

Pollutant Dispersion in and Around Buildings: A Critical Review of Modelling, Mitigation, and Future Opportunities

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Abstract: *Pollutant dispersion in and around buildings is governed by the coupled behavior of atmospheric flow, building aerodynamics, ventilation, source characteristics, and pollutant-specific transport processes. Openings, leakage, air intakes and exhausts cause an interaction between outdoor pollution and indoor emissions, resulting in spatially heterogeneous and time-dependent concentrations. This narrative review summarizes experimental and numerical studies on pollutant sources, transport, modelling, measurement and exposure mitigation. Additionally, it focuses on validation against wind-tunnel, tracer-gas, and field measurements. It compares Reynolds-averaged Navier-Stokes (RANS), large-eddy simulation (LES), and transport-based recurrence computational fluid dynamics (CFD), and it also compares URANS. The reviewed literature shows that the prediction accuracy depends on inflow turbulence, source representation, geometry, numerical resolution, atmospheric stability, validation targets and turbulence closure. While RANS provides an affordable alternative for engineering evaluation when necessary, LES can remove the effects of unsteady transport and concentration fluctuations; neither is dependable without application-specific validation and verification. The indoor-outdoor coupling concept is effective depending on facade concentration, wind direction and opening configuration and shows dilution of indoor emissions and increased intake of outdoor air pollution. These modelling limitations are connected to sensor placement, exposure assessment, and energy-air-quality trade-offs through the synthesis. The review does not provide complete coverage or combined effect estimates, as the literature collection was not achieved by a documented systematic search. Priorities include reproducible benchmarks, uncertainty-aware validation, indoor-outdoor models by pollutant, and ventilation and filtration controls based on occupant exposure, energy demand, and robustness of operations.*

Keywords: pollutant dispersion, indoor air quality, building aerodynamics, computational fluid dynamics, air-quality management

1. Introduction

Buildings are not passive containers for air; their envelopes, openings, internal partitions, mechanical systems, and surrounding urban geometry actively shape how contaminants are emitted, transported, transformed, and removed. The indoor air quality in a room is associated with the outside environment through infiltration, open windows, doors, leakage through the facade, air intakes, exhaust outlets and common ventilation systems. However, indoor exhausts and discharges at the roof level could affect neighbouring properties and public spaces. The issue is thus intrinsically coupled across indoor, facade, street-canyon, roof-wake and neighbourhood scales.

Traffic contributes to a large amount of urban nitrogen oxides and particulate matter, and construction and industrial activities may release dust, aerosols, and gaseous contaminants. Cooking, cleaning products, smoking, building materials, furnishings, occupants, and poorly maintained HVAC components are examples of indoor sources. Relevant pollutant classes in buildings include gaseous species (carbon monoxide, CO; nitrogen oxides, NO_x; ozone; volatile organic compounds, VOCs), particles (PM₁₀, PM_{2.5}), and biological aerosols (fungal spores, bacteria). These classes differ in size, density, volatility, reactivity and surface affinity; hence, they may not occur via the same transport or removal pathways.

One of the most significant outcomes of building-dispersion studies is that the strength of sources cannot be used to determine the concentration. It depends on the interaction of

emission rate and the flow field, such as separation, recirculation, turbulent exchange, thermal buoyancy and location of receptors relative to openings and wakes. Studies on isolated buildings [2] indicate that the wake may create concentration patterns not equivalent to those in open terrain; work on building arrays and street canyons [30] further indicates that neighbouring structures modify plume spread and local exposure.

Literature has progressed from wind-tunnel measurements and simplified analytical models to CFD models that solve three-dimensional flow and scalar transport. Experimental techniques are still a necessity due to the sensitivity of model accuracy to turbulence closure, inlet conditions, geometry, and pollutant-release representation. RANS techniques are computationally economical and are extensively applied to practical problems, whereas LES is more effective in the resolution of large unsteady eddies and concentration fluctuations but demands more computational resources [28]. Recent methods like unsteady RANS [14] and transport-based recurrence CFD [4] aim to find an intermediate trade-off between fidelity and cost.

