Air Quality in Latin American Buildings

Constanza Molina ⓘ**, Benjamin Jones** ⓘ**, and Giobertti Morantes** ⓘ

Abstract The air people breathe has a significant impact on their health, comfort, productivity, and well-being. Indoor air is important because it is where most exposure to airborne contaminants occurs. However, it is not always possible to know the composition of contaminants in indoor air, its variability, and changes over time, so suitable metrics are needed to regulate indoor air, and its quality improved efficiently, sustainably, and at the lowest possible cost, along with its relationships with health risks or comfort. To improve indoor air quality, source control, targeted ventilation, and space ventilation are the most effective intervention strategies, in that order. However, increasing the ventilation rate is not always a solution, especially in highly polluted cities. In many Latin American countries, there is a lack of understanding about the problems caused by poor air quality. This is aggravated by the prevalence of fuel poverty. Poor IAQ has an unavoidable impact on government spending on health care, social care, and social security. This chapter describes metrics for determining the most important airborne contaminant sources in Latin American buildings, the variables that affect IAQ, and how contaminants may be controlled and regulated to minimize their impact on a population's health and well-being.

Keywords Indoor air quality · Exposure · Ventilation · Politics

C. Molina (✉)
School of Civil Construction, Pontificia Universidad Católica de Chile, Santiago, Chile
e-mail: cdmolina@uc.cl

B. Jones · G. Morantes
Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK
e-mail: Benjamin.Jones@nottingham.ac.uk

G. Morantes
e-mail: Giobertti.Morantesquintana@nottingham.ac.uk

1 Air Quality in Buildings

The air people breathe is composed of a complex mix of chemicals of varying quantities and toxicity. It is also linked to one of the world's top causes of mortality and morbidity. An airborne contaminant is something present in the air that would not ordinarily be there. If it is toxic, it is called a pollutant. Some contaminants are common elements that are generally safe, such as carbon dioxide. Others negatively affect human health, even at low levels. The quality of indoor air has been defined by its acceptability to occupants. ASHRAE Standard 62.2 [1] defines acceptable indoor air quality (IAQ) as "air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants at concentrations that are known to pose a health risk". Therefore, both the indoor concentration and toxicity of individual contaminants must be known before IAQ can be determined. However, the composition of contaminants varies between buildings and over time, as a function of the lives and habits of occupants, and of building technologies and appliances [2].

Some contaminants are frequently monitored in the ambient, or outdoor, air to indicate their quality: particulate matter, also known as particles,[1] ground-level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). They are called criteria pollutants because they adversely affect health and well-being. Most research has focused on the outside air, yet people spend most of their time indoors, usually in their homes [3, 4]. This makes buildings the primary place where exposures to airborne pollutants occur. The Commission of Social Determinants of Health is the organization established by the WHO to study health equity worldwide. It finds that home and work conditions are two of many social determinants of health [5]. IAQ is generally unregulated beyond the chemical composition of some domestic goods and toxins in working environments.

The United Nations' Sustainable Development Goals (SDGs) are a set of 17 international priorities to provide "peace and prosperity for people and the planet, now and into the future" [6]. Goal 3 strives to ensure a healthy life for people of all ages by including a health-related indicator of air pollution mortality. The SDG indicators were updated in 2018 to provide an assessment of progress and the likelihood that each of the 195 participating countries will meet the goals by 2030. For example, 53% of the air pollution mortality goal has been achieved in Barbados, Cuba, Grenada, Saint Lucia, Dominica, Paraguay, El Salvador, Jamaica, Saint Vincent and the Grenadines, Mexico, Belize, Suriname, the Dominican Republic, and Honduras, which represent the mode. And 84% of the smoking prevalence goal has been achieved in Barbados, Antigua and Barbuda, The Bahamas, Brazil, Dominica, Belize, Dominican Republic, and Guatemala. 57% of the 195 countries have achieved 90% of the household air pollution goal [6]. Despite the Latin American and Caribbean countries showing unremarkable low air quality levels, more than

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[1] Particles are the type of pollutant rather than a single compound and are normally reported according to their mass concentration. For example, the mass fraction of particles with aerodynamic diameters smaller than 2.5 or 10 μm are reported as $PM_{2.5}$ or PM_{10}, respectively.

50% of the countries have less than a 10% probability of reaching that target. Barbados, Venezuela, Puerto Rico, Trinidad and Tobago, the Virgin Islands, and Antigua and Barbuda are the only countries to have more than a 90% probability of reaching the target [6]. Finally, Haiti has made an 18 and 94% improvement in air pollution mortality and smoking prevalence, respectively, but 0% progress in household air pollution. Haiti has a 0% chance of meeting the target for residential air pollution.

The following sections describe the current knowledge on the determinants of indoor air quality, metrics for determining the most important airborne contaminants and sources in Latin American buildings, how contaminants may be controlled and regulated to minimize their impact on a population's health and well-being, and barriers that must be overcome before implementing changes in building stocks.

1.1   Indoor and Outdoor Sources of Pollution

Indoor contaminants are either directly released from sources, when they are known as primary contaminants, or they are formed within the indoor environment after their release when they are known as secondary contaminants. They are also classified by their physical state (gaseous or particulate), their impact on health (criteria or non-criteria pollutants), or their source type[2] (outdoor sources, such as the infiltration of outdoor pollutants or those released from soil; indoor sources, such as combustion stoves or heaters; or particulates resuspended by occupant movements or cleaning activities).

