rooms

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Acetaldehyde	• Furniture and wooden products (for example, pressed board, plywood, particle board, fibreboard furniture) • Adhesives, coatings, lubricants, inks • Cosmetics (for example, nail-polish remover) • Electronic equipment (for example, photocopy machines) • Human activities (for example, smoking, cooking) • Secondary formation	• Road traffic • Certain industries • Biomass and waste-burning • Photochemical reactions	**Indoor sources:** • Choose certified, eco-labelled materials with low VOC emissions for floor/wall/ceiling coverings and furniture • If possible, remove high-VOC-emitting materials • Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals • Implement renovations and refurbishments in the first month of the summer holiday • Increase the ventilation rate for 3–4 months following renovations • Ventilate rooms adequately • Use a CO_2 monitor for effective natural ventilation • Place photocopiers and printers in separately ventilated rooms
Benzene	• Wall coverings (for example, solvent-based (water-resistant) wall paints) • Painted or varnished coatings • DIY products (for example, paints, adhesives) • Certain building materials and furniture • Flooring materials (for example, PVC flooring with adhesive, carpet backings) • Human activities (for example, smoking)	• Road traffic • Biomass and waste burning • Certain industries • Petrol station	**Indoor sources:** • Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals • Choose certified, eco-labelled materials with low VOC emissions • Use water-based paints • Open windows when working with chemicals • Use woven or knotted textile carpets instead of synthetic ones **Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less-polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Ethylbenzene	• Painted or varnished coatings • Waxes • DIY products (for example, paints, adhesives) • Flooring materials (for example, carpet backings) • Human activities (for example, smoking)	• Road traffic • Certain industries • Petrol station	**Indoor sources:** • Choose certified, eco-labelled materials with low VOC emissions • Use water-based paints, if needed • Use woven or knotted textile carpets instead of synthetic ones **Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed
Trimethyl-benzene	• Solvents, varnishes • Plastics • Household cleaning products	• Road traffic • Certain industries	**Indoor sources:** • Choose certified, eco-labelled materials with low VOC emissions **Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less-polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Xylenes	• Solvent-based (water-resistant) wall paints • Painted or varnished equipment • DIY products (paints, adhesives) • Flooring materials (for example, PVC floorings with adhesive, carpet backings)	• Road traffic • Certain industries • Petrol stations	**Indoor sources:** • Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals • Choose certified, eco-labelled materials with low VOC emissions • Use water-based paints • Open windows when dealing with chemicals • Use woven or knotted textile carpets instead of synthetic ones **Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less-polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed
Styrene	• Solvent-based (water-resistant) wall paints • DIY products (paints, adhesives) • Flooring materials (for example, PVC floorings with adhesive, carpet backings) • Plastics • Human activities (for example, smoking)	• Road traffic • Certain industries	**Indoor sources:** • Use smaller quantities of or green alternatives to paints, solvents, adhesives • Choose certified, eco-labelled materials with low VOC emission • Use water-based paints • Open windows when working with chemicals • Use woven or knotted textile carpets instead of synthetic ones • Place photocopiers and printers in separately ventilated rooms

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Toluene	• Solvents and solvent-based wall paints • Painted or varnished coatings • DIY products (paints, adhesives) • Flooring materials (for example, PVC floorings with adhesive, carpet backings) • Household cleaning products • Cosmetics (for example, nail lacquers) • Other consumer products (for example, newspapers, new books and magazines)	• Road traffic • Certain industries • Petrol stations	**Indoor sources**: • Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals • Choose certified, eco-labelled materials with low VOC emissions • Use water-based paints • Open windows when working with chemicals • Use woven or knotted textile carpets instead of synthetic ones • Use fragrance-free cleaning materials **Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed
Dichloro-benzene	• Air fresheners • Insect repellents (moth balls) • Painted or varnished coatings		**Indoor sources:** • Do not use air fresheners in rooms • Use green alternatives to moth balls • Choose certified, eco-labelled materials with low VOC emissions
Limonene	• Household cleaning products • Air fresheners • Cosmetics (for example, perfumes) • Insecticides	• Naturally occurring	**Indoor sources**: • Use fragrance-free cleaning materials (for example, those marked with an eco-label) • Use mosquito netting instead of insecticide spray

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
α-pinene	• Household cleaning products • Paint and varnish removers • Insecticides • Furniture and wooden products	• Naturally occurring	**Indoor sources:** • Use fragrance-free cleaning materials (for example, those marked with an eco-label) • Use mosquito netting instead of insecticide spray
Tetrachloro-ethylene	• Dry-cleaned textiles, curtains, carpets • Adhesives • Spot removers, stain removers, wood cleaners		**Indoor sources:** • Use washable textiles for classrooms instead of textiles that require dry-cleaning • Avoid consumer products containing tetrachloroethylene
Trichloro-ethylene	• Wood stain, paint removers • Varnishes, adhesives, lubricants • Certain household cleaning products		**Indoor sources:** • Limit the use of chemical products • Choose certified, eco-labelled materials • Avoid consumer products containing trichloroethylene
n-butyl-acetate	• Painted or varnished coatings • Paints and solvents • Cosmetics (for example, nail lacquers and nail-polish removers)		**Indoor sources:** • Use certified low-VOC-emission materials • Avoid nail varnishing in the building
Naphthalene	• Insect repellents (moth balls) • Paints • Cosmetics (for example, deodorants) • Disinfectants • Resins • Human activities (for example, smoking)	• Road traffic • Fugitive emissions • Industrial emissions (phthalate production)	**Indoor sources**: • Use certified low-VOC-emission products • Use green alternatives to moth balls

Table A.1 cont.

Chemicals	Potential indoor sources	Main outdoor sources	Recommended measures
Benzo(a) pyrene	• Human activities (for example, cooking, smoking) • Paints and adhesives	• Road traffic • Biomass and waste burning • Barbecues	**Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less-polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Take actions to prevent green waste burning and wildfires in surrounding areas • Do not light barbecues or campfires
Nitrogen dioxide	• Gas heaters in the room • Burning candles, incense, mosquito coils	• Road traffic • Industrial emission • Residential gas/oil heating	**Outdoor sources:** • Change ventilation timing (not to correspond with rush hours) • Ventilate through windows facing less polluted areas • Reduce emissions in areas surrounding buildings (for example, with anti-idling policies, changes in drop-off and pick-up zones, road closures, green boundaries) • Install mechanical ventilation with air filtering, if needed

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