Spatiotemporal Dynamics of Residential VOC Emissions and Their Contribution to Indoor–Outdoor Air Pollution Coupling and Urban Atmospheric Chemistry

Dennis Hughes
Department of Computer Science, George Mason University, Fairfax, VA, USA.
denniswork@gmu.edu

Mason C. Edwards
Department of Computer Science, University of Alabama at Birmingham, Birmingham, AL, USA.
mason260@uab.edu

Abstract

Residential buildings represent a pervasive yet under-characterized source of volatile organic compounds (VOCs) that profoundly influence both indoor air quality and the reactive chemical environment of the outdoor urban atmosphere. The spatiotemporal dynamics of these emissions—governed by building materials, consumer product usage, occupant behavior, and ventilation regimes—create a complex coupling between indoor and outdoor domains that remains poorly integrated into air quality management frameworks. This paper advances a systems-level perspective on residential VOC emissions, examining the multiscale spatial heterogeneity from individual material outgassing to neighborhood-level aggregate fluxes, as well as the temporal signatures shaped by diurnal occupancy patterns, seasonal climate forcing, and episodic events. We analyze the mechanisms of indoor-to-outdoor transport and their implications for ozone and secondary organic aerosol formation in urban canopies, highlighting structural trade-offs between energy-efficient building envelopes and dilution of indoor pollutants. Computational architectures that couple building-level emission models with urban microclimate and atmospheric chemistry simulations are reviewed, along with the deployment of low-cost sensor networks and data assimilation strategies necessary to capture ground truth across heterogeneous housing stocks. The paper further addresses governance challenges, including regulatory fragmentation between indoor and outdoor air quality standards, equity concerns arising from differential exposures in vulnerable communities, and the resilience of monitoring infrastructure under climate change. We argue that achieving sustainable urban air quality necessitates an integrated socio-technical infrastructure paradigm in which residential VOC emissions are treated as a controllable boundary flux within city-scale atmospheric chemistry management. The analysis culminates in policy recommendations for harmonized indoor-outdoor standards, anticipatory building codes, and community-based sensing frameworks that collectively address the intertwined fates of indoor environments and urban airsheds.

Keywords

indoor air quality; volatile organic compounds; urban atmospheric chemistry; indoor-outdoor coupling; spatiotemporal modeling; building emissions; smart infrastructure; environmental governance.

1. Introduction

The composition of urban air is a dynamical outcome of myriad emission sources interacting with meteorological transport and photochemical transformation. While vehicular exhaust and industrial plumes have been the mainstay of air quality regulation for decades, a mounting body of evidence underscores the contribution of volatile organic compounds (VOCs) emanating from the built environment, particularly from residential interiors, to the reactive carbon budget of cities. VOCs such as formaldehyde, benzene, toluene, and a broad spectrum of terpenoids and glycol ethers are continuously released from building materials, furnishings, cleaning agents, personal care products, and occupant activities [1,2]. Because individuals in high-income countries spend approximately 90% of their time indoors, the immediate health implications of these compounds—ranging from sensory irritation to chronic respiratory and neurological effects—have rightly motivated a rich indoor air quality research tradition [3,4]. Yet the same compounds do not remain confined within building envelopes; they are exchanged with the outdoor environment through mechanical ventilation systems, natural infiltration, and window-opening behaviors, thereby feeding into the complex photochemistry that generates ground-level ozone and secondary organic aerosol (SOA) in the urban boundary layer [5,6].

Understanding the spatiotemporal dynamics of residential VOC emissions is therefore not merely an indoor environmental health problem but a core component of urban atmospheric chemistry and a critical junction where building science, environmental engineering, and urban governance intersect. The challenge is inherently multi-scale: emission rates vary by orders of magnitude from room to room, across building typologies, and between neighborhoods of differing socioeconomic status and construction vintage, while the temporal signatures reflect diurnal occupancy rhythms, episodic use of solvent-based products, seasonal ventilation patterns, and long-term material aging effects. Capturing this variability requires moving beyond static emission factors and spatially averaged source apportionments toward dynamic, context-aware representations of the residential sector as a distributed, adaptive source field that is modulated by both human behavior and building physics. Moreover, the policy domain remains fragmented, with indoor air quality guidelines and outdoor air quality standards developed largely in isolation, despite their physical and chemical inseparability. This separation leads to suboptimal trade-offs, for example when energy-efficiency retrofits reduce air exchange rates and inadvertently elevate indoor VOC concentrations, or when outdoor ozone infiltrates and initiates indoor chemistry that generates ultrafine particles and oxidized VOCs [7].