The four related questions that are discussed in this review are: (i) the contribution of indoor and outdoor sources; (ii) the role of airflow and pollutant-specific process in dispersion; (iii) the conditions under which modelling and measurement approaches provide reliable evidence; and (iv) the effectiveness of design and operational interventions in reducing exposure while accounting for energy, cost, and implementation constraints. Previous reviews cover urban

flow, street-canyon CFD [12], building-scale dispersion, and indoor air-quality modelling [24]. Instead of stating that the new topic is completely novel, this paper highlights the connections among model validity, indoor-outdoor transfer, and mitigation decisions.

2. Sources and Types of Pollutants

2.1 Indoor pollutant sources

The indoor sources can be continuous, intermittent, or activity-dependent. Fine and ultrafine particles can be produced by cooking and frying, whereas CO and nitrogen-containing compounds may be produced by combustion appliances. Cleaning products, fragrances, paints, adhesives, sealants, carpets, and furnishings may release VOCs, including compounds the rate of emission of which can be influenced by temperature, humidity, age of the material, and ventilation. Occupants contribute CO₂, moisture, bioaerosols and resuspended dust. Smoking and some hobby or maintenance activities can produce strong local emissions. Poor filters, contaminated ducts, poor condensate management or outdoor intakes in polluted recirculation zones can also cause contaminant redistribution by HVAC systems.

The location of the source is important because indoor flow is rarely uniform. A source nearby a supply jet can be quickly diluted, while a source in a stagnant corner or behind furniture can remain concentrated. Multi-room buildings have inter-zone transfer pathways through internal doors, partitions, corridors, shafts and pressure differences. Experiments in multi-room configurations with cross-ventilation show that source location and ventilation paths can substantially alter concentration distributions, even under similar incoming-flow conditions [15]. Indoor CFD research also highlights the importance of representing the room geometry, supply and exhaust location, and contaminant transport simultaneously, as opposed to the assumption that a single well-mixed concentration would characterize all occupiable locations [27].

2.2 Outdoor pollutant sources

Examples of outdoor sources are road traffic, industrial stacks, construction activity, domestic fuel combustion, waste management, agricultural dust and natural sources such as pollen and wind-blown soil. Of particular significance are traffic emissions around street canyons and road-facing facades since the building arrangements can limit vertical and lateral exchange. Traffic pollution has a health burden based on the emissions, pollutant dispersion, time spent near the road, and the concentration-response relationship; traffic volume by itself is not an adequate proxy of exposure or risk [33].

The problem of point sources like roof stacks is different. The emitted plume can either be recaptured by the wake of the emitting building or an upwind tower, and the velocity of the exhaust and stack height can decide whether the plume will clear the roof recirculation region. It is observed that increasing stack height can have an effect similar to increasing exhaust momentum for the studied configuration,

but the resulting concentration patterns differ between the two buildings [9]. Their later comparison of k - ϵ closures found that no single tested model reproduced every part of the vertical concentration profile equally well [10]. These results caution against the use of isolated-building rules in tightly spaced buildings.

Pollutants may also find their way into buildings from the outdoors. The entry fraction is based on the facade outdoor concentration, wind direction, window-opening configuration, ventilation mode, and pressure field. In a CFD study of buildings adjacent to a street canyon, it was reported that window-opening percentage changed ventilation flux and the effective intensity of traffic pollutants entering the downstream building [31]. [18] similarly found that ventilation strategy was a key determinant of outdoor-to-indoor transfer, with single-sided ventilation drawing air from a polluted canyon posing a particularly unfavorable configuration in their cases.

2.3 Pollutant classes and transport behavior

Gases and particles should not be treated as interchangeable passive scalars. For many gases, advection and turbulent diffusion dominate short-range transport, although chemical transformation can matter for reactive species such as NO_x and ozone. Particles are additionally affected by gravitational settling, inertial impaction, Brownian diffusion at small sizes, turbulent deposition, resuspension, and interaction with surfaces. Biological particles may lose viability or be removed by filtration, deposition, or ultraviolet treatment, but such processes require pollutant-specific representations. A passive-scalar model may therefore be appropriate for a first-order gas-dispersion study, but not automatically for size-resolved aerosols or chemically reactive mixtures.

