Managing IAQ at Multiple Scales: From Urban to Personal Microenvironments

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Abstract

Indoor air quality (IAQ) is vital to human health, comfort, performance, and wellbeing as people typically spend over 80% of their time indoors. The indoor pollutants people are exposed to originate from both indoors and outdoors. In order to devise an energy-efficient and cost-effective approach to improve IAQ, it is necessary to consider strategies across multiple scales—from the outdoor environment around buildings to inside buildings, to rooms, and to the microenvironment around the occupants that directly affect the human exposure and intake of the pollutants. In this chapter, we present a 3-dimensional view of the IAQ engineering: the scales (of environments), the species (of pollutants), and strategies (of IAQ control). The objective is to improve the understanding of and assess the potential and limits of the various source control, ventilation, and air purification strategies across the different scales so that an integrated approach can be developed for managing IAQ. Existing data from previous research on the effectiveness of various IAQ strategies at the different environmental scales are discussed along with an outlook to the future work and challenges.

Keywords

Indoor air quality · IAQ control strategies · Multiscale built environmental systems · Ventilation · Source control · Air purification

Introduction

Motivation and Challenge

Good indoor air quality (IAQ) is vital to human health, comfort, performance and wellbeing for several reasons: (1) people spent vast majority of their time indoors (as high as 80–90%); (2) people's exposure to air pollutants in their lifetime takes place primarily indoors, and this is not only the case for pollutants of indoor origin, but also for some pollutants of outdoor origin; (3) air pollutants found indoors can be odorous, cause irritations to skins, eyes and membranes, respiratory diseases, cardiovascular diseases, and cancer; (4) poor IAQ has been associated with increased sick leaves, significant productivity loss as well as sick building syndrome and building related illnesses; and (5) good IAQ provides a solid foundation for reducing the risk of infectious diseases such as COVID-19 since most IAQ control strategies are also effective for reducing the dose exposure of building occupants to the virus-containing aerosols (Zhang 2020; Shen et al. 2021). Since buildings account for about 40% of the total energy consumed, it is also vitally important to devise energy-efficient and cost-effective IAQ strategies to save energy and minimize the associated carbon emissions in an effort to combat the global climate change. Providing good IAQ while saving energy and reducing carbon emissions remains a significant challenge.

Multi-scale Nature of the Built Environmental System

A built environmental system involves multiple scales in space and time (Fig. 1). Spatially, it ranges from the microenvironment around an occupant, to a cubical, a room, a floor, a whole building, and the building's surrounding airshed. Temporally, its state variables such as temperature, relative humidity and pollutant concentrations vary with time scales ranging from seconds to hours, days, months, seasons, and years depending on the perturbing events and the response times of the environmental scale. Different management and control strategies can be applied at different scales to improve the indoor environmental quality (IEQ including IAQ, thermal comfort, acoustic, lighting and visual quality), energy efficiency, and safety and security of the occupants. As we refine the management and control from a larger scale to a smaller and smaller scale with an occupant-centered approach, it is possible to significantly improve the satisfaction of building occupants from the acceptable level (80%) to near 100% satisfaction level. In this chapter, we focus on strategies for improving IAQ, which alone is affected by a multitude of factors including the media/materials where pollutants reside, the environmental conditions,

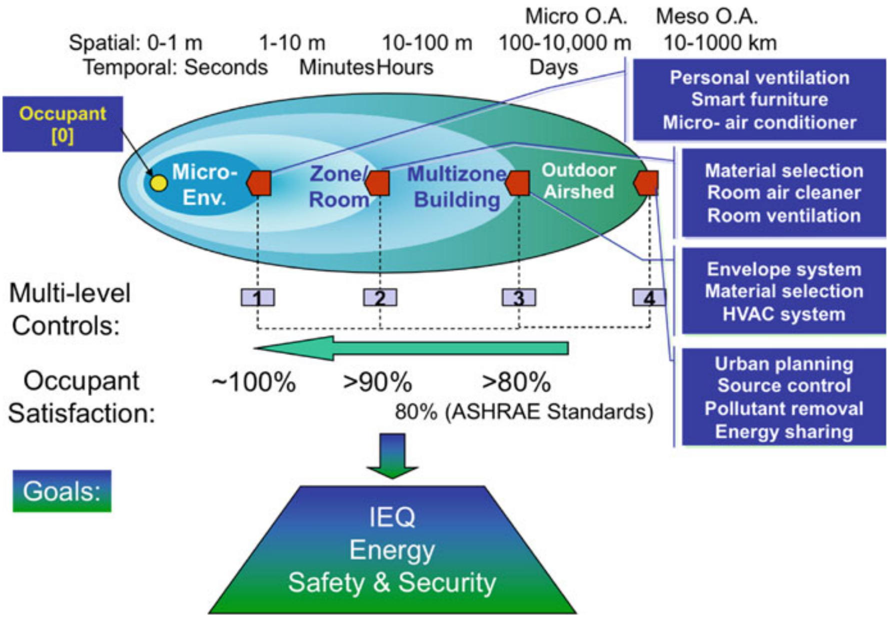


Fig. 1 Managing IEQ and energy of a built environmental system across multiple scales (Zhang 2005)

and the species of pollutants—i.e., the media, environment, and species (MES) in short.

Multitudes of Pollutants Indoors and Their Sources

IAQ is a complex problem largely because it involves many types of pollutants (Fig. 2): (1) inorganic compounds (e.g., CO, CO_2, SO_2, NO_x, and O_3); (2) organic compounds including volatile organic compounds (i.e., VOCs such as formaldehyde, acetaldehyde, benzene, toluene, styrene, 1,4-dichlorobenzene, and 4-phenyl cyclohexene or 4-PC) and semi-volatile organic compounds (i.e., SVOCs such as di-n-butyl phthalate or DnBP, butyl benzyl phthalate or BBP, and di(2-ethylhexyl), Phthalate or DEHP); (3) radioactive gases (e.g., radon); (4) particulate matters (PM10, PM2.5, and ultrafine particles); (5) bioaerosols derived from virus, bacteria, fungi, protozoa, dust mites, and pollen; and (6) Ozone-initiated oxidation products (e.g., methacrolein, methyl vinyl ketone, nitrogen dioxide, acetone, 6-MHO, geranyl acetone, 4-OPA, formaldehyde, nonanal, decanal, 9-oxo-nonanoic acid, azelaic acid, and nonanoic acid). Some indoor pollutants mainly come from indoors (e.g, CO_2, VOCs and SVOCs emitted from building materials and furnishings); some mainly from outdoors (e.g., SO_2 and NO_x); some from both indoors and outdoors (e.g., PM2.5 from outdoor air pollution and indoor emission from occupant activities, and O_3 from outdoor air pollution or due to indoor emissions from printers, copiers and some ionization-based electronic air purifiers); and some from the interaction between the pollutant from the outdoor air and the indoor air and indoor surfaces (e.g., O_3-initiated chemical reaction products). As a result, different source control and removal strategies or technologies are needed for effective reduction of different target pollutants. The effects of the co-existence of multiple pollutants on the

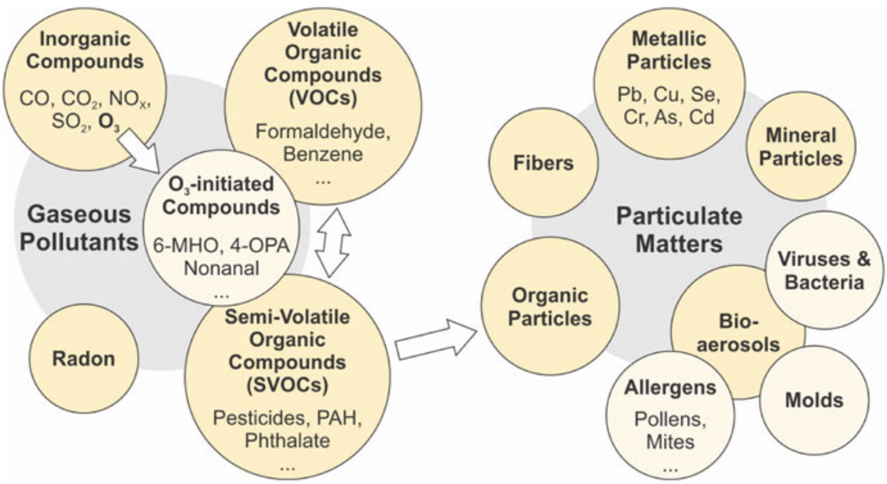


Fig. 2 Classification of indoor pollutants. (Adapted from Abadie and Wargocki 2017)

effectiveness and efficacy of IAQ strategies or technologies should be considered. For example, a particular air purification technology may have very different pollutant removal efficiencies for different gaseous pollutants. Dilution by ventilation is non-discriminative to different gaseous pollutants.

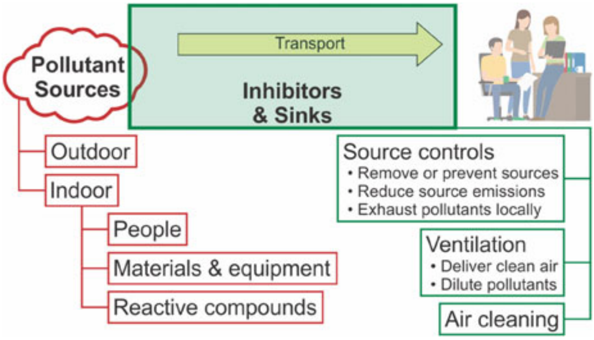
IAQ Control Principles and Strategies

Air pollution takes place when the pollutants emitted from sources transport to the space where occupants reside. IAQ control means providing inhibitors or sinks to reduce the exposure. This can be achieved by various source control, ventilation, or air purification strategies (Fig. 3). Source control is often the most effective approach and should always be considered first. Ventilation is a non-discriminative approach applicable for diluting all types of pollutants in the space. It however has an energy implication as more outdoor air needs to be conditioned to maintain the desired thermal condition in the space. In order to reduce the energy consumption while meeting the IAQ requirements, air purification can be used to remove specific compounds of interests (target compounds) so that the ventilation rate for pollutant dilution can be reduced. In addition, moisture and temperature control and management is also vital for IAQ control, especially for reducing the bio-contamination. For example, the formation and growth of mold heavily relies on prolonged access to favorable moisture and temperature conditions (WHO 2009).