Over the past 70 years, new materials and technologies have been adopted by the construction industry to increase the environmental performance of buildings. These have adversely affected IAQ and occupant health when materials emit contaminants, lifestyles and personal habits change emissions, such as the burning of incense, or when reductions in the airtightness of buildings occur without additional ventilation [7, 8]. Conversely, the prevalence of some contaminants has decreased due to restrictions on the use of some chemicals in building materials and consumer products, and changes in occupant behaviors, for example, formaldehyde is restricted as a preservative in reconstituted wood products and indoor smoking has been reduced.

Gases, particulate matter, and volatile organic compounds (VOCs) are the most prevalent pollutants found in buildings. VOCs are organic chemical compounds that evaporate under normal indoor temperatures and pressures. Construction materials, tap water, household items (such as plastics), and human breath are also common sources of VOCs. Most VOCs are present in low concentrations indoors, frequently below the detection limit of most sensors. Table 1 shows the most common contaminants found indoors and their likely indoor and outdoor sources. Table 2 shows common airborne contaminants and possible health outcomes.

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[2] Sources are defined by ASHRAE 62.2 as "an indoor object, person, or activity from which indoor air contaminants are released, or a route of entry of contaminants from outdoors or sub-building soil" [1].

Table 1 Air pollutants, main type, and possible indoor or outdoor sources

Pollutant		Main type		Related sources	
		Indoor	Outdoor	Indoor	Outdoor
Criteria pollutant	Particulate matter (PM$_{2.5}$)	✓	✓	Smoking, cooking, heating, consumer products, building materials, soil (resuspension), infiltration of foreign particles	Soil (erosion, resuspension), sea salt, combustion (biomass, industrial, fuel)
	Sulfur dioxide (SO$_2$)		✓	Infiltration of foreign particles	Combustion (biomass, industrial, fuel)
	Nitrogen dioxide (NO$_2$)		✓	Smoking, burning appliances (for cooking/heating), infiltration	Combustion (industrial, fuel)
	Ozone (O$_3$)		✓	Reaction with precursors (NOx, CO, and VOCs)	
	Carbon monoxide	✓	✓	Combustion (biomass, fuel) for cooking/heating, smoking	Combustion (biomass, industrial, fuel)
VOC^a	Benzene	✓		Smoking	Petrochemical activities
	Formaldehyde	✓		Building materials (paints, glues, varnishes, lacquers, wooden products), cleaning (detergents, disinfectants, softeners), smoking, heating, cooking, candle/incense burning, and air fresheners	–
	Trichloroethylene	✓		Construction products (varnishes, paint removers)	–
	Tetrachloroethylene	✓			
	Naphthalene	✓		Consumer products with mothballs	–
	Xylenes	✓		Smoking	Petrochemical activities
Other air pollutants	Polycyclic aromatic hydrocarbons^b	✓		Combustion (biomass, fuel) for cooking/heating, smoking	Combustion (industrial, fuel)
	Radon	✓		Underlying rocks and soils	–
	Biological agents	✓	✓	Bacteria, viruses, fungi, mold, and bacterial spores	Spores, pollen, animal/human dander

^{a}Volatile Organic Compounds

^{b}Benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenzo[a,h]anthracene, benzo[ghi]perylene, and indeno[1,2,3−cd]pyrene

Table 2 Common indoor contaminants and possible health outcomes

| | | Plausible health outcomes | | | | | | | | | | | |
| | | Mortality | | | | | | | | Morbidity | | | |
Pollutant		All cause	Cardiovascular (general)	Respiratory (general)	Lung cancer	COPD	ALRI	IHD	Stroke	Cancer	Asthma	Respiratory	Cardiovascular
Criteria pollutant	Particulate matter (PM$_{2.5}$)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
	Sulfur dioxide (SO$_2$)	✓	✓	✓	✓						✓	✓	
	Nitrogen dioxide (NO$_2$)	✓	✓	✓	✓						✓	✓	
	Ozone (O$_3$)	✓	✓	✓								✓	✓
	Carbon monoxide	✓	✓	✓							✓	✓	✓
VOC[a]	Benzene				✓					✓			
	Formaldehyde									✓	✓	✓	✓
	Trichloroethylene									✓			
	Tetrachloroethylene									✓			
	Naphthalene									✓		✓	
	Xylenes									✓			
Other air pollutants	Polycyclic aromatic hydrocarbons[b]				✓					✓			
	Radon				✓								
	Biological agents										✓	✓	✓

[a]Volatile Organic Compounds

[b]Benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenzo[a, h]anthracene, benzo[ghi]perylene, and indeno[1, 2, 3 − cd]pyrene

Indoor pollutant concentrations and individual exposures are geographically and temporally heterogeneous. This is due to a combination of factors, including the local and surrounding environment, pollution sources, building design, and occupant behavior.

