

Review

Indoor Air Quality: A Comprehensive Evidence-Gap Synthesis, Policy Failures, and a Framework for Future Action

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Abstract

Urban residents spend an estimated 80–90% of their time indoors, yet urban indoor air quality (IAQ) science remains fragmented across pollutant types, settings, mitigation strategies, and governance contexts, contributing to an estimated 6.7 million deaths annually from indoor air pollution worldwide. This review asks the following question: what are the critical, multi-dimensional research and governance gaps in urban IAQ, and how can they be systematically derived and organized into a reference framework for future research and policy? A PRISMA 2020-aligned hybrid systematic evidence synthesis, combining bibliometric science mapping and structured thematic synthesis, was conducted across 105 records, primarily published between 2011 and 2026, with three pre-2011 foundational records retained, spanning 15 national contexts. A seven-stage hybrid deductive–inductive derivation procedure was applied to the coded corpus to produce the Multi-Dimensional Gap Identification Framework (MGIF), organizing research gaps across five dimensions: knowledge, methodological, technological, policy and implementation, and equity and urban context. Recurrent gaps include the absence of multi-pollutant mixture assessment in monitoring frameworks, the lack of standardized measurement protocols limiting cross-study comparability, a systematic gap between laboratory-validated and field-measured intervention performance, the near-total absence of enforceable indoor air quality standards across most jurisdictions, and the severe underrepresentation of Global South populations in both primary evidence and regulatory design. Building on the MGIF output, the Urban Indoor Air Quality Nexus (UIAQN) is proposed as a four-level conceptual organizing architecture linking pollutant dynamics, building systems, personal exposure, and governance mechanisms. Both frameworks are grounded in the coded corpus, have not been subjected to external validation, and are designed as structured reference architectures for future research investment, standard harmonization, and equity-centered policy design rather than as empirically validated predictive models.

Keywords: urban indoor air quality; evidence synthesis; thematic synthesis; indoor–outdoor coupling; ventilation and filtration; multi-pollutant exposure; environmental justice; bibliometric analysis



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1. Introduction

Across high-, middle-, and low-income countries, urban populations spend an estimated 80–90% of their time inside buildings (homes, workplaces, schools, and transit environments), making indoor air quality (IAQ) the dominant driver of daily pollutant intake [1–3]. In urban settings, indoor air is shaped by indoor-generated pollutants (particulate matter (PM) from cooking and combustion, volatile organic compounds (VOCs) from building materials and consumer products, nitrogen dioxide (NO₂) from gas appliances, and formaldehyde (HCHO) from interior finishes) and by the continuous infiltration of outdoor urban pollution driven by traffic, industrial activity, and biomass burning [4–6]. The resulting exposure burden is substantial: indoor air pollution contributes to approximately 6.7 million deaths annually worldwide [3,7], and urban indoor PM_{2.5} and VOC concentrations frequently exceed both outdoor levels and established health guidelines [8–10].

The scientific literature on IAQ has grown substantially over the past two decades. Existing reviews have characterized the sources and concentrations of specific pollutants in defined indoor environments [5,11,12], examined health impacts of prolonged exposure to PM and gaseous contaminants [10,13–15], and evaluated performance of individual mitigation technologies including mechanical ventilation, high-efficiency filtration, and air purification systems [11,16,17]. Advances in low-cost sensor technology have expanded the capacity for large-scale IAQ monitoring [18–20], and exposure assessment methods have improved in resolution and ecological validity [21,22]. Nevertheless, critical structural gaps persist across multiple dimensions: existing reviews address single pollutants or isolated settings [5,23]; the evidence base is geographically concentrated in high-income cities [24,25]; laboratory-validated interventions frequently perform differently in real-world buildings [26,27]; and equity dimensions (the disproportionate IAQ burden on low-income, elderly, and otherwise vulnerable urban populations) remain largely unaddressed in both research and policy design [2,25,28].

Addressing these gaps requires a structured, integrative approach capable of synthesizing evidence across heterogeneous study designs and governance contexts. This paper therefore pursues the following research question: what are the critical, multi-dimensional research and governance gaps in urban indoor air quality science, and how can they be systematically derived and organized into a reference framework for future research and policy? The synthesis is conducted and reported in accordance with the PRISMA 2020 guidelines [29]; the study selection flow, eligibility criteria, and quality appraisal procedures are detailed in Section 3. Three contributions respond to this question. First, a PRISMA 2020-aligned hybrid systematic evidence synthesis combining bibliometric science mapping and structured thematic synthesis across 105 records spanning 15 national contexts provides the coded evidence base from which gaps are derived. Second, the Multi-Dimensional Gap Identification Framework (MGIF) applies a seven-stage hybrid deductive–inductive derivation procedure to organize critical research gaps across five dimensions (knowledge, methodological, technological, policy and implementation, and equity and urban context), grounded directly in the coded literature corpus. Third, the Urban Indoor Air Quality Nexus (UIAQN) translates the gap structure into a four-level conceptual organizing architecture linking pollutant dynamics, building systems, personal exposure, and governance mechanisms. Neither framework has been subjected to external validation; both are offered as structured reference architectures intended to guide future research investment, measurement standardization, and equity-centered policy design.

2. Background

Indoor and household air pollution represent major preventable environmental health burdens globally, contributing to approximately 6.7 million deaths annually [3,30]. Approx-

imately 2.3 million of these deaths are attributable to direct household air pollution from solid fuel combustion, with an additional 0.77 million arising from the pathway by which household combustion emissions escape outdoors and augment ambient PM_{2.5} concentrations [30]. In 2020, household air pollution was responsible for an estimated 3.2 million deaths, including more than 237,000 deaths of children under five [31]. This burden is geographically uneven: low- and middle-income countries in South Asia, sub-Saharan Africa, and parts of Latin America carry the greatest exposure burden while simultaneously having the weakest monitoring infrastructure and lowest regulatory capacity [24,30,32].

In urban settings, this burden is compounded by deteriorating outdoor air quality. PM_{2.5} concentrations are rising in 65% of cities globally, NO₂ is increasing in 71% of cities, and surface ozone is growing at 89% of monitoring stations [33]. These outdoor trends directly elevate indoor exposure through building infiltration, linking urban indoor air quality to ambient pollution dynamics [34,35]. Urban indoor environments are simultaneously shaped by infiltrating outdoor pollutants and by internally generated sources including cooking combustion, building material emissions, and occupant activities, creating a multi-source exposure environment that is more complex and less consistently regulated than outdoor air across most jurisdictions [6,10,23,36].

Urban indoor air contains a heterogeneous mixture of chemical, physical, and biological pollutants that substantially exceeds the conventional regulatory focus on a small set of criteria pollutants [10,23]. PM_{2.5} remains the most extensively studied and health-relevant conventional pollutant, but particle composition, not mass concentration alone, determines toxicological potency: source mixture matters as much as total mass for estimating health risk [37–39]. VOCs constitute the second most extensively studied pollutant class, generated simultaneously by building materials, combustion processes, consumer products, and outdoor transport [6,12,40,41]. Formaldehyde warrants particular attention as a Group 1 carcinogen with material emission decay times ranging from weeks to years depending on product quality [42,43]. Foundational indoor air pollution science and later residential monitoring studies also indicate that formaldehyde concentrations can vary with both building age and season [44–46]. Beyond these conventional pollutants, emerging contaminants (microplastics, magnetic nanoparticles, endocrine-disrupting chemicals, and perfluoroalkyl substances) are increasingly identified in indoor environments but remain absent from monitoring frameworks and health-level standards globally [47–49].

Figure 1 illustrates the integrated urban indoor air pollution system, showing the source–pathway–exposure architecture that the MGIF and UIAQN frameworks are designed to organize, the layered structure that Sections 4.3–4.8 document empirically before Section 4.9 maps it onto the five gap dimensions.

The regulatory landscape governing these pollutants is fragmented and predominantly non-enforceable. A comparative analysis of 26 IAQ standards across six countries plus the WHO found that biological contaminants, mixture effects, and emerging contaminants are largely absent from health-level frameworks, and that TVOC thresholds vary ten-fold across equivalent certification levels [50]. More than 840 IAQ limit values exist across 40+ countries, yet only one-third carry enforceable legal status [51]. European policy frameworks have called for coordinated action across building codes, product standards, and public health guidelines [52]. This regulatory fragmentation, combined with the multi-pollutant complexity of urban indoor air, creates a governance environment in which available technical evidence is not consistently reflected in enforceable IAQ policy frameworks.