The modelling framework should be selected according to the research objective. Scalar transport modelling may be sufficient to compare mean concentrations of a non-reactive gas under steady-state conditions. However, assessments of peak exposure, particle deposition, chemical transformation, or infection risk associated with aerosols require models that represent the processes relevant to these outcomes. Model validation should therefore rely on measurements that correspond to the quantities of interest and the conditions being investigated.

3. Mechanisms of Pollutant Dispersion

3.1 Airflow and ventilation pathways

The advection and mixing of contaminants occur in airflow due to advection and turbulent fluctuations, respectively. In natural ventilation, the pressure differences due to wind on the facades cause flow through openings, and temperature differences generate buoyancy and stack effects. A strong through-flow can be achieved with cross-ventilation in cases where the openings are well located, and pressure differences are adequate. Single-sided ventilation depends more heavily on fluctuating exchange and may be less effective at removing pollutants from deeper zones. Mechanical supply and exhaust may be more predictable but depend on the design of the diffuser, supply momentum, exhaust location,

filtration and room configuration. Reviews of wind-driven natural ventilation emphasize the dependence of predicted exchange on opening configuration and aerodynamic boundary conditions [7].

Exposure is not determined by ventilation rate. It is possible to have a high nominal air-change rate and poorly ventilated pockets when the supply jet short-circuits to an exhaust, or does not sweep the occupied space. Conversely, a well-directed flow may remove a local plume without requiring a proportionate increase in total airflow. This difference is significant to energy-conscious design: ventilation should be considered in the context of the elimination of contaminants and exposure at occupied locations, rather than the bulk flow rate.

Transport direction can be reversed by the interaction of wind and ventilation. One wind direction may act as an inlet and another as an outlet through a window. The concentration just outside a facade can be higher than the street-average concentration, so a ventilation opening can admit more polluted air than a city background monitor would indicate. Using an integrated indoor-outdoor CFD approach, substantial variability in indoor concentrations by floor, window configuration, and wind direction is reported; in some scenarios, room concentrations exceeded the spatially averaged street concentration [23].

3.2 Building aerodynamics: separation, wakes, and recirculation

Buildings behave as bluff bodies. Approaching flow speeds up around corners and over roofs, parting at sharp edges, and creating shear layers that entrain surrounding air. The downstream wake consists of recirculation, intermittent vortex shedding and strong spatial gradients. In cases where a pollutant source is present within or close to a wake, the local concentrations may increase due to the fact that the pollutant is carried over and over a recirculating region before it is removed. The wake location and size are determined by building aspect ratio, roof form, upstream turbulence, the wind direction, obstacles around and the thermal conditions. Early numerical work examined wind-induced dispersion around individual buildings [13].

The dominant vortex structure and exchange with the flow above roof level depend on the ratio of building height to street width and the direction of the approaching wind in street canyons. A canyon can sustain a primary recirculation cell, secondary corner vortices or more complicated three-dimensional structures at intersections [1]. Wind-tunnel and CFD experiments have demonstrated that the pollutant concentration is correlated with these structures, and a two-dimensional idealization can overlook significant along-street transport or intersection effects [26]. Thermal forcing is another source of variability in canyon circulation and dispersion [25].

For building arrays, the wake of one structure becomes the inflow condition for the next. This provides sheltering, channeling, and inter-building recirculation, and may extend the plumes compared to open terrain. The concentration of dust in a realistic residential community was closely related

to the flow field, with high concentrations associated with low-speed, high-vorticity regions [16]. In addition, atmospheric stability affects vertical dispersion within a building array; stable conditions resulted in higher concentrations compared to convective conditions in their wind-tunnel cases [17]. These findings indicate why the isolated-building validation cannot determine the model reliability of neighbourhood-scale prediction.