A 3-D View of IAQ Engineering

IAQ engineering can be viewed as a dynamic "3-D" process in which the various management and control ***strategies*** are applied over ***time*** to the different ***spaces*** of different scales to reduce the occupant's exposure to various pollutant ***species*** of health concern (Fig. 4). In this chapter, we focus the discussion on source control, ventilation, and air purification strategies. Hygrothermal control requires the understanding of the water vapor sorption/desorption and moisture retention

Fig. 3 Air pollution process and control strategies



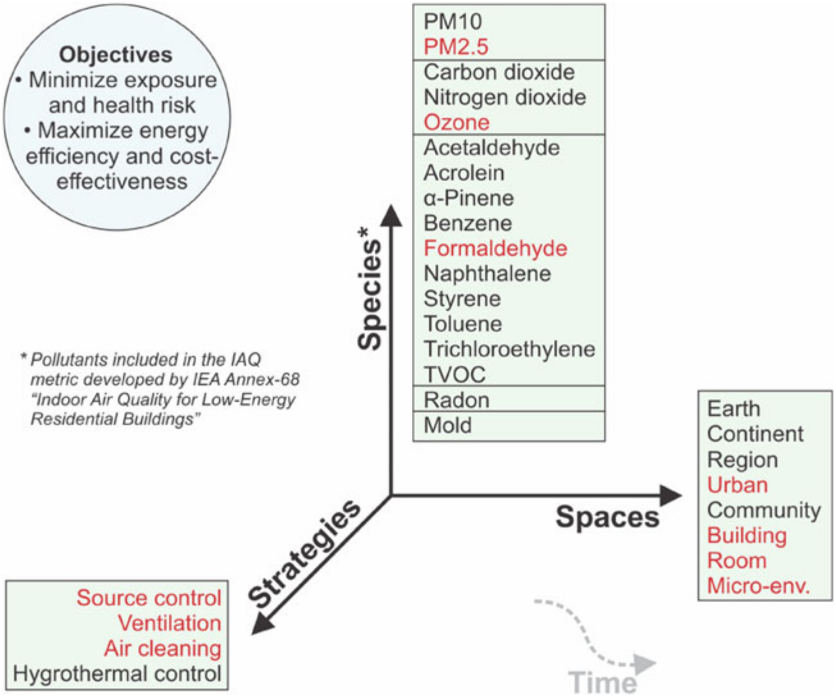


Fig. 4 "3-D" view of indoor air quality engineering

characteristics of various building and indoor materials as well as mechanical systems for humidification and dehumidification, which deserves a dedicated chapter. In the remaining discussion, we make the assumption that space air is maintained within the thermal comfort zone as defined by the ASHRAE standard 55, and the applications of the other three strategies are discussed under such hygrothermal condition unless explicitly stated otherwise. The discussion on the spaces is limited to the microenvironment around the occupant, room, building, community and urban scales with the understanding that the regional, continental and global/earth scales have significant impact on the boundary conditions of urban, community, and building environment (e.g., regional wildfires directly impact the air quality in nearby urban, community and building environment). For the pollutant species, we limit the discussion to a few representative compounds including formaldehyde (a carcinogen and a typical VOC found indoors with a low allowable concentration), PM2.5, and O_3 and SARS CoV-2 as examples to illustrate the 3-D IAQ engineering process. The goal is to understand and quantify the potential and limit of various IAQ control strategies across the different scales of the built environmental system (BES), and discuss how they can be integrated to improve IAQ while saving energy and reducing carbon emissions.

Approach and Model for Assessing the Effectiveness of IAQ Control Strategies

Overview

For the purpose of assessing the effectiveness of various IAQ control strategies, we first consider a simplified multi-scale IAQ model that can account for the interactions between different scale levels as well as between the zones within the same scale level. The model is then further simplified to focus on the effects of IAQ strategies at the different scales on the air quality in the breathing zone of occupants (i.e., in the microenvironment). Pollutant concentrations at a higher scale level are considered as the boundary condition (input) to the immediate lower scale level. A baseline IAQ condition is established based on ASHRAE standard 62.1 and 62.2 considering typical range of building operating conditions for heating, ventilating, and air conditioning of specific building types. Various IAQ strategies and their combinations are then evaluated relative to the baseline conditions. A similar approach has been developed and applied for estimating the effectiveness of various mitigation strategies for reducing the risk of COVID-19 infection in different types of buildings (Shen et al. 2021).

A Simplified Multi-scale IAQ Model

Consider a multiscale built environment system with four nested scales: microenvironment, room, building, and urban air surrounding the building (Fig. 5). Each scale level provides supply air to the level below and returns air to the level above. Each scale level can contain multiple zones, with each having its own sources and sinks. A zone receives a fraction of the total supply air from the upper scale level and returns air to the upper scale level as well as exchanges air with zones in the same scale level (represented by dashed blocks). As a simplified model, we assume that:

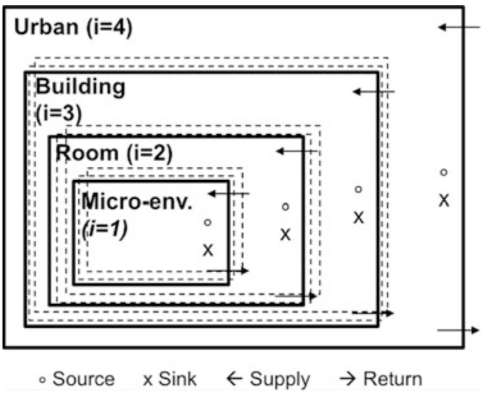


Fig. 5 A simplified model of multiscale pollutant transport in built environmental system (dashed lines indicate multiple zones in the same scale)

1. Air within each zone is perfectly mixed.
2. Exchange between the scale levels take place in an aggregated way. That is, a scale level receives the total airflow rate ($m'_{i+1\leftrightarrow i,\mathrm{sa}}$) from the upper level and distributes them to the zones with the scale according to the fractions required by each zone. The return/exhaust air from each zone is mixed and return to the upper scale level with a total airflow rate and an equivalent concentration of the mixed air ($m'_{i\leftrightarrow i+1,\mathrm{ra}}$).
3. The total airflow rate supplied to and returned from a lower scale level is balanced at all times (i.e., $m'_{i+1\leftrightarrow i,\mathrm{sa}} = m'_{i\leftrightarrow i+1,\mathrm{ra}} = m'_{i+1\leftrightarrow i,a}$).

Under the above assumptions, the mass conservation of pollutant species k in zone j of scale level i can be represented by

$$\frac{\partial}{\partial t}\left(M_{i,j,a}C_{i,j,k}\right) = R'_{i,j,k} - S'_{i,j,k} + \sum_{l(l\neq j)}^{n_i}\left[m'_{l\rightarrow j,k}C_{i,l,k} - m'_{j\rightarrow l,k}C_{i,j,k}\right] + f_{i+1\rightarrow i,j}m'_{i+1\leftrightarrow i,a}\left(C_{i+1,\mathrm{sa},k} - C_{i,j,k}\right) - m'_{i\leftrightarrow i-1,a}\left(C_{i,\mathrm{sa},k} - C_{i-1,\mathrm{ra},k}\right) \tag{1}$$

where,

$C_{i,j,k}$ = mass concentration, kg/(kg of air)
$f_{i+1\rightarrow i,j}$ = fraction of mass flow rate that zone j receives from the adjacent upper scale level
$M_{i,j,a}$ = air mass in zone j of scale level i
m' = mass flow rate of air mixture, kg/s
n_i = number of zones at the scale level i
R' = source's emission rate, kg/s
S' = sink's removal rate, kg/s
Subscripts: i = scale level (i = 1, 2, 3, 4), j = zone number (j = 1, 2, …, n_i), k = species, sa = supply air, ra = return air.

Equation (1) states that the rate of mass change for a pollutant k in zone j of scale level i is balanced by the source and sink rates in the zone, the exchange rate between zones within the same scale level, and the exchange with the upper and lower scale levels.

The source rate is the summation of emissions of pollutant k from all sources in the zone (e.g., formaldehyde emissions from building materials, indoor furniture, and office equipment and releases from O_3-initiated oxidation processes). The sink rate is the summation of the rates of removal of pollutant k from the air by all processes taking place in the zone (e.g., adsorption/deposition on surfaces, removal by air cleaners and chemical reactions). The supply air flow rate along with its pollutant concentration represents the input from the upper scale level. For a building space, it includes the outdoor ventilation rate and the infiltration rate. The return air flow rate and its pollutant concentration represent the aggregated impact of the current scale level on the upper scale level. The microenvironment inside a room is affected by the source and sink strengths and distributions, room and local air distributions, and space partitioning. For a given space configuration, the combined effect can be represented by the *relative room ventilation effectiveness* defined as

$$\eta_{\mathrm{v}} = \frac{C - C_{\mathrm{s}}}{C_{\mu} - C_{\mathrm{s}}} \tag{2}$$

where C, C_{s} and C_{μ} represent the concentrations in the room under perfect mixing condition, room supply air and the air in the microenvironment, respectively. For a perfectly mixed room air, $C_{\mu} = C$, so that $E_{\mathrm{v}} = 1$. For displacement and personal ventilation, $C_{\mu} < C$, so that $E_{\mathrm{v}} > 1$. Note that definition of the E_{v} is different from the conventional definition of ventilation efficiency or contaminant removal effectiveness where C is replaced by the C_{e}, the concentration in the room exhaust air. The pollutant concentration in the microenvironment in a room space can then be determined by first solving the mass conservation for a room zone using Eq. (1) to obtain C under the perfect mixing condition, and then be estimated with Eq. (2).

Considering a single zone/room space with outdoor ventilation rate of Q_{o}, recirculation flow rate of Q_{r}, pollutant filtration efficiency in the recirculated airflow $\varepsilon_{\mathrm{filter}}$, outdoor pollutant concentration C_{o}, pollutant penetration factor P, space volume V, net indoor pollutant emission rate R, and first-order deposition/removal rate constant of the pollutant k_{d}, Eq. (1) can be simplified to Eq. (3) for calculating the indoor pollutant concentration C:

$$\frac{dC}{dt} = \frac{PQ_{\mathrm{o}}}{V} C_{\mathrm{o}} - \frac{Q_{\mathrm{o}}}{V} C - \varepsilon_{\mathrm{filter}} \frac{Q_{\mathrm{r}}}{V} C + \sum \frac{R}{V} + \sum k_{\mathrm{d}} C \tag{3}$$

Definition of Baseline Cases

The specification in the prescriptive procedure for acceptable IAQ in the ASHRAE standard 62.1 and 62.2 can be used to define the baseline ventilation conditions for commercial and residential buildings. The baseline ventilation conditions for several space types of commercial buildings are presented in Table 1 (Shen et al. 2021).

The pollution loads for a baseline case should be specified based on the material/product emission test data, the quantity of materials/products used and occupant activities in the space type of interest. When such data are not available, the emission loads can be specified as the product of the maximum allowable concentrations of target compounds and the specified ventilation rate in the baseline case. The second approach is used here because it can be more universally applied in comparing different studies. The maximum allowable concentrations are defined as the chronic Exposure Limit Values (ELVs) of the reference compounds for quantifying IAQ (Table 2) (Abadie and Wargocki 2017).