The IAQ literature has grown substantially over the past two decades, and several systematic reviews have made important contributions to specific aspects of the field. Vardoulakis et al. [10] provided a systematic assessment of indoor exposure to selected pollutants in residential settings. Mannan and Al-Ghamdi [23] reviewed factors and

activities affecting IAQ with a focus on healthy building design. González-Martín et al. [11] conducted a comparative technology review evaluating removal efficiencies across filtration, adsorption, and biological treatment systems. Maung et al. [53] conducted a systematic review of IAQ impacts on vulnerable groups including children and people with pre-existing lung disease. Recent review and mapping work has also focused specifically on VOC emissions from building materials, further reinforcing the importance of material-related indoor pollution sources [54].

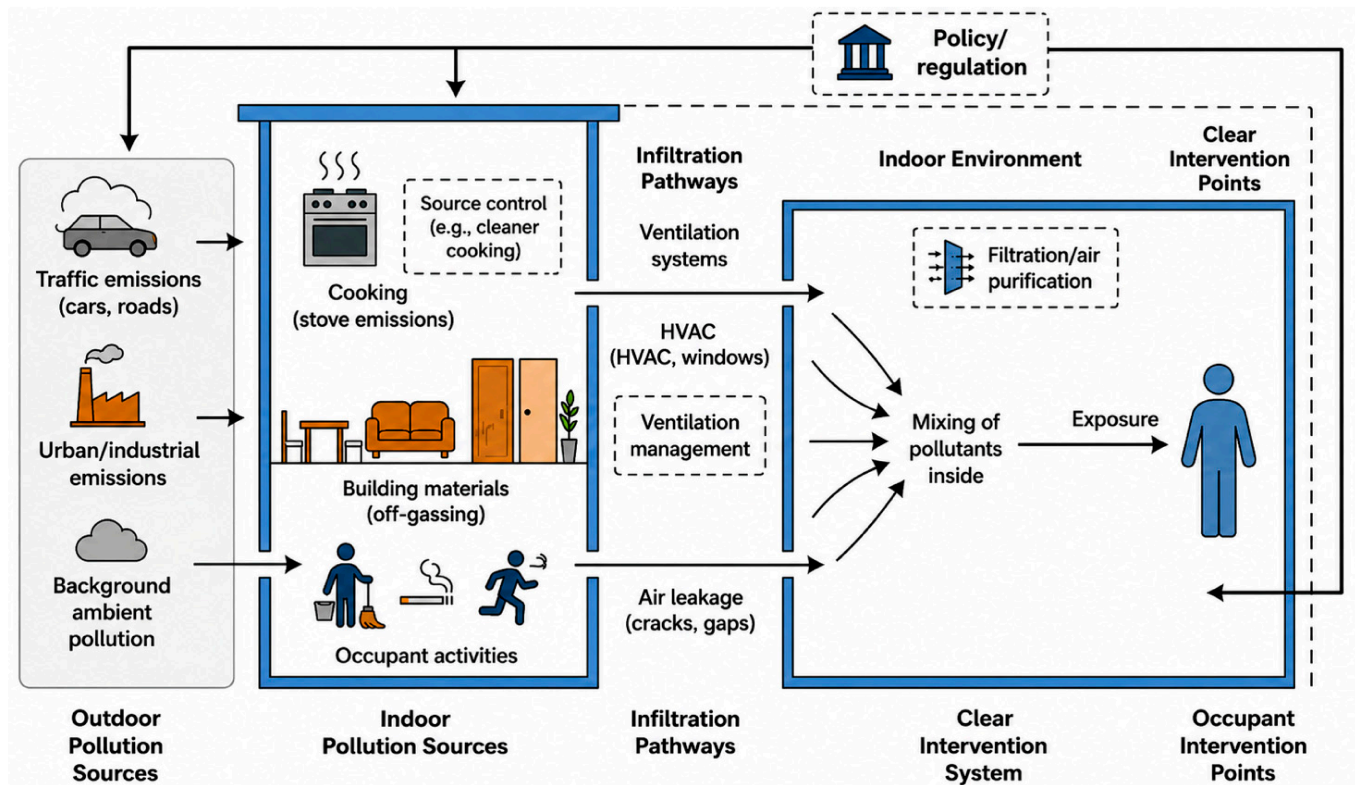


Figure 1. Integrated urban indoor air pollution system and intervention pathways.

Collectively, these reviews have advanced the field in important ways. However, they share four structural limitations that constrain their utility as a foundation for future research and policy investment. First, they address individual pollutant classes or isolated building settings rather than integrating across the multi-pollutant, multi-setting complexity of urban indoor environments [12,23]. Second, primary empirical evidence is geographically concentrated in high-income urban settings in North America, Europe, and East Asia, leaving Global South urban contexts (where the indoor pollution burden is highest) severely underrepresented [24,25,53]. Third, interventions are evaluated largely under controlled or laboratory conditions, with limited attention to the systematic performance gaps that emerge in real occupied buildings [26,27]. Fourth, equity dimensions (the disproportionate IAQ burden on low-income households, children, older adults, and vulnerable urban populations) remain peripheral rather than central in both the research designs and policy recommendations of prior reviews [2,25,28]. Prior reviews have generally not combined a procedurally documented, multi-dimensional gap identification procedure with an integrative conceptual framework within a single synthesis. The MGIF and UIAQN are distinguished from prior frameworks primarily by the transparency of the gap derivation procedure and by the explicit embedding of gap dimensions as structural components of the framework architecture, rather than by the novelty of the constructs themselves.

3. Review Design and Methodology

3.1. Research Design and Epistemological Position

This study is designed as a convergent, multi-method hybrid systematic evidence synthesis to address the research question stated in Section 1: what are the critical, multi-dimensional gaps in urban indoor air quality science, and how can they be systematically derived and translated into an integrated framework? The design integrates quantitative bibliometric science mapping, structured thematic synthesis, and evidence-gap framework development, each component serving a distinct function in answering the research question. The bibliometric component maps the intellectual structure and emerging frontiers of the urban IAQ literature through objective citation and keyword patterns. The thematic synthesis component organizes and interprets evidence across heterogeneous study designs to identify cross-study patterns and derive structured research gaps. This dual-method architecture is suited to the urban IAQ domain, a disciplinary breadth that resists reduction to either a purely quantitative or a purely interpretive synthesis approach. The hybrid systematic evidence synthesis is conducted and reported in accordance with the PRISMA 2020 guidelines [29]. The thematic synthesis component follows the six-phase framework of Thomas and Harden [55], which was developed for hybrid systematic reviews integrating evidence across heterogeneous study designs and provides explicit guidance on inductive code development, analytical theme formation, and interpretive transparency. The review protocol, eligibility criteria, search strategy, and quality appraisal instrument were fully specified prior to data extraction and are reported in detail in this section.

Unlike conventional systematic reviews restricted exclusively to primary empirical studies, the present review incorporated multiple evidence strata, each serving a distinct analytical role within the synthesis framework. Primary empirical studies (field monitoring, intervention trials, epidemiological surveys, and sensor validation studies) provided the quantitative exposure, efficacy, and health outcome evidence that anchors specific gap claims. Systematic and scoping reviews and meta-analyses were used to identify field-level consensus, characterize the geographic and thematic scope of prior evidence, and corroborate the recurrence of patterns across study populations; they were not treated as a substitute for primary evidence when primary records were available. Modeling and simulation studies contributed theoretically grounded estimates of concentration dynamics, ventilation performance, and outdoor–indoor coupling under specified conditions. Policy and technical guidance documents from authoritative bodies (WHO, US EPA, European Commission) were used exclusively to characterize the regulatory and governance landscape and were not treated as empirical evidence for health or exposure claims. A recognized methodological consequence of this mixed-evidence architecture is that some primary studies informing included systematic reviews may also appear indirectly within the corpus through the reviews that synthesized them. This potential for overlap was managed in three ways: quantitative effect estimates cited in the Results are traced to the primary empirical source wherever possible rather than attributed to the review that reported them; no statistical pooling of effect sizes was performed across evidence strata; and the four-tier inference framework described below explicitly separates the evidentiary weight assigned to each evidence type so that Tier 4 review-level claims are distinguished from Tier 1–2 primary evidence throughout. These measures reduce but do not eliminate the overlap risk, which is acknowledged as a limitation in Section 5.5.