3.3 Indoor circulation, vertical transfer, and inter-zone transport

Inside buildings, flow is shaped by supply jets, buoyant plumes, thermal stratification, internal partitions, furniture, and pressure differences between rooms or floors. Upward natural-convection flows can be produced on warm surfaces and transport pollutants vertically. The impact of pollutant transmission in a high-rise building with combined wind and thermal wall-flows highlights the impact of solar heating on the facade, which can contribute to transport and inter-flat re-entry upward [19]. Vertical transport is especially applicable in cases where exhausts, shafts, stairwells, and facade openings connect zones with different pressures.

A well-mixed-zone assumption is a useful model that can be used to quickly calculate building energy or exposure, but it may hide near-source peaks and short-circuit flow. Pressure-driven exchange between rooms can be modeled as multi-zone, and local gradients can be solved at higher computational cost using CFD. The two approaches are complementary: zone models are suitable for large scenario ensembles and whole-building mass balances, whereas CFD can supply local transfer coefficients, ventilation effectiveness, and concentration fields for representative configurations.

3.4 Mass transfer, deposition, and surface interaction

At small scales, the concentration gradients are smoothed by molecular diffusion, but in large-scale flows such as those in rooms and buildings, mixing is frequently dominated by turbulent transport. In addition to turbulent fluctuations, advection is responsible for transporting contaminants along the flow, while turbulent fluctuations redistribute contaminants across mean streamlines. Nevertheless, occupant activity, cleaning, and local air movement can lead to resuspension in the case of particles. In the case of particles, settling and deposition are the processes that remove material from the airborne phase. Semi-volatile compounds can adsorb and desorb on surfaces as well, or be involved in a chemical reaction. These processes can maintain concentrations after the original emission has been removed; their importance depends on pollutant properties and environmental conditions.

The practical implication is that the boundary conditions that are pollutant-specific are significant. A model in which all walls are assumed to be a perfect non-depositing surface can overestimate airborne persistence of certain particles; a model in which all walls are assumed to be perfectly absorbing can underestimate re-entrainment or subsequent emissions. Such simplifications are justified in studies where the aim of the research is confined to the airflow-controlled delivery of a

tracer gas, but need to be explicitly specified and not generalized to contaminant types.

4. Modelling and Measurement Approaches

4.1 Analytical and reduced-complexity dispersion models

Screening-level estimates can still be made using Gaussian plume and other empirical models because they are fast and have relatively few inputs. They are able to help in regional assessments and comparisons of emission conditions, although their assumptions of idealized source geometry and dispersion conditions restrict their accuracy in the near field of individual buildings. Additionally, Lagrangian, Eulerian, and CFD methods must be used to mirror the spatial scale, pollutant nature, available data, and computational resources [11].

Lagrangian methods are useful for transporting particles and plume statistics by following particles or computational parcels along trajectories. Eulerian methods identify solutions to transport equations on a fixed grid and are well-suited for concentration fields and chemical species. Hybrid methods are Eulerian flows that utilize Lagrangian particles or multiple representations. There is no universally best framework; it all depends on whether the target of interest is mean concentration, instantaneous peaks, deposition, chemistry, or a large collection of scenarios.

4.2 Computational fluid dynamics

4.2.1 Reynolds-averaged Navier–Stokes (RANS)

RANS models are used to solve Reynolds-averaged momentum and scalar-transport equations, and turbulence closures are used to model the unresolved stresses and scalar fluxes. Steady RANS is an approximation of stationary mean flow, and unsteady RANS is an approximation that retains resolved time dependence of the averaged flow. Common closures include standard, renormalization-group (RNG), and realizable k - ϵ models, together with k - ω and shear-stress-transport (SST) variants. Their computational cost is attractive for design comparisons, and accuracy is dependent on the flow regime and the closure assumptions. The concentration intermittency and coherent unsteady structures, which can control local peaks and turbulent exchange, cannot be explicitly resolved by steady RANS.

Comparison with wind-tunnel data indicates that performance is dependent on geometry and the output quantity. Realizable k - ϵ model performed best for one low-stack case, whereas RNG k - ϵ gave better agreement for the highest stack; none of the tested closures reproduced all vertical concentration trends [10]. As such, turbulence models ought to be evaluated based on the particular concentration locations and flow features relevant to the application, but not based on a single global residual or velocity comparison.