1.2   Removal Mechanisms

A minimum ventilation rate is required to maintain acceptable IAQ by diluting contaminants and providing oxygen for combustion (see Sect. 3.2). However, higher airflow rates are required to dissipate heat gains during the cooling season and to maintain the thermal comfort of occupants. The difference between the two airflow rates is normally the recirculation rate of a mechanically ventilated building that uses fans, ductwork, and an air handling unit to moderate the properties of supplied air. A naturally ventilated building exclusively uses the action of the wind and temperature differences to move air and so cannot moderate the properties of air or recirculate it. The pressure differences across natural ventilation openings are very small and so filters cannot be used. If outdoor air quality is unacceptable, then a naturally ventilated building may be inappropriate unless air intakes can be located away from pollution sources. Natural ventilation openings are normally sized to dissipate heat gains in the cooling season and so they should be more than capable of providing enough air for acceptable IAQ when controlled correctly. Ventilation rates for IAQ are either a requirement integrated into a country's building codes or mandated by a project's standards. They are specified according to the room's occupancy; the presence of pollution sources, such as combustion appliances; or expected highly pollutant events. However, ventilation is not the only mechanism for removing pollutants from breathed air. Others include aerosol deposition onto surfaces, pathogen biological decay, and filtering. These removal mechanisms are influenced by space volume and the behavior of a contaminant (see Sect. 3.2).

Deposition refers to the loss of indoor particulates that attach themselves to surfaces and fall out of suspension. Its rate is usually lower than that of ventilation and depends on a pollutant's properties (mass, diameter), the surface area-to-volume ratio of a room, the room air velocity, and the surface area of any furniture. Deposition rates are especially important when ventilation is restricted. However, their prediction and measurement are highly uncertain [9, 10]. Particulate dynamics also affect deposition rates, for example, particulates may coagulate, condensate, evaporate, or change their mass. This, in turn, affects indoor concentrations [11].

The biological decay rate only affects pathogens and is a function of their half-life, the time for half of all of the pathogens present in a space to become incapable of growth or damage. This process is known as denaturing or inactivation. In devices, such as UV emitters, the biological decay rate is used as the system's rate of biological inactivation.

Finally, a filter removes particulates from the indoor air by trapping them. Filter efficiency is the fraction of particulates trapped and varies with particulate size and
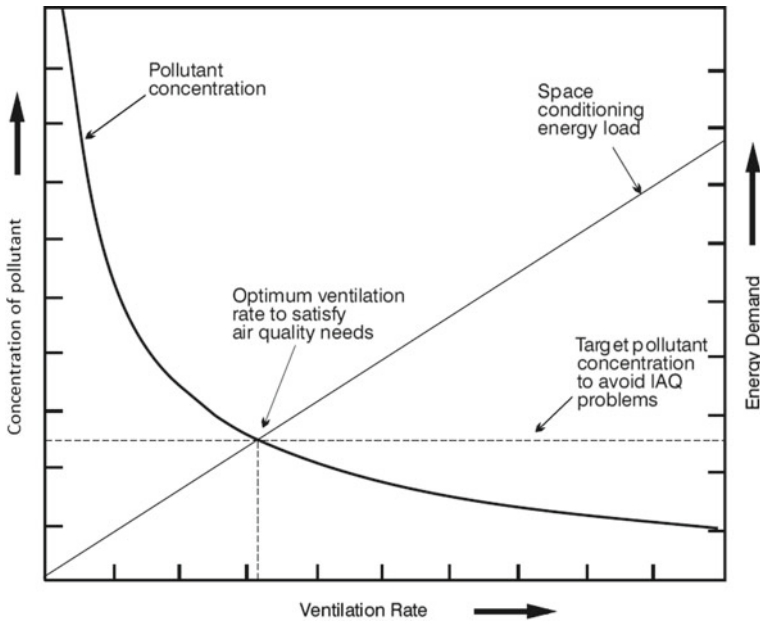
Fig. 1 Relationship between contaminant concentration, energy, and ventilation rate [12]

the filter type. For example, a MERV 1 filter traps <20% of to 99% HEPA filters. It is possible to filter some gaseous pollutants using a catalyst, but byproducts of the reaction can be harmful in some circumstances.

When increasing the ventilation rate, there is a law of diminishing returns for the maximum contaminant concentration (see Fig. 1). Furthermore, increasing the ventilation rate also increases conditioning energy demand. Therefore, it is always best to start resolving IAQ problems in the worst ventilated rooms because this achieves the greatest effects on health for the least cost. Figure 1 also shows a linear relationship between the ventilation rate and the space conditioning load, and that there is a trade-off between the contaminant concentration and the energy demand. It is possible to reduce the ventilation energy demand using heat recovery systems and by ventilating only when required. This requires an initial focus on source control, and then the identification and control of the most harmful contaminants in a room over time (see Sect. 3).

The most common metric of ventilation is a volume flow rate with units of L /s or m^3/s. These metrics are generally used to keep the concentration of a contaminant below a prescribed threshold, dissipate heat gains during the cooling season, and to maintain the thermal comfort of occupants. It is also common to use an air change rate, with units of 1/h, which are used to purge a room of contaminants in a prescribed period. Air change rates are also useful for comparing the ventilation rates in two rooms with different geometries. The processes are described in Sect. 3.2.