3.2. Literature Search Strategy

A systematic multi-database search was conducted across six sources: Web of Science Core Collection (primary source for environmental and engineering sciences), Scopus (broadest international coverage), PubMed/MEDLINE (health exposure and epidemiologi-

cal literature), Engineering Village/Compendex (building science and HVAC engineering), WHO IRIS/US EPA Publications (authoritative technical reports on IAQ standards and guidelines), and Google Scholar (used exclusively for gray literature identification and cited reference chain checking, not as a primary Boolean search database). Database searches were conducted between 14 January 2026 and 6 May 2026. Web of Science Core Collection and Scopus were searched first (14–16 January 2026), followed by PubMed/MEDLINE and Engineering Village/Compendex (19–21 January 2026), and then WHO IRIS/US EPA Publications and Google Scholar (28–30 January 2026). All searches used the same core Boolean string applied to title, abstract, and keyword fields. The search end date of 6 May 2026 reflects the date of the final Google Scholar reference chain check. Records published after 6 May 2026 are not included in the corpus. The rationale for multi-database searching is well established: single-database searches have been estimated to miss a substantial proportion of eligible studies in environmental science domains.

The search strategy, eligibility criteria, data extraction fields, and thematic synthesis structure were all organized around a PECO framework adapted for environmental evidence synthesis, ensuring structural consistency from research question to analytical output. Population represents urban indoor occupants in residential, school, office, and transit settings, corresponding to the geographic setting and indoor setting type eligibility criteria in Table 1 and to the occupant demographics and building type fields in the data extraction form. Exposure represents indoor air pollutants including PM_{2.5}, PM₁₀, UFPs, VOCs, NO₂, CO, CO₂, radon, formaldehyde, SVOCs, biological agents, and emerging contaminants, corresponding to the pollutants covered eligibility criterion in Table 1 and to the pollutants measured and instruments used extraction fields. Comparator represents different ventilation strategies, mitigation conditions, building types, and regulatory contexts, corresponding to the primary ventilation strategy and outdoor pollution context extraction fields and to the comparator terms in the Boolean search string. Outcome represents pollutant concentration levels, personal exposure metrics, health outcomes, mitigation efficacy, and policy or standards analysis, corresponding to the outcome measures eligibility criterion in Table 1 and to the key quantitative results and effect sizes extraction fields. This four-element alignment ensured that no record could be included whose evidence did not map onto at least the P and E elements, and that extraction fields captured the C and O elements consistently across all 105 records.

Table 1. Eligibility criteria applied during two-stage systematic screening.

Criterion	Inclusion	Exclusion	Rationale
Publication type	Peer-reviewed journal articles; systematic reviews and scoping reviews with explicit search methodology; meta-analyses; WHO and government technical reports with documented evidence base	Conference abstracts; editorials and commentaries without primary data; gray literature without documented methodology; preprints not yet peer-reviewed	Ensures a minimum standard of methodological transparency across all included records; technical reports from authoritative bodies (WHO, US EPA) are retained given their policy relevance and documented evidence base
Publication date	2011–2026 (primary window); seminal pre-2011 foundational works retained where they represent the primary or most cited source for a specific empirical or methodological contribution not superseded by more recent literature	Studies published before 2000 unless foundational to the field and not superseded	The 2011 start date reflects the period of substantial growth in urban IAQ monitoring and sensor technology literature; three pre-2011 records were retained under the foundational-works provision

Table 1. Cont.

Criterion	Inclusion	Exclusion	Rationale
Geographic setting	Urban and peri-urban indoor environments across all income settings and geographic regions	Exclusively rural settings with no urban comparison arm; outdoor-only studies with no indoor component	Urban specificity is central to the review scope; peri-urban settings are included given functional overlap with urban exposure contexts
Indoor setting type	Residential dwellings; school and educational buildings; office and workplace environments; transit environments; mixed-use urban buildings	Agricultural, industrial, or occupational settings without residential or public building comparator	Restricts the corpus to settings where urban residents spend the majority of their time indoors
Pollutants covered	PM _{2.5} , PM ₁₀ , ultrafine particles (UFPs); VOCs including formaldehyde (HCHO) and BTEX compounds; NO ₂ , CO, CO ₂ , ozone (O ₃); radon; SVOCs; biological agents (mold, bacteria, allergens); emerging contaminants (microplastics, PFAS, EDCs, magnetic nanoparticles)	Studies addressing outdoor-only pollutant concentrations with no indoor component or exposure pathway; studies restricted to a single occupational contaminant with no residential or public building relevance	Multi-pollutant scope is a defining feature of this review; emerging contaminants are included to support MGIF Dimension 1 (knowledge gaps) even where primary evidence is nascent
Outcome measures	Pollutant concentration measurements; personal exposure metrics; health outcome data; mitigation or intervention efficacy; policy, standards, or regulatory analysis; methodological or framework development relevant to IAQ assessment	Studies without any quantitative, semi-quantitative, or structured qualitative reporting of IAQ-relevant outcomes; purely theoretical modeling studies with no empirical validation component	Minimum reporting standard required to enable quality appraisal; purely theoretical papers are excluded unless they include empirical validation data
Language	English-language full text	Non-English publications without an English-language abstract containing sufficient data for quality appraisal	English restriction is acknowledged as a limitation in Section 5.5; non-English abstracts were screened where available to assess potential eligibility
Methodological quality	Sufficient methodological reporting to permit quality appraisal scoring (minimum score ≥ 4 on the eight-domain instrument; Table 2)	Studies with critical and unresolvable risk-of-bias issues; studies with insufficient methodological reporting to permit scoring on at least four of eight appraisal domains	The ≥ 4 threshold for inclusion reflects a minimum transparency floor; studies scoring 4–7 are included in descriptive synthesis only and excluded from effect-size citation and policy inference (see Table 2 and Section 3.3)

The core Boolean search string was validated against a test set of 20 known landmark papers selected on the basis of citation prominence and disciplinary coverage across the five MGIF gap dimensions; the string retrieved 16 of 20 test papers (80% sensitivity), confirming adequate coverage before full database deployment.

Table 2. Quality appraisal instrument for included records. Maximum score = 16.

Domain	Assessment Criteria	Score (0–2)
Research objectives	Clear, specific, and answerable research question or objective stated	0 = absent; 1 = partial; 2 = clear
Study design	Design appropriate for stated objective; design limitations acknowledged	0 = inappropriate; 1 = adequate; 2 = optimal

Table 2. *Cont.*

Domain	Assessment Criteria	Score (0–2)
Sampling strategy	Sampling locations, instruments, duration, and frequency fully reported	0 = absent; 1 = partial; 2 = complete
Measurement validity	Instrumentation calibrated against reference; detection limits and uncertainty reported	0 = absent; 1 = partial; 2 = complete
Statistical analysis	Appropriate statistical methods; effect sizes and confidence intervals reported	0 = absent; 1 = partial; 2 = rigorous
Confound management	Outdoor penetration, occupant activity, and seasonal factors identified and controlled	0 = ignored; 1 = acknowledged; 2 = controlled
Generalizability	Study population and setting described in sufficient detail for transferability assessment	0 = absent; 1 = partial; 2 = fully described
Conflict of interest	Funding sources declared; potential conflicts of interest disclosed	0 = absent; 1 = partial; 2 = fully transparent
Total range	Low quality: <8 (descriptive only); moderate: 8–12; high quality: >12	0–16

3.3. Screening, Eligibility, and Quality Appraisal

All retrieved records were imported into Rayyan, where potential duplicates were flagged automatically and confirmed or rejected through human review before screening commenced. Two-stage masked parallel screening was then conducted. Stage 1 (title and abstract screening) applied the pre-specified eligibility criteria detailed in Table 1. Two reviewers screened all 638 records independently at Stage 1 using title and abstract information. To calibrate the screening process, a random 20% subsample ($n = 128$ records) was screened independently by both reviewers as a pilot set before the remaining records were assessed. Inter-rater agreement on this pilot set was quantified using Cohen's kappa; the pre-specified minimum threshold was $\kappa \geq 0.75$ and the obtained value was $\kappa = 0.83$, exceeding the threshold. Disagreements on the pilot set ($n = 14$ records, 10.9%) were resolved through structured discussion. The remaining 510 records were then screened independently by both reviewers using the same criteria, with disagreements resolved through the same protocol. Following Stage 1, 484 records were excluded on title and abstract grounds, leaving 154 records forwarded to Stage 2 full-text assessment.