Table 1 Configurations of baseline cases. (Adapted from Shen et al. 2021)

Scenario		Space type	Space layout		Occupant status		Minimum ventilation requirement (per ASHRAE 62.1)		
			Area [m^2]	Height [m]	Density [#/100 m^2]	Number [person]	Requirement per person [L/s p]	Requirement per floor area [L/s m^2]	Required ventilation rate [L/s]
Long-term care facility	Nursing home	Bedroom (double resident)	36.8	3.0	/	2	2.5	0.3	16.0
		Dining room	70.0	3.0	/	20	3.8	0.9	139.0
		Living room	50.0	3.0	10	5	2.5	0.3	27.5
		Physical therapy room	23.2	3.0	20	5	5	0.3	32.0
Educational	K-12	Classroom	99.0	4.0	35	35	5	0.6	234.4
		Library	840.1	4.0	10	84	2.5	0.6	714.1
		Cafeteria/dining room	624.0	4.0	100	624	3.8	0.9	2932.8
		Gym	1976.2	8.0	7	138	10	0.9	3158.6
	College	Classroom (small)	51.5	3.0	/	25	5	0.6	155.9
		Classroom (large)	150.0	4.0	/	96	5	0.6	570.0
		Library (public study area)	338.6	6.0	/	96	2.5	0.6	443.2
		Auditorium	1134.0	14.6	/	1500	3.8	0.3	6040.2
		Computer lab	84.3	4.0	/	38	5	0.6	240.6
		Dining hall	573.5	4.0	100	574	3.8	0.9	2697.4
		Study lounge	84.3	4.0	/	21	2.5	0.6	103.1
		Gym (fitness area)	256.0	8.0	/	60	10	0.9	830.4

		Resident hall (bedroom)	21.5	3.0	/	2	2.5	0.3	11.5
		Greek house (social gathering)	50.0	3.0	/	20	2.5	0.3	65.0
Manufacturing facility	Meat plant	Processing room (dense)	434.0	4.0	/	108	5.0	0.9	930.6
		Processing room (sparse)	434.0	4.0	/	27	5.0	0.9	525.6
Retail	Standalone	Core shopping space	1600.4	6.0	15	240	3.8	0.6	1872.2
	Strip mall	Store (large)	348.4	5.2	8	28	3.8	0.3	210.9
		Store (small)	174.2	5.2	8	14	3.8	0.3	105.5
Healthcare facility	Hospital	Operating room	55.7	4.3	/	3	/	/	198.2
		Patient room	20.9	4.3	/	2	/	/	49.6
		Physical therapy room	487.6	4.3	/	26	/	/	186.0
		Dining room	696.5	4.3	/	75	/	/	902.4
		Lobby	1474.3	4.3	/	21	/	/	499.3
Office	Medium	Open plan office	191.9	2.7	5	10	2.5	0.3	82.6
		Enclosed office	42.3	2.7	5	2	2.5	0.3	17.7
		Conference room	43.2	2.7	50	22	2.5	0.3	68.0
		Lounge	89.6	2.7	50	45	2.5	0.6	166.3
Correctional facility	Prison	Housing (double resident cell)	10.0	3.0	/	2	2.5	0.6	11.0

(continued)

Table 1 (continued)

Scenario		Space type	Space layout		Occupant status		Minimum ventilation requirement (per ASHRAE 62.1)		
			Area [m^2]	Height [m]	Density [#/100 m^2]	Number [person]	Requirement per person [L/s p]	Requirement per floor area [L/s m^2]	Required ventilation rate [L/s]
		Housing (dormitory)	160.0	3.0	25	40	2.5	0.6	196.0
		Dayroom	160.0	6.0	30	48	2.5	0.3	168.0
Lodging	Hotel	Guest room/bedroom	39.0	3.0	/	2	2.5	0.3	16.7
		Banquet/dining room	331.7	3.0	70	232	3.8	0.9	1180.1
		Lobby	1308.2	4.0	30	392	3.8	0.3	1882.1
Other public facilities	Restaurant	Dining room (ordinary)	371.7	3.0	70	260	3.8	0.9	1322.5
		Dining room (fast-food)	116.1	3.0	70	81	3.8	0.9	412.3
	Religious	Worship hall	204.0	4.0	/	200	2.5	0.3	561.2
	Casino	Poker room	253.1	4.0	120	304	3.8	0.9	1383.0

Table 2 Exposure limit values (ELVs, chronic effects) of the reference compounds for quantifying IAQ (Abadie and Wargocki 2017)

Compound	ELV[a]
PM10	20
PM2.5	10
Nitrogen dioxide	20
Ozone	100
Acetaldehyde	48
Acrolein	0.35
α-Pinene	200
Benzene	0.2
Formaldehyde	9
Naphthalene	2
Styrene	30
Toluene	250
Trichloroethylene	2
Radon	200
Mold	200

[a]ELV concentration in μg/m^3 except for radon in Bq/m^3 and mold in CFU/m^3. These values are adopted in this study for the purpose of defining the pollution loads in the baseline case

Assessment Procedure

Once the ventilation and pollution load for a baseline case are defined, the simplified multi-scale IAQ model can be used to first calculate the concentrations of the target compounds under the baseline conditions, and then determine the potential and limits of individual and combined strategies in improving the IAQ relative to the baseline case.

Potentials and Limits of Source Control, Ventilation and Air Purification at Different Scales

Urban Scale

The major atmospheric pollutants include particulate matter (PM), ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), which can originate from industry emissions, vehicle exhausts, chemical products, construction dusts, household stove combustions, and the reactions between these compounds and the compounds on material surfaces. Considering the heavy traffic and construction activities in urban areas that generate more pollutant emissions, as well as the high density of buildings that can enhance the accumulation of pollutants in urban areas, the air quality in urban areas, particularly densely populated areas, is likely worse than other areas in the city. Urban air quality can impact the health of people who are directly exposed to the ambient air. Outdoor pollutants may also enter the indoor environments through ventilation or infiltration and affect the indoor air quality. Therefore, managing the air quality on the urban scale can benefit both outdoor and indoor environments and people's health.

Source control One approach to control the urban air quality is to control the emission sources of the concerned pollutants (Fig. 6). Pollutants generated by industry emission, vehicle exhaust, chemical products, construction dust, household stove combustion, and other potential sources should be controlled and limited. High-level air quality and pollutant emission standards/policies need to be developed and strictly implemented by the public agencies. It can promote relevant entities to upgrade their pollutant-producing facilities to reduce emissions to the atmosphere. Tremendous efforts and resources are required for mitigating emissions from various sources, but it has been proven to be effective for improving outdoor air quality. For example, the significant concentration declines in some air pollutants (e.g. SO_2, NO_x, and PM2.5) in China during the past few years is closely correlated with the implementation of the strict policies and actions on air quality, e.g. enhancing and enforcing industrial emission standards, upgrading industrial boilers, phasing out outdated industrial capacity, promoting clean fuels in the residential sector, phasing out small and polluting factories, and strengthening vehicle emission standards (Zhang et al. 2019). Pollutant sources in the urban area

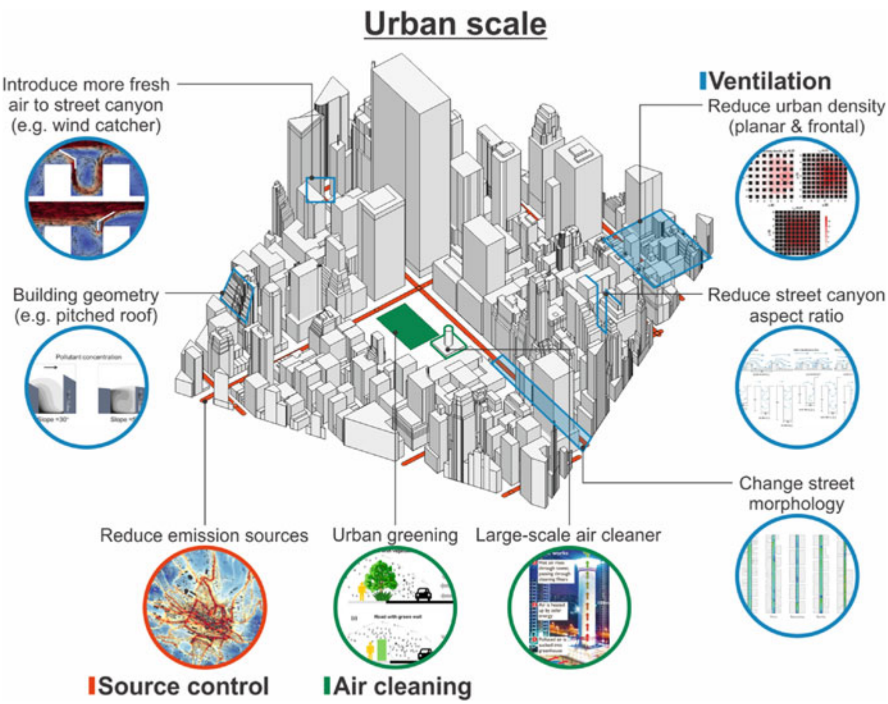


Fig. 6 Schematic of urban-scale air quality control strategies

should be managed to meet or exceed the national ambient air quality standards established by the respective government agencies. For example, in U.S. the ambient air quality standard established by the US Environmental Protection Agency (EPA) has been used as the criteria to determine if the outdoor air is sufficiently clean for ventilation or additional filtration is needed.

Ventilation Urban air quality can also be affected by urban ventilation. Wind from rural and suburban areas is usually believed to be clean and fresh for purging the pollutants emitted by vehicle exhaust and other activities in urban areas. However, the building density in urban areas impacts the urban ventilation. In-street pollutants can be accumulated within the street canyon in high-density compact urban areas due to the poor airflow patterns. Poor ventilation and unfavorable pollutant dispersion in the urban canopy result in poor air quality.

Pollutants generated in the urban canopy layer can be purged by horizontal air exchanges through street openings and vertical air exchanges through street roofs. Urban density, including planar density λ_p and frontal density λ_f (i.e., the ratios of the plan area and frontal area of buildings to the lot area, respectively) are key parameters that can significantly impact the airflow and pollutant dispersion in the urban canopy. Compact urban areas with higher planar and frontal density typically slow down the airflow velocity in the urban canopy, particularly at the pedestrian level. The mean wind velocity at the pedestrian level in urban areas can be decreased by over 35% when increasing the urban planar density from 10 to 35% (Kubota et al. 2008). The decreased wind velocity may reduce the pollutant removal and result in the accumulation of pollutants in the street canyon. It was observed that for a compact city with over 44% planar density, the city itself responses as a single obstacle, and the city breathability is greatly weakened and the pollutants tend to accumulate in the street canyon (Buccolieri et al. 2010). Increasing frontal urban density (i.e. building heights) causes pollutant accumulation in the urban canopy likely due to weaker air exchanges through the urban roof. Poor urban ventilation can be observed in urban areas with a frontal density of over 40% (Mei et al. 2017). Therefore, to improve the ventilation in the urban canopy, urban design with lower planar and frontal density is preferred. Urban heterogeneity, including planar urban non-uniformity and building height variation, can also affect the airflow pattern in the urban canopy. But its effect on urban ventilation is highly dependent on the specific urban morphology (Li et al. 2021a). The non-uniform planar building configuration may weaken the channeling flow inside the street canyon, which was supposed to purge in-street pollutants but can also decrease the vortices behind buildings, which was supposed to cause pollutant accumulation. The non-uniform building height arrangement can enhance the urban ventilation at the high-rise level of the urban canopy due to the improved vertical and horizontal air exchanges but may deteriorate the ventilation at the low-rise level because of more turbulent dissipation at the high-rise level. Thus, it requires professional designs and analyses before performing urban heterogeneity strategies to improve the urban ventilation potential.