1.3 Exposure-Response Pathway

Many indoor contaminants have the potential to cause direct and indirect harm. The risk of a susceptible person becoming unwell is related to the mass of the contaminant inhaled, known as the *dose*, and the dose required before a disease occurs. The dose is higher when there is a higher concentration of pollutants in a place, increasing the risk of harm, and when the metabolic rate of occupants is high. Exposure is defined as the contact between airborne contaminants and a person. Total cumulative exposures in a room, E_t, as a function of time are determined by Haber's law of total exposure, which is the sum of exposures in a number of rooms, E_i, and the time-weighted personal exposure to the pollutant emitted by personal activities, $E_{pact,j}$ (1).

$$E_t = \sum_i E_i + \sum_j E_{pact,j} \tag{1}$$

Exposure is defined as the product of the contaminant concentration, C_i, in a room and the time spent in it, t_i. There then must be some form of interaction between the pollutant and the human [13], which is generally inhalation. Because the contaminant concentration varies with time, an expression of total exposure is 1.

$$E_t = \frac{1}{T}(\sum_i \int C_i dt_i + \sum_j \int C_{pact,j} dt_j) \tag{2}$$

where T is the total time spent in each microenvironment and each personal activity [14].

Normally, exposure models are defined for specific ages and genders which may vary by activity and place. Mccurdy and Graham [4] analyzed US activity data and identified variables that showed that the time spent indoors, outdoors, and in vehicles has a statistically significant effect for each age and sex cohort. They recommend that exposure studies initially consider age and gender, and then consider the level of physical activities of individuals. The daily maximum temperature, the month of the year, and the day of the week are also important drivers.

Klepeis et al. [3] analyzed time-activity data for over 5000 US citizens, classifying it into 10 locations. They show people spend most of their time indoors (average 87%), primarily at home (average 69%), but that this might range from 34 to 98%. Koehler et al. [15] also studied personal exposures to air pollution and their variability by microenvironment or location (home, work, transit, eateries, and others). Results showed greater variability within-person data, which depends on the location. The highest exposures to $PM_{2.5}$ were in transit and eateries due to proximity to traffic and cooking sources, but the higher total integrated exposure was at home.

2 Researching Building Stocks

### 2.1 Describing a Building Stock

Buildings stocks are nearly always heterogeneous and often large. Ideally, data to describe existing buildings is obtained from large-scale field studies and surveys. Methods to evaluate the building performance are either direct, such as field measurements that use portable or stationary equipment, and indirect, such as modeling and simulation techniques. Indirect methods are often quicker and cheaper and can be used to understand future interventions. Computational models have been used by many countries to estimate changes attributable to policies in the energy demand and indoor environment quality in both buildings and building stocks. These stock models are an effective tool for decision-making, and some Latin American countries have developed and applied a limited set of archetypal or representative buildings, for example, Brazil [16, 17] and Chile [18].

However, there are uncertainties in model buildings and in the information required by them, which may restrict their usefulness [19]. The first is a function of the natural heterogeneity of a stock. The second is random variability which makes it possible to obtain different predictions for the same case. The third is parametric ambiguity where required data may not exist in suitably disaggregated forms. Finally, the acquisition and processing of data can introduce systematic errors. Other problems occur when the stock model suffers from oversimplification, is opaque, or has insufficient modularity [20].

To overcome these issues, recent models use advanced clustering methods to reflect the variability between groups of buildings and sampling methods to account for variability in the descriptive parameters, generate distributions of predictions, and to quantify uncertainty in them (see Fig. 2). The way predictions are assessed and presented to stakeholders is crucial. Results should not disguise the range of probable outcomes or measured values, but highlight those that are more likely to occur and those that are extreme and hence unlikely.

Modelers should also apply global sensitivity analyses to identify the input parameters that have the greatest effect on the predictions of the model. These parameters can highlight targets for remediation or a need for future field surveys when data is scarce [8, 22]. These strategies are helpful for nations with limited data, such as Latin American countries, where modeling studies of indoor environmental parameters are scarce.

Model predictions may differ from measured data and so an update or calibration process can be carried out by combining the predictions with new data or in situ measurements [19, 23–25].
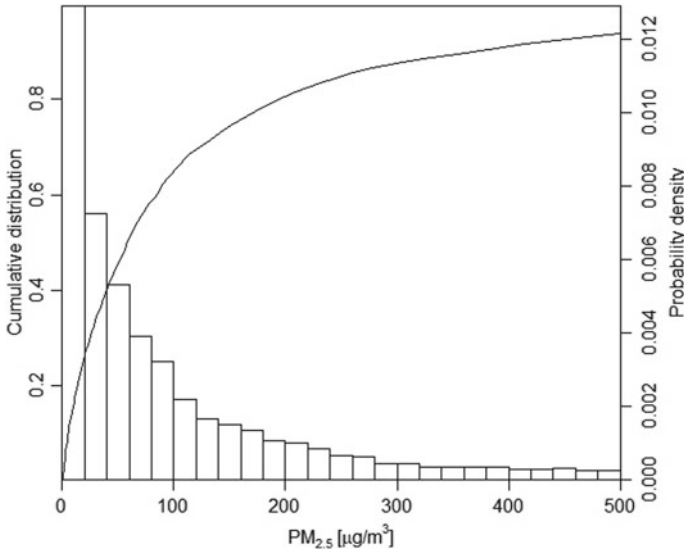
Fig. 2 Predictions of indoor $PM_{2.5}$ concentrations for the Chilean stock during winter, considering indoor sources only and infiltration with an exhaust fan as the only contributors to ventilation [21]

3 Assessing Indoor Air

3.1 Approaches

Indoor contaminant concentrations vary between buildings and zones within a building. This is due to factors that include the local environment, pollution sources, building design and use, and occupant behavior. IAQ in Latin American buildings is often assessed using measurements of CO_2, CO, and particulate matter, and research has focused on school and university buildings [26]. Other pollutants of interest include radon [27], NO_2 [28], and $PM_{2.5}$ [29]. Instantaneous measurements record concentrations at a specific time and location, and continuous sampling in a single location may not capture the variability present in others. Consequently, data from a large number of buildings and locations are required, whose acquisition can be expensive and time-consuming.