At Stage 2, both reviewers independently assessed all 154 full-text records against the eligibility criteria in Table 1. Because the corpus at this stage was small enough for complete dual review, kappa was computed across all 154 records rather than a subsample; inter-rater agreement was $\kappa = 0.86$. Disagreements ($n = 11$ records) were resolved through structured discussion; two records required third-reviewer adjudication. Of the 154 full-text records assessed, 49 were excluded. Reasons for exclusion were: wrong setting or outdoor-only design ($n = 14$), wrong population or no indoor component ($n = 11$), insufficient methodological reporting for quality appraisal ($n = 9$), wrong publication type ($n = 7$), outside date range without foundational status ($n = 4$), duplicate dataset ($n = 3$), and non-English without sufficient data in abstract ($n = 1$). These counts sum to 49 and are reported in the PRISMA 2020 flow diagram.

The primary publication date range is 2011–2026. A provision for pre-2011 foundational works was specified in the protocol prior to searching, not applied post hoc: a pre-2011 record was eligible for retention only if it satisfied two criteria: it represented

the primary or most-cited empirical or methodological source for a specific contribution relevant to the review scope, and that contribution had not been superseded or replicated by a post-2011 record in the corpus. This provision was applied conservatively. Three pre-2011 records met both foundational-retention criteria and were retained: Klepeis et al. (2001) [1] for NHAPS time–activity data, which remains the most comprehensive US indoor time–activity dataset and has not been replicated at equivalent scale; Thatcher and Layton (1995) [56] for particle deposition and penetration coefficients, which established the foundational measurement framework still referenced in post-2011 modeling studies; and Jones (1999) [12] for the foundational IAQ and health conceptual framework underpinning subsequent systematic reviews. Adamkiewicz et al. (2011) [28] falls within the primary publication window and was retained through the standard eligibility process. The final included corpus spans 2001–2026, with 97% of records published within the primary 2011–2026 window.

The included corpus contains heterogeneous evidence types with distinct analytical roles within the synthesis framework. Primary empirical studies contributed quantitative exposure, intervention, and monitoring evidence; systematic and scoping reviews were used to identify recurrent patterns, consensus findings, and established evidence domains; modeling and methodological studies informed analytical and conceptual development; and policy or technical guidance documents were used to contextualize regulatory and governance dimensions. Evidence types were therefore synthesized within a unified thematic architecture while remaining analytically distinguishable throughout coding and interpretation.

All 105 included records underwent standardized quality appraisal using the eight-domain instrument presented in Table 2, adapted from the AXIS tool, the CASP checklist, and domain-based risk-of-bias frameworks. The eight domains were selected through a three-step process. First, all domains appearing in at least two of the three source instruments were retained as candidate domains, producing an initial list of eleven. Second, domains with overlapping constructs at the operationalization level (specifically, internal validity and confound management, which both reduce to systematic bias control in non-experimental IAQ studies) were merged, reducing the candidate set to nine. Third, one domain addressing intervention allocation concealment was retired as inapplicable to the majority of included evidence types, which are observational or review-level rather than experimental. The remaining eight domains were confirmed as collectively necessary and mutually non-redundant for the heterogeneous evidence base of this review. The 0–2 scoring scale per domain was adopted from the AXIS tool’s partial-credit structure rather than binary present/absent scoring, because the included corpus contained many records that partially reported key methodological elements; binary scoring would have either excluded a disproportionate share of otherwise informative records or inflated scores by treating partial reporting as full compliance. The resulting 16-point maximum scale was piloted on 15 randomly selected records by both reviewers independently before full deployment. Pilot inter-rater agreement was $\kappa = 0.74$, just below the pre-specified threshold of $\kappa \geq 0.75$; one domain (confound management) was responsible for the majority of disagreements and was therefore accompanied by a clarifying decision rule specifying that seasonal variation and occupancy patterns must be explicitly discussed (not merely acknowledged) to score 2. Following this codebook refinement, pilot agreement rose to $\kappa = 0.79$ on re-score of the same 15 records, clearing the threshold before full corpus appraisal commenced.

Given that 51% of included records are themselves systematic reviews or meta-analyses rather than primary empirical studies, the appraisal instrument was applied to evaluate the methodological transparency of each included record on its own terms, assessing whether its methods were sufficiently reported to permit quality judgment, rather than applying

primary-study-specific criteria to review papers. All 105 included records underwent quality appraisal using the eight-domain instrument in Table 2 (maximum score 16). Score distribution across the corpus was as follows: 14 records scored below 8 (low quality; descriptive synthesis only), 67 records scored 8–12 (moderate quality; full synthesis eligible), and 24 records scored above 12 (high quality; policy inference eligible). The threshold of 8 was selected as the midpoint of the 16-point scale, reflecting a minimum requirement that at least half of the eight appraisal domains were adequately reported. Records scoring below 8 are included in Section 4 only where findings are presented descriptively without policy inference; they are explicitly excluded from effect-size citation and from the evidence anchors supporting MGIF dimension entries in the MGIF dimension matrices presented in Section 4.9.

Because the corpus incorporated heterogeneous evidence forms, appraisal scores were interpreted relative to evidence type rather than as directly equivalent measures of methodological quality across all records. Empirical studies were primarily evaluated for study design, sampling transparency, measurement rigor, and analytical validity; review papers for synthesis transparency and evidence integration; modeling studies for methodological clarity and assumption reporting; and policy or technical documents for authority, transparency, and contextual relevance. The appraisal framework therefore functioned primarily as a structured quality-screening and interpretive support mechanism rather than as a strict comparative ranking system across fundamentally different evidence categories.

To prevent overclaiming from heterogeneous evidence, findings are reported throughout the Results with explicit reference to their evidence class. Four inference tiers are applied consistently. Tier 1 (strongest inference) covers randomized controlled trials and prospective cohort studies among the primary empirical records; findings from these studies are cited as providing direct causal or near-causal evidence. Tier 2 covers non-randomized field studies, cross-sectional monitoring studies, and before-after intervention studies; findings from these are cited as providing associational evidence consistent with but not confirming causal relationships. Tier 3 covers modeling and simulation studies; findings from these are cited as providing theoretically grounded estimates under specified assumptions, not as measured field observations. Tier 4 covers included systematic reviews, scoping reviews, and meta-analyses; findings from these are cited as reflecting synthesized prior evidence rather than new primary data generated by this review. Policy and guidance documents are used exclusively to characterize the regulatory landscape and are not treated as empirical evidence for exposure, health, or intervention claims. Where a claim rests on a single study regardless of tier, this is stated explicitly. Where a claim rests on convergent evidence across multiple tiers, this is noted as the strongest form of support available in the corpus. Modeled evidence (Tier 3) contributed to synthesis in three specific ways: characterizing the relationship between building parameters (ventilation rate, window configuration, floor level, proximity to roadway) and indoor pollutant concentrations in scenarios where empirical monitoring was unavailable; estimating long-term personal exposure trajectories from ventilation strategy comparisons across climate zones [42]; and quantifying indoor–outdoor coupling ratios under controlled boundary conditions [57,58]. Across all Tier 3 records, findings were synthesized at the level of direction and approximate magnitude; no cross-model pooling or meta-regression was performed. Building types covered by the modeled corpus include single-family residences, multi-family apartments, and generic office buildings in European, East Asian, and North American urban canyon geometries; generalization to building types or climates not represented should not be assumed. It is also important to note the scope of framework derivation. The MGIF and UIAQN frameworks produced in this review are evidence-derived conceptual organizing architectures; they were not subjected to external validation through Delphi consultation,

expert panel review, structured stakeholder engagement, or independent replication by a separate research team. The inter-coder reliability procedure ($\kappa = 0.81$) documents the reproducibility of the gap identification process within the review team; it does not constitute external validation of the resulting framework structure. Both frameworks are offered as structured reference architectures for organizing future research and policy coordination, subject to the limitations described in Section 5.5.

3.4. Bibliometric and Science Mapping Analysis

Bibliometric science mapping was used in this review to characterize the intellectual architecture and emerging frontiers of the urban IAQ literature through citation, co-authorship, and keyword patterns. Six descriptive analyses were conducted using established bibliometric software tools. These analyses were conducted at the scale of the 105-record included corpus rather than as a comprehensive field-level bibliometric survey, which constrains the generalizability of network-level conclusions. Formal quantitative network metrics, including modularity scores, silhouette coefficients, and betweenness centrality values, were not computed as part of this synthesis; the bibliometric component produced descriptive mapping outputs that guided thematic synthesis rather than statistically rigorous network analysis. Readers seeking full-field bibliometric analyses with formal network statistics should consult dedicated bibliometric surveys of the IAQ literature at a larger corpus scale.