4.2.2 Large-eddy simulation (LES)

LES solves the large turbulent eddies and approximates only the smaller subgrid-scale motions. It is able to capture the unsteady separation, vortex shedding, and turbulent fluctuations, spreading the concentration laterally and vertically. When the three-dimensional street canyon is

considered, LES and wind-tunnel output are closer together in mean concentration, particularly for the horizontal diffusion connected to unsteady variations [28]. LES is shown to be applicable in situations where peak concentration is important, in the case of regular arrays of cubic buildings [20].

The primary drawbacks of LES are the computational cost and grid-resolution sensitivity, time step, inflow turbulence, and averaging duration. A simulation of LES is not sufficient; the resolved eddy field must be well-developed, and the near-wall and inlet treatments should be optimal in relation to the Reynolds number and the building configuration. LES is therefore particularly valuable for benchmark cases, high-consequence releases, and problems where concentration fluctuations are central, while routine parametric design may require less expensive methods.

4.2.3 Unsteady RANS and hybrid approaches

Unsteady RANS is able to compute selected large-scale periodic fluctuations at reduced computational cost when compared to LES, but it does not resolve the full turbulence spectrum. In order to transport the pollutants around an isolated building using URANS, the URANS work positions of the potential are compromised, where the large coherent structures are dominant, yet complete LES is not feasible [14].

Another strategy is transport-based recurrence CFD, which seeks to employ a pre-computed transport database to model different events of pollutant releases effectively. However, it shows good agreement between recurrence CFD and LES using several evaluation metrics and demonstrates rapid simulation of alternative release locations once the database is available [4]. These methods are effective in emergency planning or repeated source cases, but their applicability requires that the underlying flow configuration and the boundary conditions be similar to the actual case.

4.2.4 Boundary conditions, geometry, and numerical verification

A credible CFD study needs to have more than a turbulence-model choice. It is important that the computational domain be sufficiently large in order to prevent the occurrence of artificial blockage and outlet feedback. Additionally, the incoming atmospheric boundary layer should be modeled with the intended velocity and turbulence profiles, and the geometry of the building and source should be resolved in order to capture the flow characteristics. Inlet turbulence is the most significant. There are many different ways of generating turbulent inflow that can create materially different concentration fields around a cubical building even though the upstream velocity fields may appear similar [32]. This indicates that scalar predictions may be more sensitive to inflow details than a velocity-only comparison suggests. Sensitivity to spatial-discretisation of the flow and concentration quantities, rather than pressure or solver residuals, is also suggested to be evaluated. In predicted shear layers and turbulent exchange, near-wall resolution, mesh quality, and separation and wake-region refinement are determined. The comparison between systematically refined meshes should be done based on facade concentration, plume position, wake length, ventilation rate, and (where applicable)

integrated pollutant flux. In the case of LES, the resolved fraction of turbulence changes with grid change; apparent mesh independence is thus not sufficient evidence of adequate resolution. Residual convergence is a numerical diagnostic, not proof of physical validity. The sensitivity of computational and physical parameters can also be highlighted by studies of the dispersion of pollutants in building arrays [3].

Additional important numerical options are steady or transient solution, pressure-velocity coupling, discretisation order, scalar diffusivity, particle-wall interaction, and convergence criteria. In transient simulation, the initial spin-up period must not be used in statistics and averaging window must be long enough to capture representative fluctuations. Sensitivity analyses are supposed to change the assumptions that are likely to dominate the outcome instead of making numerous changes in the parameters without a physical explanation.

4.3 Experimental and field methods

4.3.1 Wind-tunnel testing

Boundary-layer wind tunnels allow controlled studies on building aerodynamics, stack dispersion, street canyons, and building arrays. They provide repeatable inflow conditions and permit systematic variation of wind direction, geometry, source location, and atmospheric stratification. Gas analysers or fast-response detectors can be used to measure concentration, and hot-wire anemometry, laser Doppler velocimetry, or particle image velocimetry (PIV) can be used to measure velocity fields. Scaling requirements, model simplification, instrumentation density and the difficulty of comparing full-scale thermal and chemical processes are the primary limitations.