Personal exposures can be assessed using the direct and indirect methods described in Sect. 2.1. Directly identifying individual sources of pollution in situ requires complex analyses (see Sect. 3.3). Conversely, indirect approaches rely on simplifying assumptions, and must consider uncertainty (see Sect. 2.1). Several approaches are used to minimize the oversimplification of temporal and spatial distributions of IAQ parameters. Three methods depend on the partitioning of the airspace or the desired level of spatial information. They range from basic models with (i) a single well-mixed zone to (ii) multi-zone models, and then to (iii) more sophisticated models
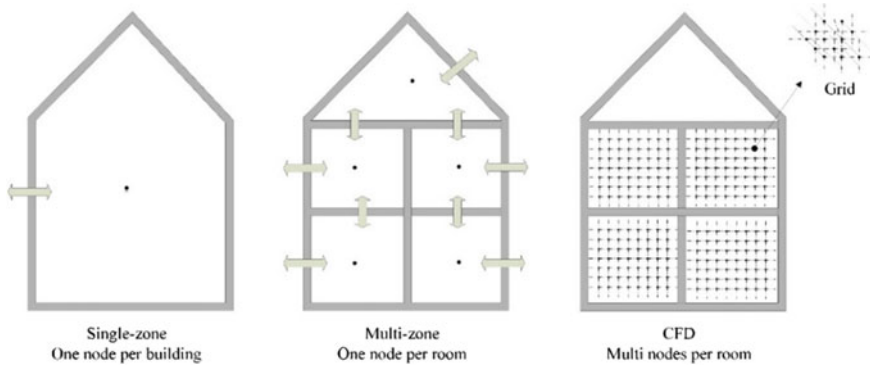
Fig. 3 Three different approaches to model the IAQ in a building. Left: Single well-mixed models; Middle: multi-zone well-mixed models; Right: CFD model. Each dot or node represents a well-mixed volume. Based on [30]

employing a non-uniform distribution of contaminants using Computational Fluid Dynamics (CFD) (see Fig. 3). The method defines the level of complexity, resolution, and detail used to represent the indoor air in a building.

Each method has drawbacks. Single-zone models with well-mixed air consider just one volume of air, which is typically homogenous in temperature and contaminant concentration. Multi-zone models consider several zones linked via airflow paths, such as doors. The contaminant concentrations in a building, or each zone, are then estimated over time using these two methods. Airflows between each zone and between each zone and the outdoor air are computed iteratively by ensuring equations where the mass through the system is conserved at each time step. Finally, a CFD model may be used to assess the distribution of a contaminant within a space and to determine flow velocities, providing further spatial detail (see Fig. 3). As detail increases, so does the required computational power and the simulation time. All predictions can be compared or calibrated using measured data to provide validation. The accuracy of the model can then be determined by its ability to predict indoor air contaminant concentrations.

3.2 Modeling Contaminant Concentrations

The concentration of a contaminant, $C(t)$, at a moment in time, t (h), in a well-mixed indoor space with volume, V (m^3), is given by the solution to a mass-balance equation

$$C(t) = C_{ss} + (C(0)) - C_{ss})e^{-(\lambda+\kappa)t} \tag{3}$$

Here, λ is the air change rate (1/h), κ is the deposition rate (1/h), and $C(0)$ is the contaminant concentration when $t = 0$ hours (h). The right-hand side of Eq. (3) is split into two parts: on the right is a time-dependent function, and on the left is a time-independent constant. As time increases, the concentration increases with time, and eventually the time-dependent part trends to zero leaving a steady-state concentration, C_{ss} (4).

$$C_{ss} = \frac{\lambda P C_b}{\lambda + \kappa} + \frac{G}{(\lambda + \kappa)\,V} \qquad (4)$$

Here, C_b is the background concentration, G is the contaminant emission rate, V is the space volume (m^3), and P is a dimensionless penetration coefficient that represents the filtering effect of the building envelope. It has limiting values of 0 and 1 that depend on the characteristics of an airflow path and the contaminant. $P = 1$ for contaminants that are not filtered by the envelope, such as gases, or for all contaminants when the opening is large, such as a window. However, some contaminants, such as particulates, are filtered. Then, $P < 1$ when the airflow path is a small crack. The units of $C(t)$ and G also depend on the contaminant type. For a gas, such as CO_2, they have units of parts per million (ppm) and cubic centimeters per hour (cm^3/h), respectively. Equation (4) shows that C_{ss} is a function of the removal mechanisms and decreases as the removal rate increases. The time taken to reach the steady-state concentration is dependent on the room volume. The bigger the volume, the longer the time. This is known as the *reservoir effect*.

These equations can only be assumed to be correct when the emission is a point source, mixing occurs rapidly throughout due to random internal air movements, the concentration of the contaminant is the same everywhere, the space does not leak, and when $P\lambda, \kappa, G$ are constant. If any of these three parameters changes, then all calculations must be re-started from $t = 0$ h, when $C(0)$ is reset.