Performance analysis was conducted in Bibliometrix (version 4.3.0) in R (version 4.4.2), mapping annual publication output, productive journals, contributing countries and institutions, and highly cited papers. Keyword co-occurrence analysis was conducted in VOSviewer (version 1.6.20). A minimum keyword co-occurrence threshold of five was applied, retaining keywords appearing in at least five records. The association strength normalization method was used. Clustering was performed using the Leiden algorithm at a resolution of 1.0. Temporal overlay maps used the average publication year of papers containing each keyword to identify emerging research frontiers.

Co-citation analysis was conducted in CiteSpace (version 6.3.R1) with a time slice of one year, minimum citation count threshold of two, and cosine similarity normalization. The top 50 most cited references per time slice were retained for network construction. Bibliographic coupling analysis was conducted in VOSviewer (version 1.6.20) with a minimum coupling strength threshold of one shared reference and association strength normalization. Documents with no coupling links were excluded from visualization.

Citation-burst detection was conducted in CiteSpace (version 6.3.R1) using the Kleinberg burst detection algorithm with a gamma parameter of 0.5 and a minimum burst strength threshold of 2.0. Burst zones were defined as keyword or document burst periods with a strength value exceeding this threshold. Geographic collaboration patterns were derived from institutional affiliation metadata extracted from corpus records using Bibliometrix, without conducting a formal co-authorship network analysis.

3.5. Thematic Synthesis

Thematic synthesis was conducted following the six-phase framework of Thomas and Harden [55], adapted for systematic literature reviews integrating quantitative and qualitative evidence. The synthesis operated at two levels. Descriptive synthesis reported findings from individual records without interpretive transformation, preserving study-level quantitative and qualitative data in a form suitable for direct citation. Analytical synthesis generated cross-study themes inductively from patterns recurring across five or more unrelated records, and deductively cross-mapped these themes against the PECO framework structure and the bibliometric cluster outputs from Section 3.4. The PECO cross-

mapping operationalized as follows: each emergent analytical theme was assessed against the four PECO elements to determine which component of the review question it addressed: themes organized around pollutant behavior and source characterization mapped to E; themes organized around building system performance and occupant behavior mapped to C; themes organized around health outcomes and personal exposure mapped to O; and themes organized around population vulnerability and geographic underrepresentation mapped to P. Themes that could not be anchored to at least one PECO element were flagged for review and either reframed or retired, ensuring that all retained analytical themes remained traceable to the original research question structure.

The criterion for elevating a descriptive finding to analytical synthesis was recurrence across a minimum of five unrelated records from different research groups, the same recurrence criterion applied in MGIF Stage 5, Dimension Development, ensuring consistency between the thematic synthesis and gap derivation procedures.

The core Boolean search string applied to Web of Science Core Collection was as follows: (“indoor air quality” OR “indoor air pollution” OR “indoor PM_{2.5}” OR “indoor PM₁₀” OR “indoor VOC” OR “indoor formaldehyde” OR “indoor radon” OR “indoor NO₂” OR “indoor CO” OR “indoor CO₂”) AND (“urban” OR “city” OR “metropolitan” OR “residential” OR “school” OR “office” OR “transit”) AND (“ventilation” OR “filtration” OR “air cleaner” OR “HEPA” OR “mitigation” OR “intervention” OR “concentration” OR “exposure” OR “health outcome” OR “policy” OR “standard” OR “regulation” OR “equity” OR “environmental justice”).

Supplementary strings targeting emerging contaminants, low-cost sensors, and equity-specific terms were added for PubMed/MEDLINE and Engineering Village/Compendex to address coverage gaps in those databases. The complete database-specific search strings for all six sources are provided in Supplementary Table S1.

The core string was validated against a test set of 20 landmark papers selected prior to database searching on the basis of citation prominence and disciplinary coverage across the five MGIF gap dimensions. The string retrieved 16 of 20 test papers (80% sensitivity). The four papers not retrieved by the core string were subsequently identified through cited reference chain checking in Google Scholar and manual screening; all four were assessed for eligibility and three met inclusion criteria and were incorporated into the final corpus. The string was refined iteratively through three rounds to balance sensitivity and specificity before full deployment.

A standardized data extraction form was developed in Microsoft Excel containing 24 fields organized into five sections: (1) citation metadata (author, year, journal, country, DOI); (2) study design (study type, setting, sample size, monitoring duration, pollutants measured, instruments used); (3) population and exposure (occupant demographics, building type, ventilation mode, outdoor pollution context); (4) findings (key quantitative results, effect sizes where reported, units, comparators); and (5) synthesis fields (quality appraisal score, thematic code assignments, gap statement extractions). Fields 1–4 used structured entry with controlled vocabulary where applicable; Field 5 used free-text entry with codebook reference. The form was piloted on 20 randomly selected records before full deployment. Minor revisions were made to three field labels following the pilot: specifically, the “ventilation mode” field was split into “primary ventilation strategy” and “supplementary ventilation use” to better capture hybrid ventilation contexts identified during piloting. No structural changes to the form were made after the pilot.

Inter-coder reliability for thematic coding was quantified using Cohen’s kappa at the code level, with a pre-specified minimum threshold of $\kappa \geq 0.75$. The reliability procedure is reported in full in Stage 6 of the MGIF derivation (Section 3.6): a 20% pilot subsample ($n = 21$ records) was coded independently by both reviewers first, yielding $\kappa = 0.76$; code-

book clarifications were made for nine ambiguous code boundaries; the refined codebook was then applied to the remaining 80% ($n = 84$ records), yielding a final full-corpus kappa of $\kappa = 0.81$. Where coding disagreements arose, resolution followed a structured discussion protocol; residual disagreements were referred to a third reviewer.

3.6. Multi-Dimensional Gap Identification Framework (MGIF): Seven-Stage Derivation Procedure

The MGIF is the central analytical output of this review, a structured, evidence-derived organizing framework produced by applying a seven-stage hybrid deductive–inductive procedure to the coded literature corpus. Gap derivation drew primarily from recurrent patterns identified across empirical and review-level evidence, while modeling and policy documents contributed contextual and systems-level interpretive support during category refinement and framework integration. It applies a structured seven-stage hybrid deductive–inductive procedure to derive research gap dimensions directly from the coded literature corpus, providing a more transparent and traceable alternative to gap narratives that proceed through undocumented expert judgment alone.

The five gap dimensions were not imposed a priori but derived through the procedure illustrated in Figure 2, which shows the PRISMA 2020 study selection flow (Part A) alongside the seven-stage MGIF derivation workflow (Part B). The connecting pathway between Parts A and B makes explicit that gap derivation begins only after systematic inclusion decisions are complete.