Wind-tunnel experiments are most applicable when they are developed as validation benchmarks rather than illustrative demonstrations. Similarity conditions can involve geometric scaling, roughness and boundary-layer profiles, turbulence properties, source momentum and buoyancy, and a suitable concentration scaling. Experimental uncertainty and instrument response time should be documented, particularly when instantaneous peaks or fluctuating concentrations are used for validation. Cross-ventilation experiments in sheltered and unsheltered conditions demonstrate the significance of external barriers in explaining contaminant transport [29].

4.3.2 Tracer-gas and full-scale measurements

Tracer-gas techniques can identify ventilation paths, inter-room transfer, air change rates, and contaminant re-entry. Real occupancy, weather, surface properties and operating conditions can also be studied in the field; they are difficult to control and can complicate the isolation of individual mechanisms [22].

PIV and other flow-visualization methods can provide spatial data on recirculation and turbulent structures that cannot be provided by point sensors. Velocity and concentration measurements cannot be used interchangeably: a flow field can appear reasonable, while the concentration field can be wrong because of source strength, scalar diffusivity, inflow

concentration, or boundary-condition errors. A strong validation programme should then make comparisons of the flow against pollutant quantities whenever feasible.

4.4 Validation, uncertainty, and model selection

Validation must be question-specific and multi-level. At minimum, it should assess (i) incoming boundary-layer profiles; (ii) velocity and turbulence around the building; (iii) concentration profiles at selected receptors; and (iv) integrated quantities such as ventilation rate or pollutant flux where measurements are available. It should not be assumed that calibration of a model to one configuration is applicable to other roof geometry, wind angle, source height, atmospheric stability, or building spacing.

Graphical comparisons can be complemented by quantitative measures like fractional bias, normalised mean-square error, correlation, and the proportion of observations that are within a factor of two of the actual. They should report their definitions, how they treat zero or below-detection-limit values, and averaging procedures. A high level of correlation does not establish low bias, and satisfactory aggregate agreement may conceal errors in receptors that are critical to exposure. Uncertainty assessment must be used to differentiate between uncertain inputs and measurements and numerical and model-form errors. They should be considered in the form of emissions, meteorology, boundary conditions, turbulence closure, discretisation, and building operation. Calibration and validation datasets should be separated wherever possible to reduce the risk of compensating errors.

5. Current challenges in pollutant dispersion management

5.1 Geometric and multi-scale complexity

Real constructions have balconies, recessed facades, parapets, courtyards, atria, internal partitions, shafts, and openings that have changing operational conditions. The sheltering and channeling are provided by neighbouring structures and the three-dimensional flow is provided by the intersections of streets and terrain. Resolving all details at once is often computationally infeasible. Simplification is unavoidable, but each simplification should be justified against the target quantity; a facade-level exposure estimate may require a different geometry from a room-level source-control study. The coupling across scales is also challenging. Small scales are molecular diffusion and surface interactions, whereas large scales are ventilation and urban recirculation, which are measured in metres to hundreds of metres. This can be solved by multi-scale modelling using nested domains, zonal models coupled with CFD or parameterisation of unresolved processes. The danger is that interface conditions between models may introduce errors that are comparable to the effect being studied.

5.2 Measurement and monitoring limitations

Pollutant concentrations are short-term near windows, exhausts, supply jets, and recirculation zones. A small number of fixed sensors may therefore fail to represent personal exposure or identify the true maximum

concentration. Sensors vary in selectivity, drift, response time, humidity sensitivity, and calibration requirements as well. The low-cost sensors may be used to scale up spatial coverage, but must be co-located, with quality assurance, drift correction, and missing data handled with care prior to application in control systems or regulatory decisions.