The ventilation and pollutant dispersion in the urban canopy are determined by the airflow patterns in the street canyon, which is dependent on both direction and aspect ratio (i.e. the ratio of street height and width, H/W) of the street canyon. When the approaching airflow is parallel to the street, the airflow inside the street canyon can be accelerated due to the channelization effect, which can help to purge the pollutants and improve the street ventilation. A higher aspect ratio may reduce the pollutant removal due to less vertical air exchanges through the street roof, although stronger channeling flow can be observed. Higher street continuity and closure (reduced building setbacks and lateral openings) can lead to a stronger channeling flow, but it reduces the pollutant removal through lateral openings of the street (e.g. intersected streets) and street roofs (Ng and Chau 2014; Shen et al. 2017). When the approaching airflow is perpendicular to the street, the airflow pattern is closely related to the street aspect ratio. If the buildings are well apart ($0.05 < H/W < 0.3$), the airflow fields around buildings do not interact but act as isolated roughness flows. If buildings are too close ($H/W > 0.7$), a skimming flow pattern is formed and a stable vortex is developed within the street canyon, which is not beneficial for removing in-street pollutants (Oke 1988). More vertical vortices are developed inside the street canyon as the street aspect ratio increases, and the wind velocity near the ground becomes weaker, which further deteriorates the air exchanges and pollutant dispersion. Typically, a street canyon with an aspect ratio of 2 (i.e. $H/W = 2$) can form two vertical vortices, and three vortices are formed when the aspect ratio reaches 3 (i.e. $H/W = 3$). In many high-density compact cities, the aspect ratios of street canyons can be higher than 5, so that the ground-level airflow is mostly in calm conditions, and there are very few vertical air changes (He et al. 2019a). Therefore, street orientations are preferred to be designed parallel to the prevailing wind from the perspective of urban ventilation and pollutant dispersion. The aspect ratios of streets are suggested to be lower for improving the vertical air exchanges. The shape of buildings along the street also affects the airflow in the street canyon. For example, sloped/pitched building roofs can improve the pollutant dispersion in the street canyon compared to flat roofs (Li et al. 2021b). Building lift-up design can also improve the local air distribution. The first-floor lift-up design may result in a 34–50% reduction in the building intake fraction and daily pollutant exposure (Sha et al. 2018).

Ventilation in the street canyon can also be enhanced by introducing more wind into the street canyon using technologies such as street wind catchers (Chew et al. 2017), and pedestrian ventilation systems (Mirzaei and Haghighat 2010). More fresh air can be introduced to the pedestrian level through wind pressure or thermal pressure gradient. But the practical effects of these potential technologies still require more studies and validations.

Air cleaning Air cleaning technologies at the urban scale aim to remove urban pollutants through sorption, deposition, or filtration. Urban greenings such as trees, shrubs, and grasslands, as well as green envelopes, play a significant role in mitigating urban pollutants (Nowak et al. 2006). The effectiveness of greenings on air quality improvement depends on the plant species, the configuration of greening infrastructure, and the greening layouts. Trees can mitigate urban pollutants mainly through the deposition of gaseous and particulate matters onto leaf surfaces, and pollutant dispersion by the dilution with clean air. However, trees can also increase the flow resistance and reduce the airflow velocity, which likely results in local pollutant accumulation. Previous studies revealed that trees in the street canyon can result in a nearly 20–58% increase in the average concentration of in-canyon pollutants, owing to the reduced air exchanges between the air above the street roof and within the street canyon (Li et al. 2021b). However, in open areas, trees have a positive impact on air quality. Vegetation barriers with thick, dense, and tall trees can remove considerable pollutants when they are planted closer to the pollutant source and plume's maximum concentration. A reduction of over 50% was observed with a 10 m thick vegetation barrier for numerous pollutants in open roads (Abhijith et al. 2017). Parks with trees and shrubs can remove traffic pollutants at ground level by over 20% compared to the surrounding areas (Yin et al. 2011). Hedges consist of shrubs and usually grow smaller than trees, but they may have higher leaf density than trees. Hedges can also hinder airflow and air exchange, but not as significant as trees. Hedges can generally reduce pollutant concentrations and improve the air quality in both street canyons and open areas. Reduced pollutant exposure by 24–61% at the footpath areas in street canyons with hedges was observed in studies (Abhijith et al. 2017). Besides, green envelopes such as green walls and green roofs have been developed as sustainable building strategies providing benefits for urban environments, which play a significant role in mitigating pollutants in the street canyon without consuming spaces at street level. Pollution mitigation by green envelopes is dominated by deposition, as green envelopes are less likely to change the airflow within the street canyon. Green walls are generally more effective than green roofs for improving in-canyon air quality. However, their ability to remove pollutants is lesser compared to trees and vegetation barriers (Abhijith et al. 2017). In addition to possible air pollution reduction, urban greenings are also beneficial for urban heat island mitigation, potential reduction in energy consumption and noise pollution, better storm water management, urban biodiversity, and climate change mitigation (Abhijith et al. 2017).

Some other approaches for air cleaning at urban/street scale have also been proposed and implemented, e.g. large-scale air cleaning system. Traditionally, air cleaners are designed to clean the indoor air by filtering particles and gaseous pollutants. A large-scale air cleaning system is proposed to purify the urban air with a similar filtration mechanism as indoor air cleaners (Cao et al. 2015; Zhou et al. 2015). A solar-driven large-scale air cleaning system with a 60 m high solar chimney was built and tested in China (Cyranoski 2018). Experiments showed that this system reduced the PM2.5 concentration by 11–19% within a 10 km area around the system. However, its practical effectiveness has been questioned by many researchers, considering its limited effective area and, particularly, its high investment and maintenance costs (Cyranoski 2018).

Building Scale

Outdoor pollutants can be introduced to the indoor environment through building openings and cracks or enter through the HVAC system. Building materials (including construction and surface materials) also produce considerable pollutants, particularly VOCs. Some reactive pollutants (e.g. O_3) readily react with VOCs or building materials, which produce hazardous by-products. As people spend over 80% of their time indoors, properly managing the indoor air quality is essential for people's health, performance, and wellbeing.

Source control Building materials can be a major source of indoor pollutant emissions if not controlled properly. To control the potential sources of indoor pollutants, it is necessary to use the materials with less emissions during building design, construction, and decoration periods. Building materials such as plywood, carpet, and some painting materials can typically generate many VOCs of concern for human health and comfort (Won et al. 2003). Reactions between O_3 and these materials or the VOCs they emitted may also result in considerable oxidized by-product yields, including C1-C13 carbonyls, dicarbonyls, and hydroxycarbonyls (Shen and Gao 2018). Therefore, it is suggested to use materials with less emissions for constructing, flooring, and painting of the building (Fig. 7).

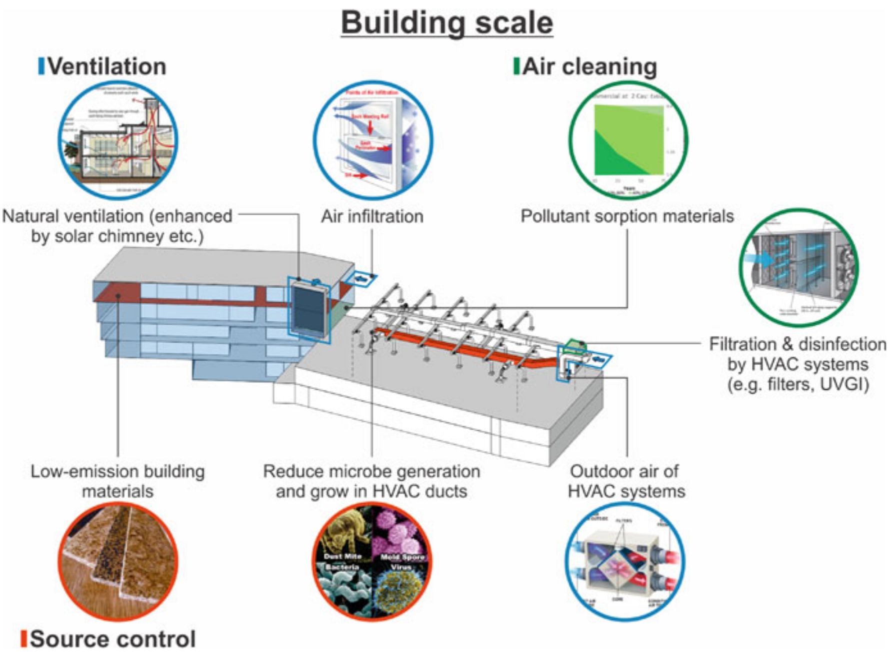


Fig. 7 Schematic of building-scale IAQ control strategies

HVAC system introduces outdoor air to ensure required ventilation of fresh air for occupants indoors. However, outdoor air may contain some pollutants that can be introduced to the indoor environment by the HVAC system. For buildings without significant indoor particle and O_3 emission sources, outdoor air is likely the primary source of indoor particle and O_3 pollution. Therefore, filters that can remove ambient pollutants (particularly the pollutants with considerable concentrations in the outdoor air, e.g. particles and O_3) are required in the HVAC system for controlling the outdoor sources of indoor pollution. Besides, due to poor control of humidity or inadequate maintenance of filters, microbes may generate and grow in the HVAC ducts or on the filters in the presence of moisture, and bioaerosols can be introduced to the indoor environment through the supply air (Batterman and Burge 1995). Elevated concentrations of VOCs such as formaldehyde and acetone may also be observed after the filters of HVAC systems, which are probably initiated from the microbes on filters (Schleibinger and Rüden 1999). Therefore, HVAC systems can also be possible sources of bioaerosols and VOCs in indoor environments. It is necessary to clean and maintain HVAC systems and their filters regularly.

Ventilation Proper ventilation can dilute indoor pollutants and improve indoor air quality. There are multiple standards or guidelines that define the minimum ventilation requirements in different buildings to keep CO_2 levels at an acceptably low level, e.g. 800 ppm or 1000 ppm (ASHRAE 2019a, b; IWBI 2019). Air infiltration though envelope cracks, natural ventilation through building openings, and mechanical ventilation by HVAC systems can contribute to the building air exchanges. Air infiltration is usually unintentional and uncontrolled and can result in heat loss and introduce outdoor pollutants and moisture condensation in building enclosures. It can be responsible for over 10% of the total annual heating and cooling energy consumption while it can even account for more than 40% of heating/cooling load in some scenarios (Han et al. 2015). Therefore, air infiltration should be minimized during construction or retrofitting. Data revealed that the average infiltration rate in buildings is generally below 0.5 h^{-1} (Persily et al. 2010; Shi et al. 2015; Cheng and Li 2018; Ji et al. 2020). Natural ventilation provides air changes by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building. When outdoor weather and air quality conditions allow, natural ventilation can be an effective approach to increase the indoor air changes and pollutant dilution. The effect is determined by factors like opening area, ambient wind direction and velocity, and temperature difference. It was found that more openings can result in the enhanced natural ventilation. Data showed the average air change rate in a residence to change from 0.76 h^{-1} for no openings to 1.51 h^{-1} for one opening, 2.30 h^{-1} for two openings, and 2.75 h^{-1} for three or more openings (Johnson et al. 2004). Besides, opening windows is a more effective method of increasing natural residential ventilation rates compared to the impact of continuously opening doors (Marr et al. 2012). Natural ventilation can introduce more outdoor air to the building incorporating with fans. Some passive technologies have been developed to improve the efficiency of ventilation, e.g. windcatcher and solar chimney. A windcatcher is a unit installed on the roof of the building, which captures outdoor air through its openings and directs it toward the indoor space. It has been widely used in the Middle East to provide natural ventilation and passive cooling inside the building. A well-designed one-sided windcatcher can provide up to 4 h^{-1} ventilation of outdoor air to a dwelling while a configuration with two one-sided windcatchers can provide up to 5.6 h^{-1} ventilation (Jomehzadeh et al. 2020). A solar chimney uses solar energy to generate airflow movements that could be used for building ventilation, and it is usually attached to the south façade of the building to maximize the solar gain. A well-designed solar chimney can typically provide relatively consistent air change rates of about 2–5 h^{-1} on average (He et al. 2021). But the effectiveness of windcatchers and solar chimneys is closely related to the local climate and to their designs. Their effects on building natural ventilation vary significantly case to case. However, natural ventilation also introduces ambient pollutants along with the outdoor air, which is not practical to filter or remove during the natural ventilation.