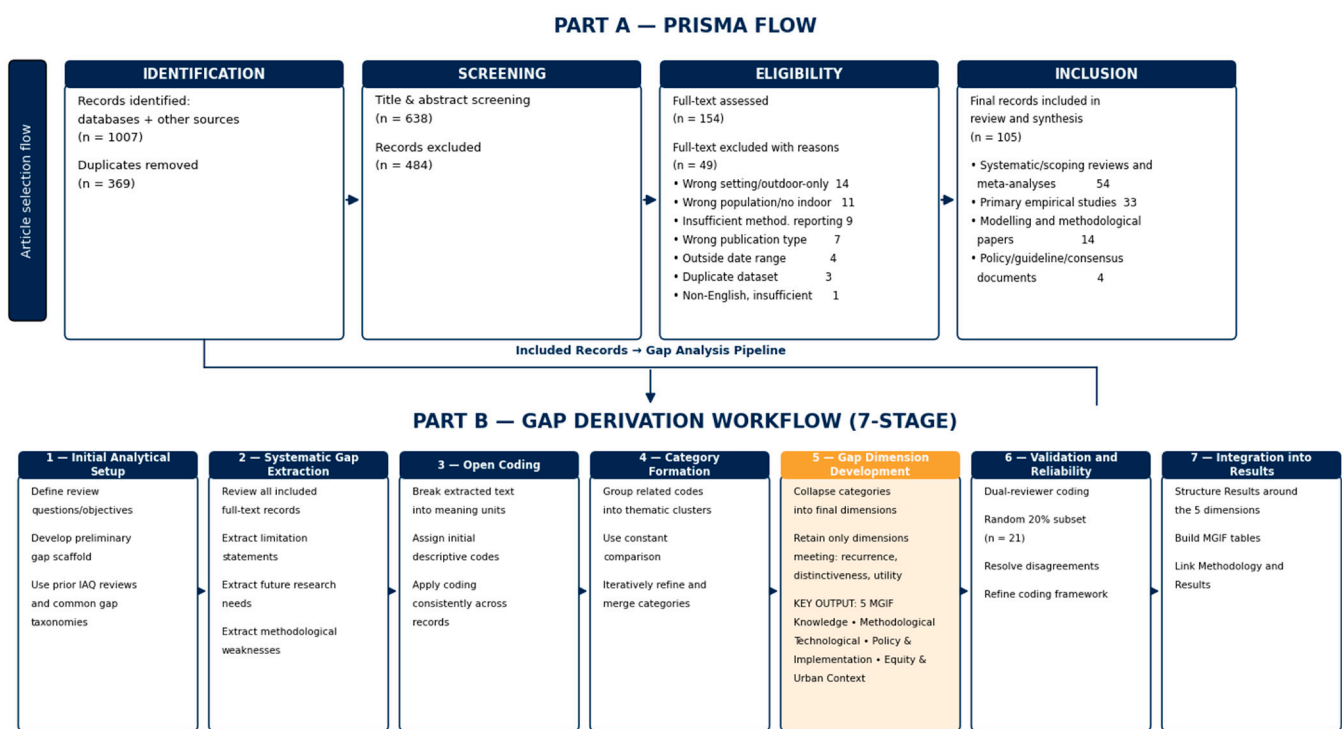


Figure 2. PRISMA 2020 study selection flow (Part A) and seven-stage MGIF gap derivation workflow (Part B).

Stage 1 (Initial Analytical Setup) established a flexible preliminary scaffold drawn from prior IAQ hybrid systematic reviews and common research gap taxonomies. This scaffold was treated explicitly as a starting orientation, not a fixed taxonomy, and was subject to revision at every subsequent stage.

Stage 2 (Systematic Gap Extraction) extracted all limitation statements, identified research needs, methodological weakness acknowledgements, and policy barrier descriptions from each of the 105 included full-text records, recording them in a Gap Coding Matrix

with study ID, verbatim extracted text, and contextual label. The complete Gap Coding Matrix is maintained by the authors and is available from the corresponding author on reasonable request.

Stage 3 (Open Coding, Inductive Analysis) broke extracted text into discrete meaning units and assigned initial descriptive codes applied consistently across all 105 records. This stage generated 1247 initial codes in total, averaging 12 codes per study across the full corpus, with higher code density in hybrid systematic reviews (mean: 15 codes per study) than in primary empirical records (mean: 10 codes per study), reflecting differences in the length and structure of limitations and future directions sections across study types. Codes were assigned at the sentence or clause level, preserving the authors' original language without interpretive transformation.

To strengthen traceability, the MGIF derivation procedure was documented through a coding audit trail linking extracted gap statements to initial codes, intermediate categories, final MGIF dimensions, and retained or retired category decisions. This audit trail was used to distinguish evidence-derived patterns from author interpretation and to ensure that each final dimension was supported by recurrent, conceptually distinct, and actionable evidence across the reviewed corpus.

Stage 4 (Category Formation, Pattern Detection) grouped related codes into thematic clusters through constant comparison across records and settings, iteratively merging and splitting categories to maximize within-cluster coherence and between-cluster distinctiveness. This process reduced the 1247 initial codes to 94 intermediate categories through four rounds of iterative merging, with each round producing progressively broader and more analytically stable clusters. For example, initial codes including "no standardized averaging period reported," "detection limits absent from methods," and "instrument calibration not described" were grouped into the intermediate category "measurement protocol inconsistency," which subsequently contributed to MGIF Dimension 2 (methodological gaps). Each initial code represented a discrete gap-related meaning unit extracted from limitation statements, future research recommendations, methodological weaknesses, or policy barriers reported in the included records. Codes were kept close to the wording of the source text during this stage to minimize premature interpretation. A second illustrative example: codes including "HAP burden highest in South Asia," "Africa underrepresented in primary evidence," and "LMIC building stock absent from intervention trials" were grouped into the intermediate category "Global South evidence deficit," contributing to MGIF Dimension 5 (equity and urban context gaps).

The reduction from 1247 initial codes to 94 intermediate categories occurred through four iterative rounds of constant comparison. In the first round, duplicate or semantically equivalent codes were merged. In the second round, closely related codes addressing the same methodological, technical, policy, or equity problem were grouped into provisional categories. In the third round, categories were refined to improve within-category coherence and between-category distinction. In the fourth round, low-frequency or overly narrow categories were either merged into broader categories or flagged for retirement if they did not meet the recurrence threshold.

Stage 5 (Gap Dimension Development) collapsed the intermediate category set into the final five dimensions, retaining only those that satisfied three operationalized criteria. These criteria were specified prior to Stage 5 consolidation and applied independently by both reviewers; any category whose assignment was disputed was resolved through the structured discussion protocol used in Stage 6.

Recurrence: The gap pattern appeared in at least five unrelated records from different research groups, consistent with the minimum threshold applied in thematic synthesis (Section 3.5). **Conceptual distinctiveness:** The dimension did not substantively overlap with

any other retained dimension at the level of its defining sub-categories, operationalized as less than 20% shared intermediate-category membership between any two candidate dimensions. Analytical utility: The dimension could be translated into specific, actionable research or governance directions, assessed by whether at least three of its sub-categories generated identifiable research or policy recommendations in Section 4. The candidate dimension labels were drawn from the Stage 1 deductive scaffold, constructed from established gap taxonomies in prior hybrid systematic IAQ reviews before any inductive coding began, ensuring that dimension names reflected recognized analytical categories rather than post hoc interpretive choices.

The candidate dimension labels (knowledge, methodological, technological, policy and implementation, and equity and urban context) were drawn from the Stage 1 deductive scaffold, which had been constructed from established gap taxonomies in prior hybrid systematic IAQ reviews before any inductive coding began; this anchoring constrained the label space and ensured that dimension names reflected recognized analytical categories rather than post hoc interpretive choices. Of the 94 intermediate categories formed in Stage 4, 61 were merged into existing sub-categories within dimensions where they expressed the same underlying gap in different study-specific language; eight were split across two dimensions where they contained analytically distinct components belonging to separate gap domains, most commonly categories spanning the boundary between knowledge and methodological gaps, or between policy and equity gaps; and 13 were retired as insufficiently recurrent, having appeared in fewer than five unrelated records and therefore not meeting the threshold for a field-level gap claim. The remaining 12 categories were retained as distinct sub-category anchors, each sufficiently recurrent, distinctive, and actionable to stand alone within its assigned dimension. The five final dimensions collectively account for all 81 retained intermediate categories, with each dimension grounded in between 14 and 19 intermediate categories and organized into four to five analytically distinct sub-categories.

The five final MGIF dimensions were retained because they represented the smallest stable set of higher-order domains capable of organizing all retained intermediate categories without substantial conceptual overlap. A four-dimension structure was rejected because policy-implementation- and equity-related gaps became analytically conflated, obscuring the distinct role of social vulnerability, geographic underrepresentation, and environmental justice. A six-dimension structure was rejected because several candidate domains overlapped strongly with existing methodological or technological categories and did not provide sufficient additional explanatory value. The five-dimension structure therefore provided the most parsimonious and analytically useful organization of the coded evidence. Both reviewers independently applied all three retention criteria to the 94 intermediate categories before any consolidation discussion, and initial dimension-assignment agreement was $\kappa = 0.78$, confirming that the consolidation outcome was replicable rather than idiosyncratic to a single analyst's judgment. Table 3 shows some example coding pathways from the extracted gap statement to the MGIF dimension.