The equations only consider $P\lambda$, and κ to be removal mechanisms, and so may not apply to some contaminants, such as VOCs in some environments (see Sect. 1.2). They do apply to inert gases, such as CO_2, when $\kappa = 0$ and $P = 1$, or to PM$_{2.5}$ when $\kappa = 0.39$ and $P = 0.8$ [31].

When designing regulation and standards, the steady-state concentration C_{ss} can be used to set a ventilation rate, λV (m^3/s), so that a threshold contaminant concentration is never reached. For example, a steady-state CO_2 concentration can be used to indicate the ventilation rate when the emission rate is known. When $G = 5$ cm^3/s per person [32], the ventilation rate is $\lambda = 10$ L /s per person, $\kappa = 0$/h, and the ambient CO_2 concentration is $C_b = 500$ ppm. The steady-state concentration can be calculated to be $(500 + 5/(10 \times 10^{-3})) = 1000$ ppm. Accordingly, when a CO_2 concentration is above 1000 ppm in any room, then the ventilation rate is less than 10L /s per person.

The time-dependent element of Eq. (3) can be used to set an air change rate, λ (1/h), required to dissipate a fraction of a contaminant concentration over a specific period of time. For example, after a cleaning activity, a gaseous contaminant is no

longer emitted so that $G = 0$ cm^3/s. Then, to lower its concentration in the indoor air by 95% over time period T, the required air change rate is (5)

$$\lambda = -\ln(1 - 0.95)T^{-1} - \kappa \tag{5}$$

When $T = 20$ min (or 0.33 h) and $\kappa = 0$/h, the required air change rate is $\lambda = 9$/h. This is converted to a ventilation rate by multiplying λ by the space volume.

3.3 Measuring IAQ

Measuring contaminant concentrations requires complex and costly equipment, which often requires expert knowledge to use and maintain. For their measurements to be meaningful, the equipment must be calibrated frequently.

One of the most cost-effective contaminants to measure is CO_2, which is commonly done using non-dispersive infrared gas sensors (NDIR), where the absorption of the characteristic wavelengths of infrared light is measured and used to estimate the CO_2 concentration in air. CO_2 sensors are prone to a gradual changing of the scale of zero, known as zero-*drift*, and so they require frequent calibration. Non-scientific sensors, such as those used to operate ventilation, can self-calibrate by determining the ambient concentration during a prolonged period of inoccupancy.

Optical particle counters (OPCs) are commonly used to measure temporal changes in $PM_{2.5}$ concentrations. The $PM_{2.5}$ concentration is inferred from the light scattering properties of the particles sampled, which vary by source and composition. Accordingly, OPC measurements must be scaled by a calibration factor, a multiplier derived from concurrent gravimetric sampling. A gravimetric sampler collects $PM_{2.5}$ on a filter over the defined sampling period. The filter's mass is determined before and after the sampling period allowing for the calculation of an average $PM_{2.5}$ concentration. OPCs are often most sensitive to $PM_{2.5}$ of a particular size, and so OPCs capable of disaggregating $PM_{2.5}$ concentrations by their diameter can be used to select an appropriate OPC for a particular source.

Gas chromatography can be used to separate and analyze compounds found in the air, such as VOCs. There is a range of methods for doing this, which are described by Helmig [33]. The equipment is both bulky and expensive but has a high resolution.

3.4 Metrics to Evaluate Exposure Consequences

Policymakers often strive to reduce the energy demand of buildings by sealing them up or by limiting ventilation rates. An unintended consequence could be a reduction of the quality of indoor air with corresponding negative health effects for individuals and increased burdens on public healthcare systems. Current standards specify a minimum ventilation rate that is fundamentally set for odor control and that is

also assumed to minimize contaminant exposures and, therefore, protect occupant health. Accordingly, there is a need for performance-based health-centered IAQ metrics supported by our best knowledge of health effects. They must be measurable, achievable, and have a positive impact on the physical and mental health of occupants of buildings.

An air quality standard or norm should identify when the quality of indoor air is unacceptable and be based on its effects on human health and comfort, acknowledging that they may not be immediate. Health-adjusted life years (HALY) are measures of health over time and give weighted years a person of cohort lives with a disease and/or disability. Disability is weighted by its effect on a person's life in general, and so can account for mental illness. There are two key HALY metrics. The first is the disability-adjusted life year (DALY), which measures the disease burden in a population, expressed as the sum of the number of years lost due to morbidity and mortality, where a value of 0 represents no loss. In the case of IAQ, the disease burden is a measurement of the difference between the current health status of a population of building occupants and an ideal situation where they all live into old age, free of disease and disability. The second is the quality-adjusted life year (QALY), which reflects the quality of life of a person or cohort but is the approximate inverse of a DALY because it considers the health gained from an intervention where a value of 1 represents a year lived in perfect health and 0 is death. Both the QALY and DALY can be used to assess the financial values of exposures to poor IAQ and interventions designed to minimize it. Other metrics include money, premature deaths, or working days lost.