This paper undertakes a systematic examination of residential VOC emissions as a coupled indoor-outdoor phenomenon, emphasizing system-level architecture, modeling infrastructure, monitoring networks, governance, and equity. We trace the emission pathways from source materials through indoor transport and eventual venting to the urban atmosphere, discuss the fidelity and computational trade-offs of integrated simulation frameworks, and assess the social and policy dimensions that will determine whether future urban airsheds can be managed in a truly holistic manner. The analysis is grounded in the recognition that residential buildings are not passive containers but active chemical reactors and gateways whose collective behavior shapes the atmospheric commons.

2. Residential VOC Emission Sources and Spatial Heterogeneity

Residential VOC emissions arise from a heterogeneous portfolio of sources that differ fundamentally in their release mechanisms, time constants, and spatial distributions within buildings. Building materials—engineered wood products, adhesives, paints, varnishes, and insulation foams—constitute a persistent baseline emission that typically decays over months to years following construction or renovation, following characteristic diffusion-limited kinetics [8]. In parallel, a large and chemically diverse set of consumer products, including cleaning sprays, air fresheners, personal care items, and hobby materials, generate episodic, high-intensity emission pulses whose magnitude and composition are dictated by occupant choices and cultural practices [2,9]. Cooking activities and the use of gas stoves introduce additional VOCs such as acrolein and carbonyls, while resuspension of semi-volatile organic compounds sorbed onto indoor surfaces contributes to a continuously evolving gas-phase mixture [10].

The spatial structure of these emissions is hierarchical. At the microscale, individual rooms can exhibit VOC concentrations that vary by a factor of five or more depending on the presence of a freshly painted wall, a new piece of furniture, or the storage of cleaning chemicals. At the dwelling scale, floor plan, ventilation zoning, and the operation of localized exhaust fans create strong intra-unit gradients. Scaling up, building-level aggregates are affected by construction type, with multi-family housing blocks often showing distinct emission signatures compared to single-family detached homes due to differences in material inventories, maintenance schedules, and centralized ventilation systems. At the neighborhood and district scale, residential VOC source density becomes a function of housing age, renovation rates, occupant demographics, and commercial activity mixing. Socioeconomic gradients further pattern this landscape: lower-income housing stock tends to be older and may feature higher formaldehyde emissions from legacy pressed-wood products, while also experiencing smaller floor areas per occupant and lower ventilation rates, amplifying concentration exposures [11,14]. Conversely, affluent neighborhoods may exhibit higher per-capita usage of volatile chemical products, generating a different mixture of oxygenated VOCs that are highly reactive with respect to ozone and hydroxyl radical chemistry.

Accounting for this spatial heterogeneity is not a matter of academic nuance but an essential prerequisite for reliable urban air quality modeling and equitable public health policy. Bottom-up emission inventories that treat the residential sector as a uniform per capita or per-square-meter source strength will systematically misrepresent the concentration fields and reactivity distributions that determine secondary pollutant formation. Similarly, interventions such as low-VOC product mandates or mechanical ventilation standards will have differential efficacy across the building stock if not stratified by construction era, occupancy patterns, and baseline material emissions. A systems approach demands that spatial source models be composable—able to aggregate from material-level emission factors to room, dwelling, building, and city scales while preserving essential variability and uncertainty structures.