HVAC system is designed to control the indoor thermal comfort, but it also needs to introduce outdoor air to meet the ventilation requirement for occupants. Based on the ASHRAE 62.1 standard (ASHRAE 2019a), each person in a typical office with 5 persons per 100 m^2 requires approximately 8.5 L/s minimum outdoor air, which accounts for around 0.6 h^{-1} air changes. This requirement is based on the minimum accepted level of indoor CO_2. Higher air change rates are preferred for improving the indoor air quality. The outdoor air fraction of the supply air in the HVAC system is typically 25% (Persily and Gorfain 2004). Increasing the fraction of outdoor air can elevate the ventilation rate but also require more energy for heating/cooling the outdoor air. Increasing the total supply air flow rate can provide more outdoor air but require more energy consumption as well. The extend to which the outdoor air supply can be increased is also limited by the HVAC system capacity. Considering that most HVAC systems have filters installed, the ambient pollutants in the outdoor air are probably not a significant risk for indoor air quality. If the filters in HVAC systems are not well-designed or maintained, the outdoor pollutants become a potential risk.

Air cleaning HVAC systems incorporated with in-duct air cleaning units can significantly improve the indoor air quality in the building scale. Typically, MERV 8 filter and activated carbon filter are installed in the HVAC system. A MERV 8 filter can remove approximately 50% of particles and bioaerosols >0.3 μm in diameter. Higher MERV-rating filters can remove particles more efficiently, e.g. over 99.9% particle removal efficiency for HEPA filter, but also increase the flow resistance, resulting in higher energy consumption for delivering the same amount of air. Overall effectiveness of reducing particle concentrations depends on several factors, including filter efficiency, airflow rate through the filter, size of the particles, and location of the filter in the HVAC system. Activated carbon filters remove odors and some VOCs and can decompose O_3 readily without significant by-product yields. Other common in-duct filtration/disinfection components include UVGI lights (which is typically used for inactivating viruses, bacteria and fungi, but may also have O_3 leakage), and bipolar ionization units (which high voltage electrodes create reactive ions in air that react with airborne contaminants, including viruses, but may emit O_3 as well) (ASHRAE 2020). Some units may intentionally generate O_3 in the duct to react with unsaturated VOCs. But the by-products become a new challenge for indoor air quality and they must be removed before recirculating the air to the room. The effectiveness of these in-duct air cleaning units may vary greatly.

Some building materials can also be considered to be air cleaning technologies due to the effects of sorption and deposition on the building surface. For example, some inorganic materials, e.g. bricks, clay-based plasters, perlite-based ceiling tiles, and activated carbon cloth, are usually considered as the most promising passive removal materials (PRMs) for indoor O_3, since they can remove substantial O_3 while yielding negligible by-products (Gall et al. 2011; Shen and Gao 2018). The use of these PRMs in the building construction/renovation may result in a lower level of O_3 and by-products, hence a better air quality, while they do not consume additional energy for ventilation or air cleaning. In addition, some sorption materials embedded in gypsum wall and ceiling boards have been developed as an effective solution on the market to reduce the formaldehyde concentration levels indoors (Pétigny et al. 2021). A formaldehyde deposition velocity of 2.08 m/h has been tested in commercial buildings and 1.02 m/h in residential settings, with a high level of formaldehyde removal (70–80% reduction in concentration) even after 50 years, which has a high potential for long-term IAQ improvement (Pétigny et al. 2021).

Room Scale

Source control The indoor pollutants in a room not only originate from the construction materials (i.e. constructing, flooring, painting materials), but also from indoor furnishing and equipment, as well as occupants and their activities. Indoor furnishing, equipment, and occupancy depend on the room function and settings. For example, an office has totally different settings of furnishing, equipment, and occupancy as compared to a residential space such as a bedroom. A typical office has multiple workstations (likely cubicles with partitions) with desktop computers, and some office devices such as printers and photocopiers. It may contain several occupants working from 9 am to 5 pm during the weekdays. A typical bedroom can have a bed, a table, and a closet with large areas covered by fabrics. Commonly, there are commonly two people sleeping during the night. Therefore, the potential indoor pollutant sources are in great differences for various spaces. Household furniture may generate considerable VOCs. Workstations or partitions in offices may also release pollutants. Some air cleaning/disinfection devices, e.g. portable UVGI lights and ionization-based air cleaners, and printing devices such as printers and photocopiers may generate abundant O_3 (Guo et al. 2019). Occupant activities like smoking and cooking generate a large number of particles and VOCs, which is hazardous for people's health. In order to control the emission sources, furnishing with less emissions are encouraged (Fig. 8). Emission devices should be used less frequently, in separated rooms or when nobody occupying the room. Smoking should be prohibited in indoor environment, especially when other people are

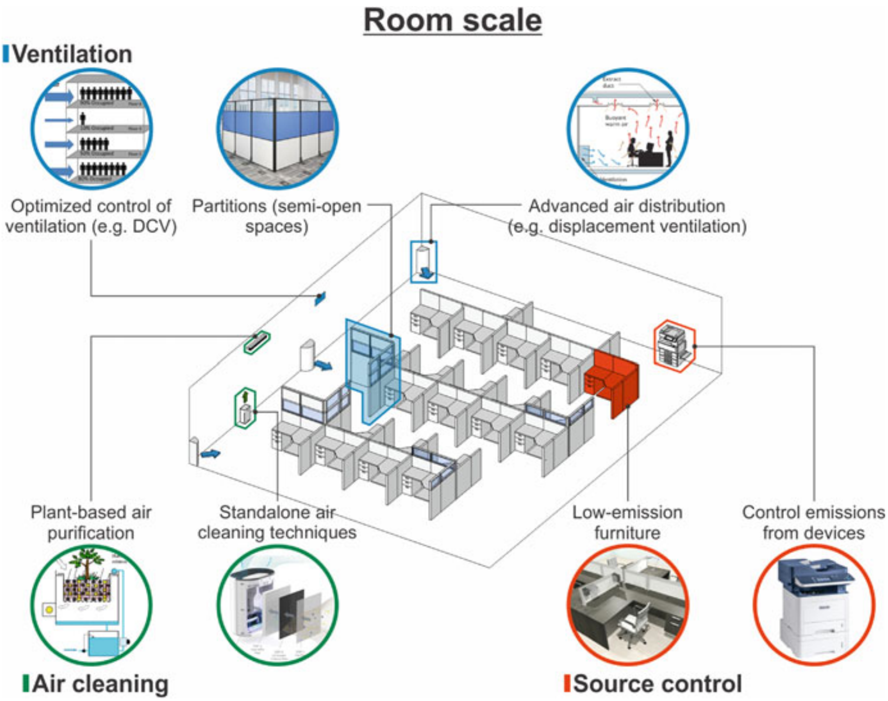


Fig. 8 Schematic of room-scale IAQ control strategies

sharing the same room. Cooking exhaust should be removed immediately and an efficient hood should be used..

Ventilation The design of diffuser and exhaust of the HVAC system can have an impact on the air distribution in the room. The air distribution affects the efficiency of ventilation and pollutant dilution in the room and people's exposure to pollutants. Typical HVAC systems provide mixing ventilation for the room, which is designed to supply sufficient conditioned fresh air to the whole space. The air circulation due to supply and return air can help to mix and dilute the pollutants. It ideally distributes the pollutants from emission sources to the room air uniformly, although the room air may not be perfectly mixed in real conditions. Ideally, the room air pollutant concentration equals the pollutant level in the return air, which is not a very efficient approach for mitigating pollutants and has the possibility of increasing the local pollutant concentration in some areas in the room and resulting in cross contamination. In terms of the control of airborne transmission for respiratory diseases, the mixing ventilation can cause cross contamination between the patients and other healthy people and increase the infection risk for susceptible people in the room.

Therefore, improved air distribution strategies are suggested for improving the ventilation efficiency. Displacement ventilation is a room air distribution strategy where conditioned air is supplied at a low velocity from air supply diffusers located near floor level and extracted above the occupied zone, usually at ceiling height (Chen and Glicksman 2003). Displacement ventilation is typically used for cooling. The near-floor clean air is delivered to the breathing zone by the thermal plume around the human body, which ideally would not result in pollutant mixing in the room and reduce the risk of cross contamination. It can improve the clean air delivery efficiency with a typical ventilation effectiveness of 1.2–2 compared to the well-mixing ventilation (Chen and Glicksman 2003). But displacement ventilation requires professional design and implementation to maximize its performance. Underfloor air distribution (UFAD) system is also widely used in many commercial buildings like offices. Air can be delivered through a variety of supply outlets located at floor level (most common), or as part of the furniture and partitions. It usually exhibits better performance in removing indoor pollutants compared to conventional overhead (ceiling-based) systems. A well-designed UFAD system can provide as much IAQ efficiency improvement as a displacement ventilation system (Cermak and Melikov 2016). However, both displacement ventilation system and UFAD system are often claimed to bring contaminants at floor level to the breathing zone, resulting in an equivalent removal efficiency for floor pollutants as a mixing ventilation system (Cermak and Melikov 2016). For example, resuspended particles at the floor level can cause problems in an UFAD system (Zhang and Chen 2006). But both of them are highly effective in removing exhaled pollutants and reducing cross-contamination (Cermak and Melikov 2016).

The room air distribution can also be affected by the furnishing and partitions in the room, which may block the air flow. Partition screens have been widely used during the COVID-19 pandemic since they can ideally reduce the transmission of droplets. In terms of the transmission of airborne pollutants (including viruses), well-designed partitions can reduce the risk of cross contamination while poor designs may increase the risk in some locations (Rooney et al. 2021). Cubical workstations in open office plan settings are a common scenario with many partitions. The partitions can typically reduce cross contamination between cubicles with a typical ventilation effectiveness of 1.1–3.6 (require well-designed ventilation and air distribution) (Haghighat et al. 1996). When partitions are incorporated with other strategies such as displacement ventilation, the ventilation efficiency can be even higher (Halvoňová and Melikov 2010). But all these strategies require professional design of partition layouts in coordination with room air distribution and proper operation control to maximize their effectiveness. Poor design can lead to a worse performance than the conventional mixing ventilation.