The DALY metric has been used to estimate the population average annual cost of chronic air contaminant inhalation in U.S. residences [34] (see Fig. 4). It estimates that the most harmful contaminant is particulate matter with a diameter of $\leq 2.5\mu g/m^3$ ($PM_{2.5}$), by an order of magnitude. These particles are small enough to bypass biological defenses and are linked to chronic respiratory and cardiovascular diseases, and cancer [35]. The [36] recommends mean $PM_{2.5}$ concentrations in all air breathed by a person is less than $15\mu g/m^3$ per day and $5\mu g/m^3$ per year. Mean annual external concentrations exceed the WHO limit in many cities making the provision of unfiltered ventilation a health risk in those areas. There are also many internal sources (see Table 1), such as cooking, and behavior modification and adequate ventilation should be encouraged. The contaminant sources described in Fig. 4 also exist in the houses of other countries, and so its findings can be extrapolated outside of the U.S.A.

3.5   Regulating IAQ

IAQ is governed by an ever-expanding number of regulations and standards. Many standards for non-domestic buildings aimed to control odor, which led to a common minimum ventilation rate of 7.5 L/s per person. This was increased to 10 L/s per person in many building types to account for other contaminants, such as those
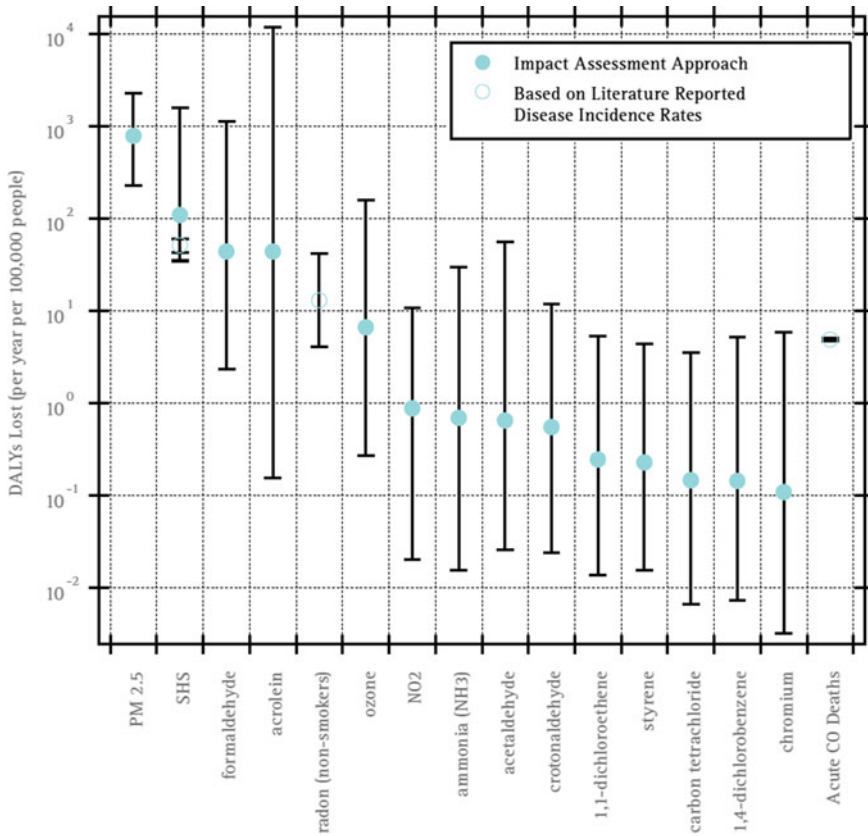
Fig. 4 Estimated population-averaged annual cost, in DALYs, of chronic air contaminant inhalation in U.S. residences. Reproduced from [34]. Technical Note AIVC 68. Residential Ventilation and Health. Brussels: Air Infiltration and Ventilation Centre

released by materials and furnishings [37]. The regulation of ventilation rates in houses generally aims at controlling moisture and diluting the byproducts of combustion. However, these are evolving to consider pollutant sources and harm. The ANSI/ASHRAE 62.2 standard [1] aims at providing *acceptable* IAQ in residential buildings (see Sect. 1.1).

Standards that give threshold values establish them for a population by considering the effects of exposure on public health [38]. Table 3 presents a summary of threshold values for air pollutants in indoor settings. Many Latin American countries apply the IAQ standards of international bodies or other countries [38, 39]. Accordingly, the values of the World Health Organization and the U.S. Environmental Protection Agency values are considered here because they are most often applied in Latin American countries.

Table 3 Threshold values for main indoor and outdoor air pollutants

Pollutant		Indoor/occupational		Threshold	By
		Units (μg/m^3)	Time		
Criteria pollutant	Particulate matter (PM$_{2.5}$)	5	1 year	Guideline	WHO
		15	24 h	Guideline	WHO
		15	1 year	Standard	US EPA
		35	24 h	Standard	US EPA
		65	24 h	Standard	ASHRAE
	Sulfur Dioxide (SO$_2$)	40	24 h	Guideline	WHO
		80 (0.03*)	1 year	Standard	US EPA
	Nitrogen	10	1 year	Guideline	WHO
	Dioxide (NO$_2$)	25	24 h	Guideline	WHO
		100 (0.05*)	1 year	Standard	US EPA
		1800 (1*)	15 min	Standard	NIOSH/US EPA
	Ozone (O$_3$)	200 (0.1*)	8 h	ELV/Standard	OSHA/US EPA
		100	8 h	Guideline	WHO
	Carbon monoxide	4***	24 h	Guideline	WHO
		10***	8 h	Guideline	WHO
		55***(50*)	8 h	PEL/Standard	OHSA/US EPA
		35*	8 h	REL/Standard	NIOSH/US EPA
VOC^a	Benzene	No safe level of exposure can be recommended			
	Formaldehyde	0.1***	30 min	Guideline	WHO
		0.1***	30 min	Standard	ASHRAE
	Trichloroethylene	2	Whole life	ELV	VGAI
		2.3	Whole life	Guideline****	WHO
	Tetrachloroethylene	250	1 year	Guideline	WHO
	Naphthalene	10	1 year	Guideline	WHO
		9	1 year	REL	OEHHA
	Xylenes	22000	1 h	REL	OEHHA
Other air pollutants	Polycyclic aromatic hydrocarbons^b	No safe level of exposure can be recommended			
	Radon	200*****	1 year	Guideline	Canada
	Biological agents	200	1 year	Guideline	EU