3. Temporal Dynamics and Human Activity Patterns

The temporal dimension of residential VOC emissions is shaped by an intricate interplay of deterministic material physics, stochastic human behavior, and externally forced environmental cycles. Emission rates from building materials typically follow a long-term decay that can be described empirically by power-law or double-exponential models, reflecting diffusion-limited release from semi-infinite slabs [4,8]. Superimposed on this slow decay are short-term fluctuations driven by temperature and relative humidity, with laboratory studies demonstrating that an increase of 10 degrees Celsius can multiply formaldehyde emission rates by a factor of 1.5 to 3.0. These thermal accelerations produce strong seasonal signals in naturally ventilated homes, where summer indoor temperatures rise in parallel with outdoor conditions, inducing a summer maximum in baseline VOC concentrations that coincides with the peak photochemical season, thereby amplifying the potential for indoor-outdoor coupling at the worst possible moment for urban ozone formation.

Human activity introduces a much higher-frequency modulation. Diurnal patterns are dominated by occupancy: mornings and evenings see spikes in product use, cooking, and showering that release complex VOC mixtures, while daytime hours in unoccupied homes often feature a quiescent period during which air exchange rates may be low in closed-up dwellings, allowing concentrations to accumulate. Weekday-weekend contrasts in time-activity patterns alter the timing of emission pulses, with potential implications for the specific hours at which residential VOC plumes merge with the evolving urban boundary layer [11]. Transient events such as cleaning binges, home repairs, or the introduction of new furnishings create episodic releases that can dominate a home's integrated monthly VOC budget. These events are difficult to predict without either extensive occupant diaries or passive sensing infrastructure capable of detecting chemical perturbations, posing a challenge for both exposure assessment and regional emission accounting.

Ventilation behavior functions as a critical gatekeeper that determines the fraction of emitted VOCs that are retained indoors versus released to the outdoor environment. The temporal pattern of window opening, mechanical fan operation, and central air handling system cycling is itself a complex function of outdoor temperature, perceived air quality, noise, and cultural norms. Energy-conscious retrofits that tighten building envelopes and reduce background infiltration may paradoxically increase both indoor VOC concentrations and the burst-like character of outdoor emissions, because the same tight envelope that limits continuous dilution causes occupants to periodically purge the space by opening windows, generating intense, short-duration effluent plumes. These dynamics underscore the need for models that couple stochastic occupant behavior modules with deterministic indoor air physics to faithfully reproduce both exposure peaks and cumulative atmospheric loadings.

4. Indoor-Outdoor Exchange Mechanisms and Urban Atmospheric Coupling

The physical pathways by which indoor VOCs enter the urban atmosphere are multiple and modulated by building design, mechanical systems, and micrometeorology. Air exchange between indoors and outdoors occurs through purpose-designed ventilation flows, leakage through the building envelope, and occupant-controlled window and door openings. In mechanically ventilated buildings, the exhaust airstream concentrates VOCs from multiple rooms and discharges them at a localized point, creating a point-source-like emission plume whose near-field dispersion can affect immediate outdoor air quality on sidewalks, in courtyards, and adjacent to air intakes of neighboring buildings. In naturally ventilated or leaky buildings, emissions are distributed over the entire façade and roof area, behaving as an area source that merges smoothly into the urban canopy layer.

Once outdoor, residential VOCs encounter a highly oxidizing environment where they participate in photochemical cycles that generate ozone, peroxyacyl nitrates, and secondary organic aerosol. The reactivity of residential VOC mixtures is often dominated by terpenoids such as limonene and alpha-pinene, which are abundant in fragranced products and cleaning agents, and which possess very high rate constants with ozone and nitrate radicals [5,6]. This high reactivity means that residential plumes can significantly influence local ozone production regimes, particularly in urban neighborhoods where nitrogen oxides from traffic and domestic combustion provide the necessary catalytic partners. In regions with strong weekend ozone effects, the shift in the VOC-to-NOx ratio partially attributable to residential activities and reduced commercial vehicle traffic underscores the sensitivity of atmospheric chemistry to the timing and composition of indoor-emitted VOCs. Moreover, the oxidation of these biogenic-like but indoor-sourced compounds contributes to the formation of secondary organic aerosol, with chamber studies demonstrating substantial SOA yields from limonene ozonolysis under atmospherically relevant conditions.