The advanced/intelligent control of ventilation system also has the potential in improving IAQ and energy efficiency. Demand control ventilation (DCV) system estimates the occupant number in the room based on CO_2 detection or occupant detection, and then signals the system controller to change the ventilation volume, which is mainly designed for reducing energy consumed by heating/cooling outdoor air when less people occupying the room. But it also works for providing sufficient/required clean air to all occupants in the room when more people enter the room (within the system capacity). Some advanced control algorithms have been developed to optimize the effectiveness of DCV system, including PID control, model predictive control (MPC), or data-driven control. As an example, the application of machine-learning-based CO_2 concentration prediction in DCV can reduce the HVAC energy consumption by 51.4% and provide ventilation as needed (Taheri and Razban 2021). The optimization of ventilation system control has been proved to have a high potential for IAQ improvement and energy efficiency.

Air cleaning Standalone air cleaning technologies can usually work efficiently for indoor pollutant removal. They have been widely used in indoor environments, which can typically improve IAQ through catalytic oxidation, filtration, ozone oxidation, plasma, sorption, or UVGI. Most catalytic oxidation air cleaning studies focus on UV or visible light photocatalytic oxidation (PCO). UVPCO technology has the potential to degrade organic contaminants efficiently with low airflow resistance (Chen et al. 2005). But it is not yet ready to be applied in practice due to potential byproduct formation and short service life. Other PCO technologies currently have low efficiency in pollutant removal (Zhang et al. 2011). Filtration is the most used technology in air cleaners. Particles can be filtered readily using high-efficiency filters such as HEPA filters (over 99.9% removal efficiency). Other filters such as activated carbon filter can remove some VOCs and O_3. In general, mechanical filters can efficiently remove particles, but are not as effective for organic and inorganic chemical pollutants. The main problem with mechanical filters is that they act as a pollution source if they are not properly used (Zhang et al. 2011). Therefore, filters are usually recommended to be replaced every 6–12 months. Ozone is an oxidant that can react with some indoor pollutants, and therefore, has been used in some air cleaners for oxidizing some organic chemical pollutants and disinfection. However, considering that ozone and ozone-initiated by-products are quite harmful for people, caution should be taken when using ozone-emitting air cleaning techniques. Plasma air cleaners have been reported to remove particles at high efficiency, e.g., within the range of 76–99% (Zhang et al. 2011). But it is not efficient at removing gas-phase pollutants. The production of secondary pollutants such as NO_x and O_3 is a major drawback of plasma technology. Sorption is good for gas pollutant removal (such as VOCs and O_3), while its efficiency depends on sorption mechanism, specific sorbent surface area, porosity, and diffusion characteristics of target pollutants. UVGI technique in standalone air cleaners is typically used for disinfection (e.g. inactivating viruses, bacteria, and fungi). Upper-room UVGI system has been developed to kill airborne pathogens, which refers to a disinfection zone located above people (the upper area of the room) preventing direct UV exposures to people. Proper use of upper-room UVGI system can typically provide an equivalent 6.7–33 ACH ventilation to the room, depending on its operating conditions and circumstance (Riley and Nardell 1989; Xu et al. 2003; U.S. CDC and NIOSH 2009). Its efficiency also relies on the room air distribution. For example, displacement ventilation may reduce the efficiency (around 78% of the efficiency incorporating with mixing ventilation (Kanaan and Abou Moughlbay 2018)) as it decreases the residence time of pathogens in the disinfection zone. Some UVGI systems may produce unintended O_3, which also need certain caution.

The combined application of multiple air cleaning technologies in standalone air cleaners typically has elevated efficiency. For example, the combination of plasma and UV-catalytic technology can provide improved removal efficiencies for formaldehyde, benzene, toluene, and xylene (Zhang et al. 2011). According to a market survey, a common room air cleaner can typically supply a median clean air delivery rate (CADR) of 361 m^3/h to the room (Zhao et al. 2020). The CADR per square meter of room is roughly between 6 and 16 m^3/h (Liu et al. 2017). The Association of Home Appliance Manufacturers (AHAM) recommended a minimum CADR of 12 m^3/h per square meter when selecting an air cleaner for home use (AHAM 2021), which is in accordance with the U.S. EPA's guide (U.S. EPA 2018).

Potted plants have demonstrated abilities to remove VOCs indoors. However, the efficiency may not be very significant in real scenarios. The distribution of single-plant CADR spanned orders of magnitude, with a median of 0.023 m^3/h, necessitating the placement of 10–1000 plants/m^2 of a building's floor space for the combined VOC-removing ability by potted plants to achieve the same removal rate that outdoor-to-indoor air exchange already provides in typical buildings (~1 ACH) (Cummings and Waring 2019). It is impractical to directly use potted plants for improving IAQ. One solution might be to integrate plants and mechanical air cleaning or ventilation system. Dynamic botanical air filtration (DBAF) system is therefore developed. It consists of an activated-carbon/hydroculture-based root bed for potted-plant, a fan for driving air through the root bed for purification, and an irrigation system for maintaining proper moisture content in the root bed. A well-designed DBAF system is effective for removing formaldehyde and toluene over a long period, and has the ability to supply an equivalent CADR of 476 m^3/h (Wang and Zhang 2011).

Personal Microenvironments

Pollutant concentration and air quality in personal microenvironments, such as the space around a person or the breathing zone, are closely associated with people's exposure to air pollutants and health. A personalized environmental control system or micro-environmental control system has the potential to restore people's thermal comfort as well as provide fresh outdoor air to the people directly and hence save energy (Khalifa 2017; Kong 2017).

Source reduction Human body can produce considerable particles and VOCs through primary emission due to respiratory activities or sweating (Žitnik et al. 2016; Shen et al. 2021), or secondary emission caused by the reactions between O_3 and skin oil (Shen and Gao 2018). The average emission rate of total VOC (TVOC) from the whole-body was 742.8 μg/h, while the average TVOC emission rate from the breath samples was 41.4 μg/h (He et al. 2019b). People's movement can raise the floor dust and resuspend particles in the air. The thermal plume around the human body may introduce some pollutant-like particles from the floor level to the breathing zone and increase people's inhalation. Personalized/localized air exhaust aims to remove as much contaminants as possible directly from the occupants who produce pollutants before it can significantly mix with the bulk flow (Dygert and Dang 2010).

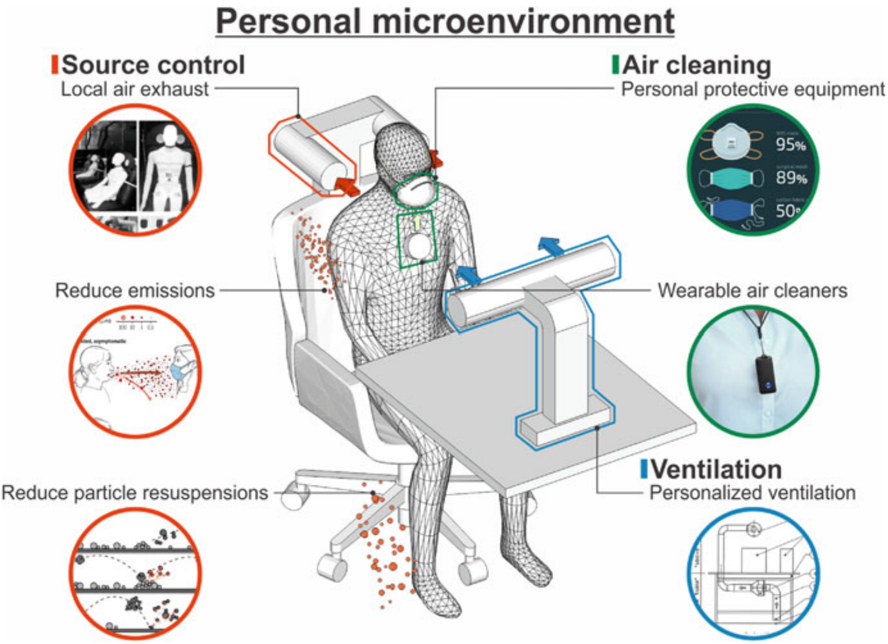


Fig. 9 Schematic of personal-scaled IAQ control strategies

The pollutant removal process is accomplished using localized suction orifices near and around the source occupant to unobtrusively ingest the individual's thermal plume and filter it or exhaust it from the occupied space. A well-designed local air exhaust system can reduce the cross-contamination with typical ventilation effectiveness of 1.4–10 (Dygert and Dang 2012). Source control can be performed in personal microenvironments by reducing the near-person emissions and chemical reactions or particle resuspension (Fig. 9).

Ventilation Personal ventilation increases clean air supply to the personal microenvironment and has the potential to improve the air quality by a typical factor of 1.7, depending on diffuser location and airflow rate (Melikov et al. 2007), which is close to the air distribution effectiveness in ASHRAE Standard 62.1 (ASHRAE 2019a). Local air exhaust ventilation is designed to remove the pollutants near the emission sources, which is usually used to reduce the exhaled pollutants by occupants and mitigate the cross contamination between occupants. It can reduce the cross contamination with a typical ventilation effectiveness of 1.4–10, depending on the local partition configuration, exhaust location and airflow rate (Dygert and Dang 2012).

Air cleaning There are some air cleaning technologies for personal microenvironment. Wearable air cleaner is a technique similar to portable room air cleaner but can directly deliver filtered/clean air to the breathing zone. It can provide corresponding mass removal rates of PM 2.5 between approximately 0.5–5.4 h^{-1}. But some models with ionization units may produce a number of O_3 (up to 670 μg/h), which need to be considered in practice.

A low-cost air cleaning technique that protects the breathing zone is wearing masks, which can efficiently filter the inhaled air and remove particles. A cloth mask can provide an overall 30% particle filtration efficiency considering leakage from gaps caused by improper fir (Konda et al. 2020), while a surgical mask has an overall 50% particle removal efficiency and a N95 mask can provide over 95% particle reduction (Rothamer et al. 2020; Konda et al. 2020). Conventional masks can only remove particles through filtration, but some novel masks (e.g. with activated carbon cloth) can also remove reactive gaseous compounds (e.g. O_3) and/or some VOCs. Masks are also very useful for mitigating infection risk of respiratory diseases through airborne transmission, which has been highly recommended since the COVID-19 pandemic (Shen et al. 2021).