Monitoring design should be driven by the question: source identification may require high-frequency near-source sensors; exposure assessment may require measurements in the breathing zone; and model validation may require a distributed array across the plume. Fixed sensors can be combined with mobile measurements, tracer tests, occupancy data, and weather observations to increase interpretability. By contrast, personal exposure could differ from the area-average concentration, because individuals travel between microenvironments and spend different amounts of time near sources.

5.3 Energy, comfort, and indoor-air-quality trade-offs

Outdoor-air ventilation can be increased to dilute indoor-generated contaminants, but can also bring in outdoor pollution, add heating and cooling loads, or decrease thermal comfort. In certain cases, closing windows may help to reduce the entry of outdoor pollutants but may increase indoor-source accumulation. So, there is no single rule that fits all, like always maximizing natural ventilation or always sealing the envelope. Decisions should consider outdoor air quality, indoor source strength, occupant density, climate, filtration, and clean-air supply.

Particularly in older buildings, where facade modifications, duct installation, and advanced filtration can be either technically difficult or too expensive, retrofit constraints are especially applicable. The performance is also different with occupant behaviour; windows may be opened to achieve comfort, noise, odour or perceived freshness, and the maintenance of filters may be inconsistent. Good strategies need to be strong enough to be realistic in their operation and communicate trade-offs instead of being based on idealized design assumptions.

5.4 Standards, governance, and emerging contaminants

The covered pollutants differ in average period, measurement method, and enforcement of air-quality and building standards. Outdoor ambient standards may not capture short-term indoor peaks or exposure at an open window, and building energy standards may not specifically address outdoor pollution penetrating naturally ventilated rooms. New monitoring and risk-assessment challenges arise from emerging contaminants and altered exposure patterns.

Policy translation should clearly show the interrelation of source control, ventilation, filtration, building geometry, and exposure. The regulatory guidance must differentiate between source reduction and dilution, when outdoor-air intake must be limited or filtered, and encourage performance verification. Green-building certification can include measurable indoor-air-quality outcomes, but metrics should not reward energy savings at the cost of unacceptable contaminant exposure.

6. Opportunities and future directions

6.1 AI, machine learning, and sensor-model integration

Machine learning can be used to make surrogate prediction more efficient, detect patterns in high-dimensional sensor data, and enable optimization across many combinations of window state, fan speed, filtration, weather, and occupancy. Its strongest near-term application would be as a complement, rather than a replacement, to physical models. CFD can generate physically structured training data, and field sensors can correct model bias and update predictions in operation. Hybrid systems should maintain physical constraints, quantify uncertainty, and signal out-of-training conditions.

Real-time control cannot be achieved using a high-precision offline model. Sensors should be reliable, data latency needs to be minimal, and the controller should consider actuator limits, occupant comfort, energy consumption and pollutant-specific response time. A promising architecture combines source detection, short-term outdoor forecasts, indoor sensors, and a reduced-order model to select ventilation and filtration actions. These systems must be tested during sensor failure, changing occupancy and unusual weather conditions, not just during nominal conditions.

6.2 Smart ventilation and hybrid purification

Demand-controlled ventilation may adjust the outdoor-air supply based on occupancy and indoor indicators, whereas outdoor pollution sensors may help in deciding when the air needs to be filtered, when the windows need to be closed, or when the locations of intake need to be changed. However, CO₂ is an occupancy-related ventilation indicator rather than a universal pollutant proxy; it cannot reliably indicate PM, VOCs, ozone, or all biological aerosols. Multi-sensor control must thus be pollutant-conscious and must not assume that the air is clear based on a single indicator.

Depending on the mixture of pollutants, filtration, sorbents, electrostatic collection, photocatalytic processes, and other purification technologies can be combined. Particle filtration is not equivalent to gas-phase removal, and a device effective for one pollutant may be ineffective for another. Purification has to be measured in clean-air delivery rate, pressure drop, energy demand, formation of by-products, maintenance needs and performance in service life. Emissions from operations can be reduced by using renewable electricity and solar-powered systems; however, this requires climate, storage, and reliable operation.