Capturing this coupling in predictive frameworks demands multi-media models that treat the indoor environment as a well-mixed or multi-compartment chemical reactor that exchanges mass and energy with an outdoor atmospheric boundary layer scheme. The air exchange rate, typically parameterized as a simple constant or temperature-dependent function in building energy models, must instead be recognized as a dynamic variable that co-evolves with indoor pollutant concentrations, outdoor meteorology, and occupant behavior. Furthermore, the chemical transformation of VOCs during the exfiltration process—through reactions with ozone and hydroxyl radicals in the building envelope cavity or the immediate lee of the building—remains poorly characterized yet could alter the reactive potency of the emission flux that ultimately reaches the neighborhood scale. Bridging the indoor-outdoor interface at the level of chemical detail required for regulatory-grade air quality modeling represents a frontier that demands tightly coupled building physics and atmospheric chemistry modules, as well as observational constraints from simultaneous indoor-outdoor measurements at neighborhood scales.

5. System-Level Modeling and Computational Architecture

Developing a system-level understanding of residential VOC dynamics requires computational architectures capable of integrating sub-models that operate across at least six orders of magnitude in spatial scale and fifteen orders of magnitude in temporal frequency. At the finest granularity, material emission models resolve diffusion and surface partitioning within a single board or adhesive layer, while at the coarsest, regional chemical transport models simulate the cumulative impact of entire metropolitan housing stocks on downwind ozone exceedances. Connecting these scales in a computationally tractable manner imposes fundamental trade-offs between mechanistic fidelity and parametric efficiency.

Multi-scale modeling frameworks that couple building energy simulation engines such as EnergyPlus or CONTAM with urban canopy parameterizations embedded in mesoscale meteorological models provide one pathway [10,13]. In such frameworks, individual buildings or representative archetypes are modeled as single-zone or multi-zone compartments with internal VOC sources, temperature-dependent emission factors, and ventilation flows resolved at sub-hourly time steps. The aggregated exhaust fluxes are then passed to a street-canyon dispersion model or directly injected into the lowest grid cells of an atmospheric chemistry-transport model. This approach preserves the causal link between indoor processes and outdoor concentrations, but it faces severe scaling bottlenecks when applied to cities containing hundreds of thousands of buildings. To address this, reduced-order emulators trained on large ensembles of detailed building simulations using machine learning techniques have been proposed, enabling the encapsulation of complex building physics into computationally lightweight parameterizations that can be embedded in urban airshed models [16].

Data assimilation presents another architectural pillar. The deployment of Internet-of-Things (IoT) enabled low-cost VOC sensors across residential and outdoor nodes, combined with mobile monitoring platforms, generates streaming data streams that can be ingested into digital twins of urban air quality. Sequential estimation methods such as ensemble Kalman filters can then nudge building emission parameters and ventilation rates to maintain consistency with observed concentration fields, effectively transforming the building stock into a distributed sensor-actuator network [12]. However, such architectures raise challenges of data harmonization, sensor drift correction, and latency-tolerant communication protocols, as well as profound questions about data ownership, privacy, and the potential for algorithmic discrimination if emission profiles are linked to identifiable households or communities. The design of the computational stack—from edge computing nodes that perform local anomaly detection to cloud-based fusion centers that run district-scale forecasts—must therefore navigate a space of trade-offs among accuracy, latency, energy consumption, and participatory governance, with the explicit recognition that air quality data infrastructure is inextricably a socio-technical system.

6. Infrastructure Deployment, Monitoring, and Governance

Translating research-grade understanding into operational management of residential VOC emissions requires a monitoring and intervention infrastructure that spans scales from individual homes to airshed regulatory bodies. Recent advances in low-cost metal oxide and photoionization sensors, when calibrated through co-location with reference instruments and augmented by machine-learning-based interference correction, have made dense spatiotemporal VOC monitoring technically feasible at costs that are orders of magnitude below those of traditional gas chromatography-based networks [11,17]. Such sensor networks, if strategically deployed across representative housing archetypes, can capture the subtle spatial gradients discussed in Section 2 and resolve the temporal dynamics of Section 3, providing the empirical foundation for data-driven emission inventories.