Stage 6 (Validation and Reliability) applied dual-reviewer independent coding to a randomly selected 20% subset ($n = 21$) of included records. Initial inter-coder agreement on this subset was $\kappa = 0.76$, meeting the pre-specified threshold of $\kappa \geq 0.75$ but indicating scope for codebook clarification at specific code boundaries. Disagreements were resolved through structured discussion, producing a refined codebook with clarified decision rules for nine ambiguous code boundaries, primarily at the interface between knowledge and methodological gap categories, where gap statements relating to measurement limitations were occasionally assigned to either dimension depending on whether the reviewer interpreted them as a deficit in scientific understanding or a deficit in research design. The

refined codebook was then applied independently by both reviewers to the remaining 80% of the corpus ($n = 84$ records), yielding a final full-corpus inter-coder kappa of $\kappa = 0.81$, confirming substantial agreement and meeting the pre-specified threshold comfortably.

Table 3. Example coding pathway from extracted gap statement to MGIF dimension.

Extracted Gap Statement/Example	Initial Code	Intermediate Category	Final MGIF Dimension	Rationale
"Instrument calibration was not consistently reported across IAQ monitoring studies."	Calibration reporting absent	Measurement protocol inconsistency	Methodological gaps	Relates to reproducibility and comparability of measurement protocols
"Few studies assessed indoor exposure to pollutant mixtures rather than single pollutants."	Limited mixture assessment	Multi-pollutant evidence gap	Knowledge gaps	Reflects missing scientific understanding of combined exposures
"Laboratory-tested filtration systems showed lower or inconsistent performance in occupied buildings."	Field performance uncertainty	Lab-to-field intervention gap	Technological gaps	Relates to real-world intervention performance
"IAQ standards were often non-enforceable or inconsistent across jurisdictions."	Weak regulatory enforceability	Fragmented governance standards	Policy and implementation gaps	Relates to policy design and implementation
"Low-income and Global South urban populations were underrepresented in primary field studies."	Underrepresentation of vulnerable contexts	Geographic and equity evidence deficit	Equity and urban context gaps	Relates to unequal evidence coverage and vulnerable populations

Stage 7 (Integration into Results) structured the Results section around the five gap dimensions and constructed the five MGIF dimension matrices presented in Section 4.9 as the direct analytical output of the MGIF derivation procedure. Each table entry includes a sub-category label, specific gaps identified through open coding, the primary literature anchor from which the gap was derived, and the recommended research or policy direction, ensuring that every element of the Results section is traceable to the Gap Coding Matrix produced in Stage 2.

3.7. Urban Indoor Air Quality Nexus (UIAQN): Framework Development

The UIAQN framework was developed through a structured three-phase iterative process grounded in the MGIF gap output.

Several prior reviews have proposed multi-level conceptual structures for organizing IAQ evidence. Mannan and Al-Ghamdi [23] presented a building-centered framework linking indoor sources, occupant activities, and health outcomes. Vardoulakis et al. [10] organized residential exposure evidence around pollutant pathways. Tran et al. [5] structured their synthesis around pollutant–disease–technology triads. While these frameworks advanced the field’s conceptual organization, they share three structural limitations: governance mechanisms are treated as external context rather than as an integral framework level; identified research gaps are not embedded as structural components of the architecture; and equity and contextual moderators are positioned as background variables rather than

as cross-cutting determinants. The UIAQN is designed to address these limitations, and its relationship to prior frameworks is evaluated in detail in Section 5.3.

Phase 1 assembled the five MGIF gap matrices and identified the cross-dimensional interactions documented in Section 5.1, establishing the evidence and gap landscape the framework needed to organize.

Phase 2 mapped the thematic clusters and gap sub-categories to intervention and governance leverage points, identifying which aspects of the IAQ problem system are most amenable to research, technology, or policy action at each level. Alternative architectural configurations were explicitly evaluated at this stage before settling on four levels. A three-level structure collapsing Levels 1 and 2 was rejected because pollutant dynamics and building system responses operate on fundamentally different timescales and require distinct intervention logics, a distinction reflected throughout the corpus, where studies on emission source characterization and studies on ventilation or filtration technology form bibliographically decoupled clusters (Section 4.2). A five-level structure separating personal exposure from health outcomes was rejected because the corpus contained insufficient primary evidence linking exposure trajectories to health outcomes at the individual level to warrant treating these as analytically separable levels; the majority of included records address exposure measurement and health outcomes as a single paired construct. A four-level structure was retained because each level corresponds to a distinct class of actionable intervention (emission source control, building system design, occupant-level monitoring and protection, and governance), and because this correspondence is directly traceable to the four functional categories of gap sub-categories that Phase 1 identified in the MGIF matrices.

Phase 3 derived the final nested conceptual structure: Level 1 (pollutant dynamics) encompasses emission sources, chemical transformation processes, and outdoor–indoor transport pathways; Level 2 (building systems and occupant behavior) covers ventilation strategy, filtration technology, building envelope characteristics, and occupant activity patterns; Level 3 (personal exposure and health outcomes) links personal exposure pathways to health outcomes across life stages and vulnerability profiles; and Level 4 (governance and policy mechanisms) addresses standards setting, enforcement frameworks, equity instruments, and cross-sector coordination. Each level is connected to adjacent levels by bidirectional feedback pathways grounded directly in the reviewed corpus: the governance-to-building-system pathway is evidenced by the WHMV compliance failures documented in Antonopoulos et al. [26], where regulatory design determined whether building systems were installed and operated correctly; the building-system-to-exposure pathway is evidenced by the ventilation mode I/O ratio comparisons in Martins and da Graça [9] and Hernandez et al. [59]; and the exposure-to-governance feedback pathway is evidenced by Morawska et al. [60] and Haverinen-Shaughnessy et al. [51], both of which use measured exposure data to argue directly for regulatory reform. These are not theoretical linkages asserted by the authors; each arrow in the framework architecture has a literature anchor in the corpus. Contextual moderators—urban morphology, climate zone, socioeconomic stratum, and occupant demographics—operate across all four levels simultaneously. The five MGIF gap dimensions map directly onto the framework levels: knowledge and methodological gaps correspond to Level 1 and Level 3 deficiencies; technological gaps to Level 2 failures; policy gaps to Level 4 deficiencies; and equity gaps to the contextual moderators shaping outcomes across all levels.

Figure 3 presents the Urban Indoor Air Quality Nexus (UIAQN), a four-level conceptual organizing architecture developed from the systematic synthesis and MGIF derivation process. The framework integrates pollutant dynamics, building systems, personal exposure pathways, and governance mechanisms within a unified multi-level structure while

embedding the five MGIF gap dimensions and cross-cutting contextual moderators identified throughout the review. Bidirectional feedback pathways between levels reflect the dynamic interactions linking environmental processes, building operation, exposure burden, and policy response across urban indoor environments. The UIAQN has not been externally validated against independent data, expert consensus, or stakeholder review; it is offered as a conceptual organizing architecture for structuring future research programs and policy coordination, not as a tested predictive model. The UIAQN's structural relationship to prior IAQ conceptual frameworks is evaluated in Section 5.3.