6.3 Nature-based measures and urban form

Plants change flow and intercept particles in a context-specific way. Trees can remove some airborne particles, but can also reduce ventilation in a street canyon, which in some configurations increases local concentrations. Canyon flow and concentration changes due to trees [5], and this must be stressed, require consideration of vegetation type, canopy structure, particle deposition and the aerodynamic impact of vegetation planting [6]. Therefore, the assessment of nature-based interventions should be based on pollutant removal and

flow obstruction, species and planting geometry in the street or courtyard context.

Urban design can reduce exposure by separating sensitive inlets from major sources of emission, positioning exhaust outlets away from re-entrainment, maintaining exchange pathways above street canyons, and employing building massing which does not trap pollutants near pedestrian zones. All wind directions and atmospheric stability conditions should be considered in the evaluation of these interventions, as one geometry may be effective for one prevailing wind but not for other common or high-risk conditions.

6.4 Sustainable, equitable, and climate-resilient solutions

The air-quality strategies in future buildings should collaboratively address exposure, energy, cost, and resilience. The balance between outdoor-air supply and indoor protection could shift because of heat waves, wildfire smoke, dust events, and changing ventilation behaviour. Climate-adaptive operation should combine weather forecasts, outdoor pollution data, indoor sensing, and safe filtration capacity. Design should also consider occupants who cannot afford advanced filtration or live in buildings with limited retrofit options.

One implementation issue is equity. The populations living near major roads or industrial facilities might have higher outdoor concentrations and may have fewer options to relocate or retrofit. Emission control at source can be complemented by publicly available monitoring, transparent exposure mapping, and targeted support with ventilation and filtration. Transport, industrial, and land-use policies that reduce emissions prior to reaching occupied environments should not be replaced by building-level interventions.

6.5 Priority research agenda

The reviewed evidence results in five priorities. Develop open and reproducible benchmark cases that combine velocity, turbulence, concentration and uncertainty data for isolated buildings, street canyons, building arrays and indoor-outdoor configurations. Reporting of inflow turbulence, domain dimensions, mesh sensitivity, source definition, averaging duration, and validation metrics should be standardized as the second step. Third, couple indoor and outdoor models with realistic window operation, thermal buoyancy, filtration and pollutant-specific processes. Fourth, develop reduced-order models that are aware of uncertainty and can be updated based on sensor data. These models should be used in control without covering up any physical limitations. Fifth, assess interventions using exposure- and health-relevant metrics, and energy and cost, such as performance in adverse weather and unequal access to mitigation.

7. Conclusions

A coupled flow, transport, exposure and operational problem is pollutant dispersion around buildings. Indoor emissions, outdoor pollution, and building-to-building transfer interact through pressure-driven ventilation, buoyancy, turbulence, recirculation, and surface processes. Pollutants can be held in building wakes and street-canyon vortices, whereas opening

configuration and ventilation pathways can either dilute indoor emissions or increase outdoor-pollutant infiltration. Spatially averaged concentrations therefore provide only an incomplete description of exposure at occupied locations. CFD can address spatial patterns that sparse measurements might overlook, but model selection must be based on target quantity and available validation evidence. RANS is useful for lower-cost assessments of mean conditions; LES is more appropriate when resolved unsteadiness and concentration fluctuations are central; and URANS or recurrence methods offer conditional compromises for selected applications. These differences are not a global scale of accuracy. There are a number of factors that influence reliability, including inflow conditions, source representation, pollutant physics, numerical resolution, and statistically sufficient sampling. Instead of converged residuals or plausible velocity profiles, validation should include concentration quantities relevant to the exposure or design decision.

The synthesis supports a combined strategy of source control, geometry-sensitive design, pollutant-aware ventilation, filtration, and measurements based on validated models. Before generalizing proposed sensor-model and adaptive-control systems, one should evaluate their benefits (in terms of uncertainty, energy demand, maintenance and realistic operation). Open benchmarks and regular reporting would improve cross-method comparisons and translate the findings better into building decisions. The conclusions are qualitative due to the non-systematic selection of the literature and the heterogeneity of the configurations examined; they identify priorities but do not establish universal efficiencies of interventions or health benefits.

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