However, the deployment of residential sensing infrastructure immediately intersects with domains of governance, privacy, and public trust. Continuous monitoring inside homes, even of a class of compounds related to air quality rather than personal activity, can be perceived as intrusive. Transmitting indoor concentration data to municipal servers, even in anonymized or aggregated form, risks re-identification and misuse for purposes such as insurance profiling or code enforcement. Governance frameworks must therefore incorporate privacy-preserving designs, such as federated learning, on-device processing, or differential privacy mechanisms, that allow the extraction of aggregate emission statistics without exposing individual households' temporal activity patterns [20]. Furthermore, the distribution of sensors across the social geography of a city is rarely neutral; lower-income communities and communities of color, which frequently bear a disproportionate burden of outdoor air pollution, often have lower participation rates in voluntary sensor deployment programs unless specific community-based participatory research models are employed. Failure to address these equity dimensions in infrastructure deployment will reinforce existing environmental health data gaps and bias the evidence base that informs policy.

Regulatory governance of residential VOCs presents a fragmented institutional landscape. Indoor air quality is typically governed by voluntary guidelines, building codes that specify ventilation rates without source control targets, and product labeling schemes such as GREENGUARD or the European Union's indoor air emission classes. Outdoor VOC emissions from stationary residential sources fall under ambient air quality regulations in some jurisdictions, yet the diffuse and individually small nature of residential emissions has historically exempted them from permitting requirements that apply to industrial point sources. As scientific understanding of the aggregate atmospheric impact of residential VOCs grows, a policy gap becomes apparent: the existing regulatory architecture lacks mechanisms to incentivize or mandate source reductions in the residential sector that are commensurate with the sector's contribution to urban ozone and SOA. Bridging this gap will require innovative governance instruments that link building codes, product standards, real-time monitoring, and perhaps dynamic airshed management budgets that treat the residential building stock as a distributed source class subject to collective accountability.

7. Sustainability, Robustness, and Equity Considerations

The drive toward urban sustainability—expressed through deep energy retrofits, passive house standards, and high-density urban living—exerts a powerful but ambivalent influence on residential VOC dynamics. Reducing envelope leakage and installing heat-recovery ventilators can dramatically lower energy consumption for space conditioning, yet these same measures reduce the dilution of internally generated VOCs if source control is not simultaneously addressed. Chronic exposure to elevated indoor concentrations may then offset the health benefits of thermal comfort improvements. Conversely, natural ventilation strategies that lower indoor temperatures without mechanical energy input also allow greater ingress of outdoor ozone and particulate matter, which can initiate indoor chemistry that generates secondary pollutants. The sustainable building design space thus presents a multi-objective optimization challenge in which VOC source strength, ventilation rate, filtration efficiency, and energy use must be jointly managed, and where simplistic prescriptions are likely to create unintended harm.

Robustness of the indoor-outdoor air quality system under a changing climate adds further complexity. Rising outdoor temperatures and more frequent heatwaves increase both the temperature-driven emission rates of indoor materials and the likelihood that occupants will seal their homes and engage air conditioning, altering the ventilation pattern and potentially trapping VOCs indoors during the hottest hours. Wildfire smoke events, which are increasing in frequency and severity across many regions, prompt occupants to close windows and operate recirculation modes, drastically reducing air exchange rates and causing a buildup of indoor-emitted VOCs that can synergize with infiltrated smoke particles to degrade indoor air quality catastrophically. The monitoring and modeling infrastructure described earlier must be robust to these compound hazard scenarios, capable of operating during power outages and communication disruptions, and adaptive enough to provide actionable guidance to residents and emergency managers.

Equity remains a persistent cross-cutting theme. The capacity to mitigate residential VOC exposure through material substitution, ventilation upgrades, and air cleaning technologies is unevenly distributed across income strata and housing tenures. Renters have limited agency to replace VOC-emitting flooring or cabinetry, and low-income homeowners often lack the capital for deep retrofits. At the same time, policies that increase the stringency of building codes or mandate the use of certified low-emitting materials may raise construction costs and exacerbate housing affordability crises if not accompanied by financial support mechanisms. A truly just transition to healthier indoor environments and cleaner urban air must therefore integrate housing policy, energy policy, and air quality policy, recognizing that the residential building stock is simultaneously a determinant of public health, a climate action lever, and a zone of lived inequality.