^{a} Volatile Organic Compounds
^{b} Benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenzo[a, h]anthracene, benzo[ghi]perylene and indeno[1, 2, 3 − cd]pyrene
* ppm
** ppb
*** μm^3
**** excess lifetime cancer risk of 1:1,000,000
***** Bq/m^3
****** CFU/m^3
REL: Recommended exposure limit; PEL: Personal exposure limit; WHO: World Health Organization; USEPA: United States Environmental Protection Agency; VGAI: Valeurs Guides de qualité d'Air Intérieur, France; OEHHA: Office of Environmental Health Hazard Assessment, USA; Government of Canada, Residential Indoor Air Quality Guidelines, 2016; EU: European Union

The WELL Building Standard [40] focuses on the people in buildings and identifies over 100 policies, design strategies, and performance metrics that can be implemented to enhance the health and well-being of building occupants. IAQ is one very important factor.

Most standards are in a state of constant flux and are updated frequently as new knowledge becomes available. They are challenging to develop because they must support innovative and flexible design approaches so that designers can deliver high-performing sustainable buildings for the people who occupy them, without compromising the needs of regulators, policymakers, and building owners [41].

4   Barriers to Change

There is currently little or no regulation in many Latin American countries that ensures acceptable IAQ in new and existing buildings. This may stem from a general lack of awareness of the issues caused by unacceptable IAQ and a perception that this issue is not a priority. Therefore, it is important for construction professionals, academics, and learned societies to lobby their governments for changes in the law to require acceptable IAQ. It is easier to regulate new buildings because appropriate measures and systems can be implemented at the design stage. Later changes can be implanted that require changes to existing buildings when they are renovated.

The implementation of IAQ regulation will be a non-trivial process. Finance, public awareness campaigns, and the need to make the case against competing concerns in the construction industry will be required. Regulations must be agreed upon by stakeholders and legislated for. A process for checking adherence to regulations must be implemented. Therefore, political engagement is essential.

It is in the interest of governments to regulate IAQ because the negative effects increase government expenditure on health care, social care, and social security, and reduces economic growth. The impacts on children are particularly important as this has the potential to reduce their educational attainment and future earning potential. Sick children require parental care that limits their ability to earn. Adults with chronic illnesses caused by poor IAQ may be unable to work and become a burden on the state rather than contributing tax. These consequences are likely to affect several government ministries, such as housing, health, and social security. Here, it is important to acknowledge that each of these ministries has competing agendas.

The academic community can support change by providing peer-reviewed evidence that shows the most cost-effective interventions using multi-criteria cost-benefit analyses [42]. Scientific funding bodies need to be encouraged to fund research into geographic and building stock appropriate regulations. Business can be engaged to create a new industry that seeks to provide solutions. And, if the supporting regulation is performance based, so that it gives targets rather than mandating solutions, it will encourage design innovation. Learned societies need to mediate

between business, government, and academics to drive change. They can follow the examples of ASHRAE, REHVA, and the CIBSE.

Implementing change in existing houses poses a significant barrier to change. Many houses are not airtight and are poorly constructed [21]. The costs of heating or cooling them may be significant. Fuel poverty affects householders who may face the unseemly choice between comfort and acceptable air quality. It is particularly important to transition away from solid-fuel heating to avoid indoor contaminant emissions and the re-entry of smoke from the outside.

Stakeholders should be under no illusions that implementing a reduction to the harm caused by unacceptable IAQ in Latin American buildings is a significant challenge that will take time to succeed.

5   Summary

The indoor air is composed of a complex mix of particles, gases, and contaminants, varying in concentration and toxicity. Mechanisms for removing contaminants from indoor spaces include ventilation, aerosol deposition, pathogen biological decay, and filtering. It is possible to reduce the ventilation energy demand using heat recovery systems and by ventilating only when required. This requires an initial focus on source control and then identifying and controlling the most harmful contaminants in a room over time.

There is a lack of awareness of the issues caused by unacceptable IAQ in many Latin American countries, exacerbated by the prevalence of households affected by fuel poverty that may have to choose between comfort and acceptable air quality. Thus, policymakers must be aware of the unintended consequences of building interventions on indoor air quality, which would have adverse health outcomes for people and an increased burden on public health. Poor IAQ inevitably affects government spending on health care, social care, and social security while reducing economic development. Air quality standards or norms should establish the acceptability of indoor air, based on its short- and long-term effects on human health and comfort. It is important for construction professionals, academics, and learned societies to lobby their governments for changes in the law to require acceptable IAQ at the design stage. Implementing a reduction in the harm caused by the poor indoor air quality in Latin American buildings is a difficult task that will take time to complete.

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