Integration of IAQ Strategies

To demonstrate the analysis for the potential of source control, ventilation, and air cleaning strategies at different scales, the standard open plan office environment (ANSI/BIFMA M7.1) presented in ► Chap. 1 "Testing and reducing VOC emissions from building materials and furniture to improve indoor air quality" of this book section (Testing and reducing VOC emissions from building materials and furniture to improve indoor air quality) is adopted to define the example case. An open plan office with ten workstations (ten occupants) is defined based on the information in Chap. 1. The space configuration parameters of the reference office are shown in Table 3. The total floor area is 59.5 m^2 since the standard floor area per workstation with common area is 5.95 m^2 and there is an assumption ofe ten workstations in the reference case. Four typical indoor pollutants are simulated to study the indoor air quality of the reference office, including PM 2.5, O_3, formaldehyde, and virus-laden aerosols (considering the serious situation of pandemic). The average pollutant concentrations of PM2.5, O_3, formaldehyde, and infectious aerosols in outdoor air

Table 3 Configuration parameters of the reference open plan office (per ANSI/BIFMA M7.1)

Parameter	Open plan office
Room information	
Total floor area (m^2)	59.5 (5.95 × 10)
Room height (m)	2.7
Room volume (m^3)	162.8
Total wall area (m^2)	93.5
Workstation/occupant number (#)	10
Workstation components	
Total panel vertical area (m^2)	110.8 (11.08 × 10)
Total work surface horizontal area (m^2)	61.0 (6.10 × 10)
Total storage external surface area (m^2)	45.7 (4.57 × 10)

in the U.S. are 8 μg/m^3, 135 μg/m^3 7.2 μg/m^3, and 0 quanta/m^3, respectively (WHO 2010; U.S. EPA 2021a, b; Chirizzi et al. 2021). The infiltration rate for the reference office case is assumed to be 0.2 h^{-1}. The penetration factor for O_3 and formaldehyde through building envelope is typically 1, while the penetration factor for particles is assumed to be 0.9 (Chen and Zhao 2011). The indoor emission source of PM 2.5 is assumed to be 600 μg/h per occupant (due to generation or resuspension through occupant activities) (Qian et al. 2014), while no significant O_3 source exists in the reference case. For infection risk analysis, only one infector is assumed to be in the office, which can exhale 58 infectious quanta of virus-laden particles (one quantum in the inhalation risk estimation model represents an infectious dose that would infect 63% of the population with the exposure) (Shen et al. 2021). Formaldehyde is released from building materials (Salthammer 2019) and workstation components (Carter and Zhang 2007), as well as through the oxidation reactions between O_3 and building materials (Gall et al. 2013), workstation components, and occupant surfaces (e.g. skin or clothes) (Rai et al. 2014). The reactions between the chemicals on these surfaces and O_3 can remove considerable O_3 due to irreversible oxidation, resulting in O_3 deposition on surfaces (Di et al. 2016; Shen and Gao 2018), and yield secondary by-product emissions, which can be quantified by the molar yield factor (Gall et al. 2013; Rai et al. 2014). The O_3 deposition and formaldehyde production by different materials are illustrated in Table 4, which are from the literature data (Carter and Zhang 2007; Gall et al. 2013; Rai et al. 2014; Di et al. 2016; Shen and Gao 2018; Salthammer 2019). The particle deposition relies on an approximate

Table 4 Ozone deposition and formaldehyde production by different materials

	Ozone deposition factor	Formaldehyde emission factor	
	Deposition velocity, v_d (m/h)	Primary emission rate (μg/m^2 h)	Secondary molar yield factor (ozone oxidation reactions)(−)
Room surfaces			
Floor (carpet)	3.4	3.9	0.01
Wall (painted drywall)	1.4	2.3	0.01
Ceiling (painted drywall)	1.4	2.3	0.01
Workstation components			
Panel	1.5	50	0.01
Work surface	0.2	15	0.01
Storage	0.2	0	0.01
Occupant surfaces			
Occupant Skin/Clothes	10.8	0	0.02

estimate of gravitational settling (Nicas et al. 2005), while the deposition of formaldehyde is not considered. The inactivation rate of the virus-laden particles is defined based on the data for SARS-CoV-2 (i.e. 0.63 h^{-1}) (van Doremalen et al. 2020). The pulmonary rate for occupants is 0.3 m^3/h, while the exposure time is 8 h (U.S. EPA 2011). The ventilation rate of outdoor air provided through the HVAC system is defined to be 0.9 h^{-1} based on the ANSI/BIFMA M7.1 standard (Carter and Zhang 2007). Considering that the average outdoor air fraction for building ventilation system is around 25% (Persily and Gorfain 2004), the total supply airflow rate of the HVAC system in this simulation is 3.6 h^{-1}. A MERV 8 filter is included in the HVAC duct, which can remove approximately 20% of PM2.5 particles and 50% of infectious particles (Shen et al. 2021). Mixing ventilation is used in the reference case (ventilation effectiveness = 1).

The simulation through the simplified multiscale pollutant transport model (Eq. 3) revealed that the steady-state concentrations in the breathing zone for the reference open plan office case are 23.1 μg/m^3, 25.2 μg/m^3, 48.1 μg/m^3, and 0.1 quanta/m^3 for PM 2.5, O_3, formaldehyde (HCHO), and infectious aerosols, respectively. The infection risk for the susceptible occupants is 20.4%, which is estimated by the inhaled dose of infectious quanta through the Wells-Riley model (Shen et al. 2021). Several selected IAQ control strategies at different scales are applied in the reference office case (Table 5). The effectiveness of each strategy is analyzed comparing to the IAQ metrics of the reference case (reduction percentage).

Reducing ambient pollutant concentrations by 50% can improve indoor PM 2.5, O_3, and formaldehyde concentrations by 8.2%, 50.0%, and 8.9%, respectively. But it does not impact the indoor infection probability due to the exposure to viral particles exhaled by the infector. Using green building materials (ceiling, wall, and floor materials) with 50% less primary and secondary formaldehyde emissions can reduce the formaldehyde concentration by around 4%, while using green furniture (workstations) can reduce formaldehyde exposure by 37.8%. Improving building ventilation by using 100% outdoor air improve indoor PM 2.5 level by 34.6%, formaldehyde level by 59.3%, and infection risk by 24.0%, but also increase the indoor O_3 concentration since it is mainly from the ambient air and there is no O_3 filtration for the HVAC system. Increasing building airtightness (reducing building air infiltration) can reduce indoor O_3 (by 11.5%) but increase other indoor pollutants. Natural ventilation that provides 0.5 h^{-1} more indoor ventilation also introduces more O_3 indoors (by 34.1%) while it reduces concentrations of other pollutants of indoor origin. Upgrading HVAC system filter to HEPA filter at the building scale can reduce indoor PM2.5 level by over 59% and infection probability by 24% but has no effects on improving indoor O_3 and formaldehyde levels. It has a high potential for reducing indoor particle exposure and infection risk. Using additional activated carbon filter in the HVAC system that has 80% efficiency on O_3 reduction has a high potential on decreasing indoor O_3 exposure, which has a 74.6% O_3 reduction and 2.3% formaldehyde reduction due to reduced secondary emission. Replacing wall and ceiling materials by depolluting materials that can absorb formaldehyde with a deposition velocity of 2.08 m/h can greatly improve the indoor formaldehyde level (by 93.1%), indicating a high potential for indoor formaldehyde improvement.

Table 5 Effectiveness of selected IAQ control strategies in the reference office case

Scale	Category	Strategy	Description	IAQ metrics				Effectiveness on IAQ improvement			
				PM2.5 (μg/m^3)	O_3 (μg/m^3)	HCHO (μg/m^3)	Infection probability (%)	PM2.5 (%)	O_3 (%)	HCHO (%)	Infection (%)
Outdoor air				8.0	135.0	7.2	0				
Reference open plan office				23.1	25.2	48.1	20.4				
Urban	Source control	Reducing emissions	50% reduced ambient pollutant level	21.2	12.6	43.8	20.4	8.2	50.0	8.9	0
	Ventilation	Higher ventilation	20% reduced ambient pollutant level	22.4	20.2	46.3	20.4	3.0	19.8	3.7	0
	Air cleaning	Urban greenings	10% reduced ambient pollutant level	22.8	22.7	47.2	20.4	1.3	9.9	1.9	0
Building	Source control	Low-emission building materials	50% less primary and secondary formaldehyde emissions	23.1	25.2	46.1	20.4	0	0	4.2	0
	Ventilation	Higher ventilation	20% more total supply airflow rate of HVAC system	20.6	28.5	42.5	18.5	10.8	−13.1	11.6	9.3
			50% outdoor air fraction of HVAC	19.0	39.7	30.1	18.5	17.7	−57.5	37.4	9.3

			100% outdoor air fraction of HVAC	15.1	59.7	19.6	15.5	34.6	−136.9	59.3	24.0
		Higher airtightness	Reduced air infiltration (0.05 h^{-1})	24.5	22.3	54.3	21.2	−6.1	11.5	−12.9	−3.9
		Natural ventilation	0.5 h^{-1} more ventilation	19.8	33.8	35.6	18.3	14.3	−34.1	26.0	10.3
	Air cleaning	Upgrading filter of HVAC system	Using MERV 13 filter	10.3	25.2	48.1	18.6	55.4	0	0	8.8
			Using HEPA filter	9.4	25.2	48.1	15.5	59.3	0	0	24.0
			Adding activated carbon filter (80% efficiency on O_3 reduction)	23.1	6.4	47.0	20.4	0	74.6	2.3	0
		Formaldehyde absorption material	Deposition velocity for HCHO = 2.08 m/h (area = wall and ceiling area)	23.1	25.2	3.3	20.4	0	0	93.1	0
Room	Source control	Low-emission furniture	50% less primary and secondary formaldehyde emissions	23.1	25.2	29.9	20.4	0	0	37.8	0

(continued)

Table 5 (continued)

Scale	Category	Strategy	Description	IAQ metrics				Effectiveness on IAQ improvement			
				PM2.5 (μg/m³)	O_3 (μg/m³)	HCHO (μg/m³)	Infection probability (%)	PM2.5 (%)	O_3 (%)	HCHO (%)	Infection (%)
	Ventilation	Displacement ventilation	Ventilation effectiveness = 1.5	17.9	33.0	36.5	16.1	22.5	−31.0	24.1	21.1
	Air cleaning	Portable air cleaner	CADR = 361 m³/h (HEPA filter and activated carbon filter)	10.7	19.4	47.7	13.4	53.7	23.0	0.8	34.3
Personal	Source control	Local air exhaust	Reduced viral particle exhalation (ventilation effectiveness = 5)	23.1	25.2	48.1	6.5	0	0	0	68.1
	Ventilation	Personal ventilation	Ventilation effectiveness = 1.7	16.5	35.8	33.5	14.9	28.6	−42.1	30.4	27.0
	Air cleaning	Wearing mask	50% on particle filtration	11.6	25.2	48.1	5.5	49.8	0	0	73.0

Displacement ventilation (ventilation effectiveness = 1.5) can improve indoor PM2.5, formaldehyde, and infection risk levels but also increase the indoor O_3 concentration owing to less O_3 deposition because of imperfect air mixing. Portable air cleaner that has a CADR of 361 m^3/h (with HEPA filter and activated carbon filter) can reduce indoor PM2.5, O_3, formaldehyde, and infection probability by 53.7%, 23.0%, 0.8%, and 34.3%, respectively. Improving the IAQ in personal microenvironments by using local air exhaust technique that can remove viral particle exhalation with a ventilation effectiveness of 5 can reduce the infection risk by 68.1%, which has a high potential on reducing the infection risk. Personal ventilation (effectiveness = 1.7) can improve indoor PM2.5, formaldehyde, and infection risk levels but also increase the indoor O_3 concentration. Masks can remove 50% particles (including PM2.5 and infectious particles). Wearing masks can reduce PM2.5 inhalation by almost 50% and infection risk by 73% (reduction on both infectious particle exhalation and inhalation).

It can be found that most IAQ control strategies cannot remove all indoor pollutants effectively. They may be effective against certain pollutants, but ineffective against others. Some strategies may even introduce some pollutants when working against other pollutants. To meet certain IAQ criteria, the integrated implementation of multiple IAQ control strategies in indoor environments are usually necessary. Like the optimization of HVAC system control, the optimal control of other strategies (e.g. standalone air cleaners and local air exhaust) also has great potential of IAQ improvement. Especially, the coordination of different strategies can be optimized through optimal control algorithms, e.g. the combination of UFAD, personal ventilation, and partitions in office settings (Kong et al. 2015). Intelligent/optimized control of IAQ strategies has great potential in improving IAQ while saving energy.