8. Policy Implications and Future Directions

The mosaic of findings synthesized in the preceding sections leads to the inescapable conclusion that a paradigm shift is needed in how residential VOC emissions are governed.

Current bifurcation between indoor air quality guidelines and outdoor air quality standards is intellectually obsolete and operationally counterproductive. A unified indoor-outdoor air quality management framework would treat buildings as active elements of the urban atmospheric system, with emission performance standards that are sensitive to both the absolute toxicity of emitted compounds and their outdoor reactivity. Such a framework could take the form of building air quality budgets analogous to energy budgets, where a new construction or major renovation must demonstrate through modeling and post-occupancy measurement that its projected indoor VOC concentrations and outdoor emission fluxes fall below prescribed thresholds under typical meteorological and occupancy scenarios.

Product-oriented interventions, such as extending California's low-VOC consumer product regulations to address reactivity-based metrics rather than simple mass-based content limits, represent a near-term avenue with proven efficacy. However, product standards must be complemented by real-time performance monitoring enabled by building automation systems and community sensor networks, creating a feedback loop that can detect non-compliance, drive behavioral change, and iteratively refine standards. The emergence of digital product passports that track the chemical content of building materials across their lifecycle could provide the informational substrate necessary to construct whole-building emission inventories at the time of design and to facilitate deconstruction and material reuse that minimizes legacy VOC burdens.

On the research frontier, several grand challenges demand interdisciplinary collaboration. Developing community-resolved urban atmospheric chemistry models that assimilate indoor sensor data streams in real time will require advances in scalable inference algorithms, privacy-preserving data aggregation, and probabilistic emulation of building physics. Laboratory and field studies that characterize the chemical evolution of residential VOC mixtures during exfiltration through building envelope materials and within the complex flow fields of urban canopies are urgently needed to close the gap between emission factors and effective atmospheric reactivity. Longitudinal cohort studies that track the health outcomes of populations living in housing retrofitted to different VOC emission and ventilation standards would provide the evidence base necessary to quantify the public health benefits and costs of integrated indoor-outdoor management. Finally, transdisciplinary action research that codesigns sensor deployment programs, data governance protocols, and policy interventions with communities most affected by air pollution can ensure that the transition to smart, healthy buildings does not replicate the environmental injustices of the past.

9. Conclusion

Residential VOC emissions constitute a paradigmatic example of a coupled human-natural-technical system whose dynamics span the molecular scale of diffusion within a wood composite to the regional scale of photochemical smog formation. The spatial heterogeneity of sources across rooms, buildings, and neighborhoods, combined with temporal rhythms driven by product usage, occupancy, meteorology, and building physics, demands that research and policy move beyond static average emission factors toward dynamic, context-sensitive, and infrastructure-mediated representations. The indoor-outdoor exchange of VOCs is not a simple dilution process but an active chemical interface that modulates both human exposure indoors and the oxidative capacity of the urban atmosphere outdoors. Computational architectures capable of simulating this coupling are within reach, enabled by advances in building energy modeling, machine learning emulation, and low-cost environmental sensing, yet their deployment at societal scale hinges on resolving profound governance challenges around privacy, equity, and institutional fragmentation. As cities worldwide pursue aggressive climate and health goals, the intelligent management of residential VOC emissions—through source control, dynamic ventilation, and anticipatory regulation—must be recognized as an integral component of sustainable urban infrastructure, on par with energy grids, transportation networks, and water systems. Only by embracing the full spatiotemporal complexity of the indoor-outdoor atmospheric continuum can we design built environments that safeguard both the intimate air of the home and the shared air of the city.

References

1. Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., ... & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Analysis and Environmental Epidemiology, 11(3), 231–252.

2. McDonald, B. C., de Gouw, J. A., Gilman, J. B., Jathar, S. H., Akherati, A., Cappa, C. D., ... & Trainer, M. (2018). Volatile chemical products emerging as largest petrochemical source of urban organic emissions. Science, 359(6377), 760–764.

3. Weschler, C. J. (2009). Changes in indoor pollutants since the 1950s. Atmospheric Environment, 43(1), 153–169.

4. Xiong, J., Wei, W., & Zhang, Y. (2016). Indoor air quality and health: Formaldehyde and other aldehydes. Building and Environment, 107, 91–106.

5. Liu, S., Thompson, S. L., Stark, H., Ziemann, P. J., & Jimenez, J. L. (2019). Gas-phase carboxylic acids emitted from cooking and their contribution to ambient organic aerosol. Environmental Science & Technology, 53(21), 12420–12428.

6. Pagonis, D., Price, D. J., Algrim, L. B., Day, D. A., Handschy, A. V., Stark, H., ... & Jimenez, J. L. (2022). Time-resolved measurements of indoor volatile organic compound emissions from human occupants and their ozone-initiated oxidation products. Environmental Science & Technology, 56(15), 10722–10732.

7. de Gouw, J. A., Gilman, J. B., Kim, S. W., Alvarez, S. L., Dutton, S. J., Lerner, B. M., ... & Warneke, C. (2018). Chemistry of volatile organic compounds in the Los Angeles basin: Formation of oxygenated VOCs and the relative importance of anthropogenic and biogenic sources. Journal of Geophysical Research: Atmospheres, 123(4), 2278–2295.

8. Fan, Y., Hu, C., Wang, Z., Wang, H., Zhang, R., Jiang, D., ... & Koutrakis, P. (2025). Residential VOC from building materials: Exposures, health risks, and ambient hazards. Sustainable Cities and Society, 119, 106080.

9. Nazaroff, W. W., & Weschler, C. J. (2004). Cleaning products and air fresheners: exposure to primary and secondary air pollutants. Atmospheric Environment, 38(18), 2841–2865.

10. Dols, W. S., & Polidoro, B. J. (2015). CONTAM user guide and program documentation version 3.2. NIST Technical Note 1887.

11. Morawska, L., Thai, P. K., Liu, X., Asumadu-Sakyi, A., Ayoko, G., Bartonova, A., ... & Williams, R. (2018). Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environment International, 116, 286–299.

12. Choi, W., Paulson, S. E., & Winer, A. M. (2019). Data assimilation of real-time indoor and outdoor air quality measurements for source apportionment and predictive control. Building and Environment, 165, 106388.

13. Martilli, A., Clappier, A., & Rotach, M. W. (2002). An urban surface exchange parameterisation for mesoscale models. Boundary-Layer Meteorology, 104(2), 261–304.

14. Adamkiewicz, G., Zota, A. R., Fabian, M. P., Chahine, T., Julien, R., Spengler, J. D., & Levy, J. I. (2011). Moving environmental justice indoors: Understanding structural influences on residential exposure patterns in low-income communities. Environmental Health Perspectives, 119(6), 806–812.

15. Zhu, Y., Hinds, W. C., Krudysz, M., Kuhn, T., Froines, J., & Sioutas, C. (2015). Penetration of freeway ultrafine particles into indoor environments. Journal of Aerosol Science, 36(3), 303–322.

16. Zhou, X., Zhou, Z., & Liu, J. (2020). Machine learning for indoor air quality prediction: A systematic review. Science of The Total Environment, 748, 141352.

17. Logue, J. M., McKone, T. E., Sherman, M. H., & Singer, B. C. (2011). Hazard assessment of chemical air contaminants measured in residences. Environmental Health Perspectives, 119(6), 815–820.

18. Fisk, W. J., Black, D., & Brunner, G. (2011). Benefits of energy efficiency and the unintended consequences for indoor air quality. Indoor Air, 21(5), 357–363.

19. Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., & Djurovic-Petrovic, M. (2010). A review of bottom-up building stock models for energy consumption in the residential sector. Energy and Buildings, 42(10), 1988–1999.

20. Poirot, R. L., Koutrakis, P., & Suh, H. H. (2021). Community-based air monitoring in environmental justice neighborhoods: From data to action. Environmental Research, 195, 110831.