Case Study: IAQ Design and Control Strategies for a LEED Platinum Building: SyracuseCOE Headquarters

The Syracuse Center of Excellence (SyracuseCOE) Headquarters is a five-story building located at the southeastern corner of the intersection between two interstate highways (I-81 and I-690), near the downtown of Syracuse, NY (Fig. 10). This LEED Platinum certified office building was built for environmental and energy technologies and building research, development and demonstration, equipped with the facilities such as green roof, geothermal system, natural ventilation, personal ventilation systems, advanced building heat recovery/reuse systems, air quality monitoring of outside air and integrated controls for improving/protecting indoor air, etc. The HVAC system in the building uses 100% outdoor air and can coordinate with natural ventilation (window opening). The narrow-shape design is good for the application of natural ventilation as well as for maximizing the benefit of daylighting. High-efficiency filters are used to filtrate outdoor air before supplying it to indoor spaces. Low-emission materials and furniture (per ANSI/BIFMA M7.1) are selected and used in the building to minimize indoor pollutant sources.

Fig. 10 SyracuseCOE case study

The Total Indoor Environmental Quality (TIEQ) Lab is located on the fourth floor of SyracuseCOE. The lab space spans two floors. There is an open mechanical space on the fourth floor and two configurable suites with raised floor systems on the fifth floor, directly above. The configurable spaces can be used for simulating multi-zone office and classroom settings, testing various ventilation, air distribution, and environmental control technologies, and studying the control of the micro-environments around individual occupants. When the configurable spaces are used for office settings, each space can typically contain up to 12 workstations (cubicles) (Fig. 10). The building management system of the lab is isolated from the building's main HVAC system. The main air handler and 12 individual air treatment modules are combined to control the relative humidity (RH), temperature and CO_2 levels. Temperature, RH, CO_2, and VOCs can be monitored at the supply, room, or the individual level at each workstation. Demand-controlled underfloor air distribution (UFAD) ventilation system can be applied in the space. Personal ventilation system is mounted on the desk of each cubicle and can be used to control the micro-environments around occupant. The major IAQ control strategies at different scales used in the SyracuseCOE case are illustrated in Table 6.

At the urban scale, the I-81 highway on the west wide of the SyracuseCOE building is planned to be rerouted in a few years. Though this is primarily from the urban transportation and community interaction planning point of view, it can also reduce the pollutant emissions from traffic. It has been found that traffic is the primary source of the particles near the highway. According to the field measurement near I-81, the traffic on I-81 has a significant impact on the particle level in nearby communities (Kong et al. 2016). Particularly, the particle level in the downstream area is much larger than the particle level in the upstream area. Considering that the

Table 6 Major IAQ control strategies at different scales used in the SyracuseCOE case

	Source control	Ventilation	Air cleaning
Urban scale	Removing traffic emissions by I-81 (planned)	First-floor lift-up design	Green roof
Building scale	Low-emission building materials (per ANSI/BIFMA criteria)	100% outdoor air mechanical ventilation Natural ventilation (potential strategy)	High-efficiency filters in HVAC (MERV 13 + activated carbon)
Room scale	Low-emission furniture (per ANSI/BIFMA criteria)	Underfloor air distribution system Demand control ventilation	Standalone air cleaner (potential strategy)
Personal scale		Personal ventilation	

prevailing wind in Syracuse is from the west, traffic emissions from I-81 can very likely have a considerable impact on the local air quality surrounding the SyracuseCOE building. Therefore, rerouting I-81 is assumed to have the ability to reduce the outdoor particle level around the SyracuseCOE building by 50%. First-floor lift-up design of the building can ideally improve the local ventilation and reduce the pollutant accumulation in local areas. But its effectiveness on air quality improvement is questioned since the building is located in the downstream side of the pollutant source. Green roof is mainly used for improving local thermal and hydrologic environment. However, due to the limited area of the green roof on the SyracuseCOE building, its impact on pollutant removal is probably very little. Thus, first-floor lift-up design and green roof are assumed to have insignificant impacts on local pollutant reduction.

Building materials and furniture in the SyracuseCOE building were selected per ANSI/BIFMA criteria (see Chap. 1). They are assumed to have 50% lower emissions than regular materials and furniture. The HVAC system in the building uses 100% outdoor air and MERV 13 and activated carbon filters for filtration. The demand controlled UFAD system is assumed to improve the ventilation by an equivalent effectiveness as the displacement ventilation (ventilation effectiveness = 1.5). A field test in the TIEQ lab revealed that the studied personal ventilation system can improve the IAQ in the breathing zone by a factor of 3–5 (Kong et al. 2015). In this study, its ventilation effectiveness is assumed to be 3.

In addition, natural ventilation can also be utilized by opening windows. However, currently, windows can only be opened manually, which means natural ventilation probably cannot be utilized very well. An optimal control that coordinates mechanical and natural ventilation has the potential for enhancing indoor ventilation and improving IAQ. It can be assumed that the use of natural ventilation can provide additional 0.5 h^{-1} outdoor air to the room. Standalone air cleaner is another potential strategy that can further improve IAQ of the building. The studied air cleaner is assumed to use a HEPA filter (99.9% removal efficiency on particles) and an activated carbon filter (80% removal efficiency on ozone), which can provide a CADR of 361 m^3/h.

The TIEQ lab (6.3 m × 10.5 m × 3.2 m) is defined as the studied case, with 12 cubicles arranged in 2 rows. A reference case with same dimensions and occupancy settings is also defined. The reference settings defined in the previous section are adopted to define the building systems of this reference case. The total supply airflow rate of the HVAC system is assumed to be 3.6 h^{-1} (25% outdoor air for the reference case while 100% outdoor air for the SyracuseCOE case). The potential strategies, including controlled natural ventilation and standalone air cleaner, are used to define a case with potential improvement. The outdoor concentrations of PM2.5, O_3, and formaldehyde in Syracuse are around 6.4 μg/m^3, 84 μg/m^3, and 2.6 μg/m^3, respectively (Han et al. 2014; U.S. EPA 2020).

Based on the analysis approach introduced in the previous section, it can be observed that the current strategies used in the SyracuseCOE case (TIEQ lab) can significantly improve IAQ compared to the baseline case (Fig. 11), particularly for pollutants that are mainly generated indoors (such as PM2.5, from occupants activities, formaldehyde, and infectious particles; see the reference settings in the previous section). Potential strategies can further reduce these pollutants but with minimal effect on the O_3 concentration, because more outdoor air is introduced through natural ventilation while outdoor air is the main source of indoor O_3. Therefore, the LEED Platinum certified SyracuseCOE building can provide quite a good IAQ for occupants with the existing control strategies, while the potential strategies, including controlled natural ventilation and standalone air cleaner would only have small further improvement (1–2% reduction comparing to the baseline condition).

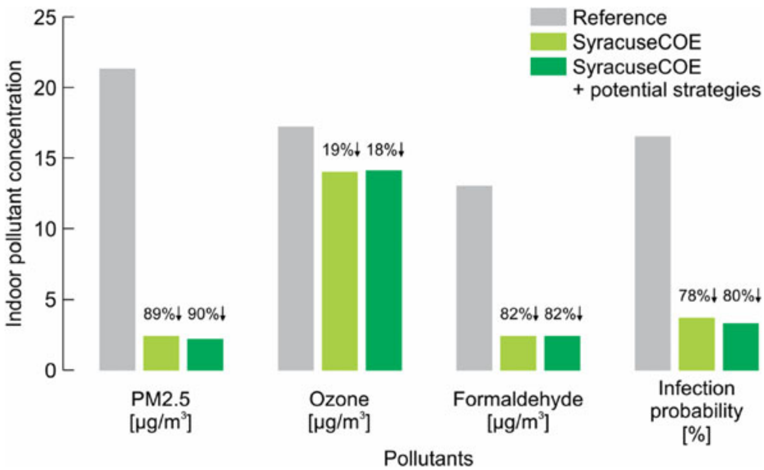


Fig. 11 IAQ metrics in studied cases

Concluding Remarks and Future Outlook

In the foregoing sections, we introduced a simplified IAQ model and used it to assess the effectiveness of source control, ventilation, and air purification at urban, building, room, and personal microenvironment scales in reducing the occupant's exposure to various pollutants with indoor or outdoor origins. Baseline cases were defined for various commercial and institutional building spaces so that the various IAQ strategies can be evaluated as relative percent of improvement against the defined baselines. In particular, results for typical open plan office spaces were obtained and a case study analysis was presented for a LEED Platinum-certified building. The same approach can be extended to other types of buildings such as residential buildings.

The analysis has been limited to several individual pollutants of indoor or outdoor origins, and to the reduction of concentrations. Future work should include an analysis of the combined effects of major indoor pollutants on the overall IAQ and of how the various IAQ improvement strategies at different scales can be integrated and optimized in building design and urban planning. Such analysis would require the development and use of more comprehensive IAQ metrics such as the DALY (Disability-Adjusted Life Years) metric or the ELV method that accounts for a pre-defined set of indoor pollutants (Abadie and Wargocki 2017).

The analysis has also been limited to steady state conditions. It can be extended to dynamic conditions in which both indoor and outdoor pollution loads can vary over time, and building occupancy also changes over time. Analysis for dynamic conditions also offers additional opportunity for further optimizing the implementation and integration of the various IAQ strategies. For example, outdoor ventilation rate and air purification at the building scale can be optimized to improve indoor air quality while saving energy (Han et al. 2014). Model predictive control method can be applied to further optimize the application of the various IAQ strategies in real or near real time (Woldekidan 2015). The arrival of Internet of Things (IOT) technologies is expected to make the implementation of the dynamic control and optimization more convenient and at a lower cost as it would depend less on initial infrastructure setup. It would make it easier to install and operate a plug and play system with the different products/IAQ strategies that communicate and coordinate with each other for whole system optimization.

Energy and cost implications of the various IAQ strategies at the different scales have not been discussed in detail. Future work should include the quantification of energy consumption, cost, and carbon emissions of the IAQ strategies. Such data are needed to perform multi-objective optimizations of the built environmental systems (BES) as pertaining to IEQ improvement, energy saving and reduction of carbon emissions and building safety (Fig. 1).

Cross-References

- ► ASTM and ASHRAE Standards for the Assessment of Indoor Air Quality
- ► Deposition
- ► Filtration and Air Cleaning
- ► Guidelines for Indoor Air Quality (WHO, EU)
- ► IAQ Demands in Green Building Labelling Systems and Healthy Building Labelling Systems
- ► Indoor Air Quality Control System
- ► Indoor Air Quality in the Context of Climate Change
- ► Influence of Ventilation on Indoor Air Quality
- ► Labelling System for Indoor Materials and Furniture
- ► Occupant Emissions and Chemistry
- ► Resuspension
- ► Simulation for Indoor Air Quality Control
- ► Source/Sink Characteristics of SVOCs
- ► Source/Sink Characteristics of VVOCs and VOCs

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