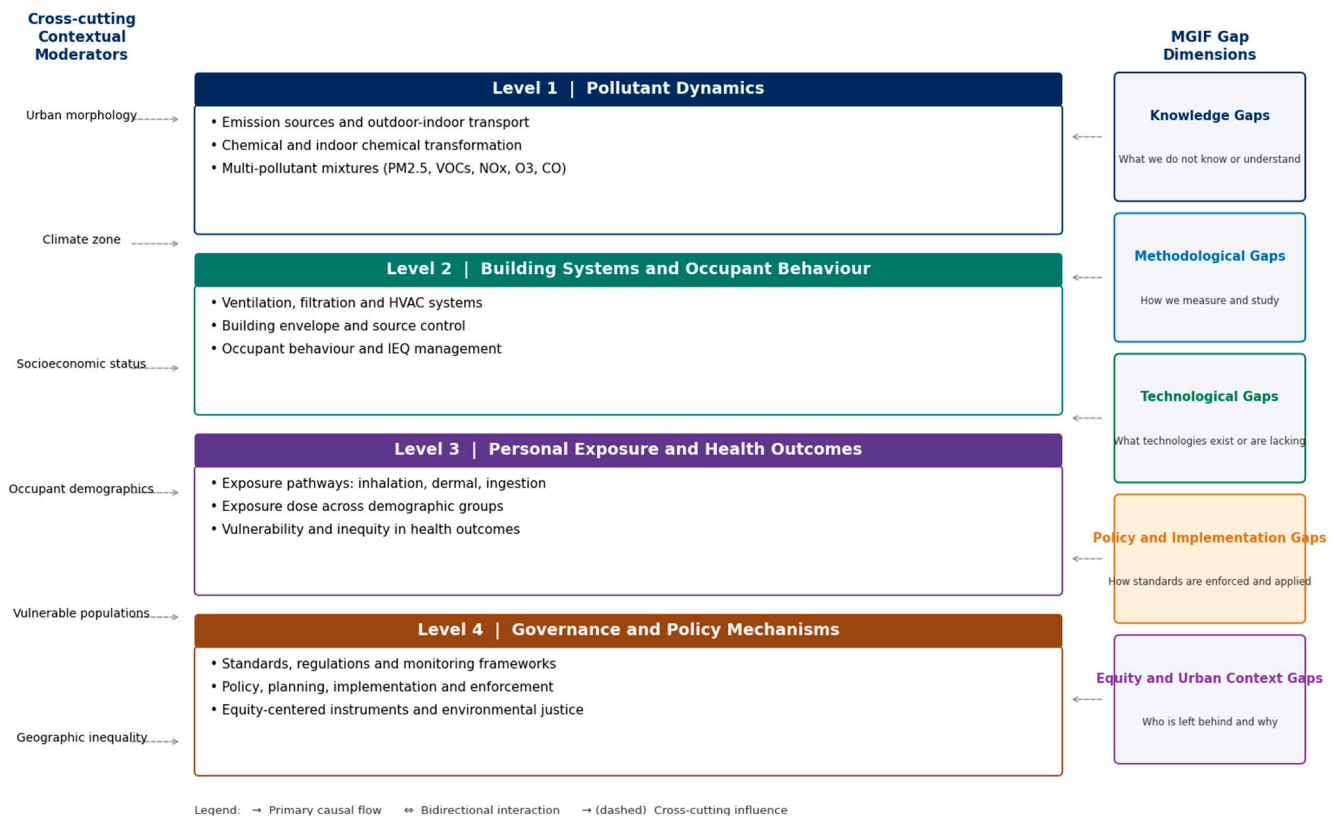


Figure 3. UIAQN four-level conceptual framework diagram.

4. Results

Findings are reported by evidence class throughout, using the four-tier inference framework defined in Section 3.3. Where findings from different tiers converge, this is noted as the strongest available form of support; where a finding rests on a single study this is flagged regardless of tier.

4.1. Corpus Profile (Stage 1–2 Output)

The systematic search retrieved 638 unique records after deduplication, of which 105 met all eligibility criteria following two-stage screening (484 excluded at Stage 1; 49 at Stage 2). The included corpus spans 2001–2026, with 97% of records published within the primary 2011–2026 window (median publication year approximately 2023). As shown in Table 4, systematic and scoping reviews plus meta-analyses constituted 51% of the corpus ($n = 54$), primary empirical field and intervention studies 31% ($n = 33$), modeling and methodological development papers 13% ($n = 14$), and policy, guideline, and expert consensus documents 4% ($n = 4$). Publication output accelerated markedly after 2020. Geographically, primary empirical evidence was concentrated in North America (approximately 20 records), Europe (approximately 22 records), and East Asia (approximately

23 records), while Africa contributed one primary study and Latin America contributed three records within relevant systematic reviews. Figure 4 illustrates the corpus composition by study category.

Table 4. Corpus profile of included evidence base ($n = 105$ records).

Study Category	n	%	Representative Records
Systematic/scoping reviews and meta-analyses	54	51%	Levy & Kibilko [2]; Maung et al. [53]; Valls Roche et al. [4]; Lozinsky et al. [61]; Mannan & Al-Ghamdi [23]; González-Martín et al. [11]; Vardoulakis et al. [10]
Primary empirical (field/intervention/monitoring/epidemiology)	33	31%	Antonopoulos et al. [26]; Tang et al. [62]; Sun & Wallace [63]; Lu et al. [8]; Chen et al. [64]; Hernandez et al. [59]; Kang et al. [65]; Nduka & Jimoh [66]; Nibagwire et al. [67]; Rose et al. [68]
Modeling, framework, and methodological development	14	13%	Santiago et al. [57]; Tong et al. [58]; Salthammer et al. [43]; Chojer et al. [18]; Wu et al. [69]; Liu et al. [42]; Ramadan et al. [70]
Guideline/policy/perspective/expert consensus	4	4%	Haverinen-Shaughnessy et al. [51]; Morawska et al. [60]; Wei et al. [50]
TOTAL	105	100%	Primary publication window: 2011–2026; final included corpus: 2001–2026, including three pre-2011 foundational records; median publication year $\approx$ 2023; 15 national contexts represented; 105 included corpus records. The full reference list additionally includes methodological and regulatory sources used to document the review process and policy context. Abbreviations: IAQ = indoor air quality; PM = particulate matter; VOC = volatile organic compound; HVAC = heating, ventilation, and air conditioning; WHO = World Health Organization; LMICs = low- and middle-income countries; RCT = randomized controlled trial

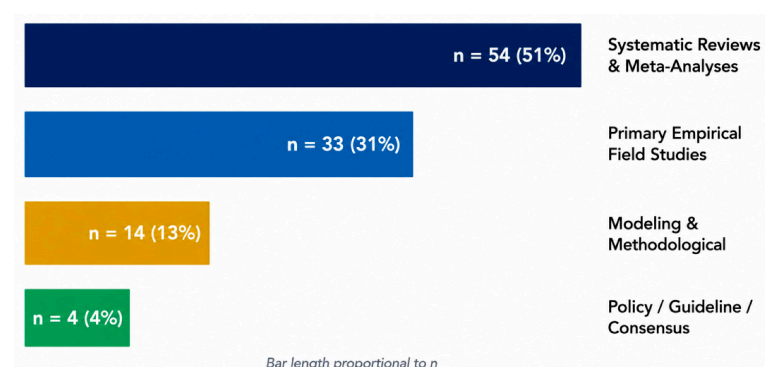


Figure 4. Corpus composition of the 105 included records by study category.

4.2. Bibliometric and Science Mapping Findings (Stage 3 Output)

Descriptive bibliometric analysis of publication output across the 105-record corpus revealed a compound annual growth rate of approximately 18% in urban IAQ records over 2014–2024, with a marked acceleration after 2020. This estimate reflects patterns within the included corpus rather than the full field and should be interpreted as indicative rather than definitive. The most highly cited papers in the corpus covered multi-pollutant epidemiology [37], technology reviews [11], outdoor–indoor coupled modeling [57,58], and global burden analyses [3,30].

Keyword co-occurrence analysis identified five major thematic clusters: PM_{2.5} and health outcomes; VOC sources and characterizations; ventilation and filtration interventions; standards and policy; and equity and vulnerable populations. The equity cluster showed the highest citation-burst intensity over 2021–2026. Additional high-burst keywords included low-cost sensors (2020–2025), wildfire smoke (2020–2024), and HEPA filtration (2021–2025). Bibliographic coupling revealed limited cross-citation between engineering and public health literature, indicating a structural disciplinary divide within the field. Citation-frequency analysis of the 105 included records identified Building and Environment, Indoor Air, Environmental Research, and Science of the Total Environment as the most frequently represented publication venues in the corpus, consistent with their recognized roles as core outlets for IAQ and building science research. The descriptive bibliometric summary is presented in Table 5. As noted in Section 3.4, formal network metrics (modularity, centrality, silhouette scores) were not computed; Table 5 reports corpus-scale descriptive outputs only.

Table 5. Bibliometric and science mapping summary findings across six descriptive analyses of the 105-record included corpus.

Bibliometric Indicator	Value/Finding	Leading Countries/Institutions	Interpretation
Annual publication growth (2014–2024)	~18% compound annual growth rate; marked acceleration post-2020	China, USA, UK, Spain, Portugal, South Korea	The COVID-19 pandemic acted as a citation-burst trigger for ventilation and IAQ topics
Top cited papers (>200 citations)	Zanobetti et al. [37]; González-Martín et al. [11]; WHO reports; Tong et al. [58]	Harvard, Lawrence Berkeley National Laboratory, University of Birmingham	Multi-pollutant epidemiology and technology reviews dominate the intellectual base
Keyword co-occurrence clusters	Five major clusters: PM _{2.5} /health; VOC/sources; ventilation/filtration; standards/policy; equity/vulnerable populations	Equity cluster shows rapid citation growth (burst 2021–2026)	Equity and environmental justice identified as emerging high-priority frontier with growing interest but sparse primary evidence
Citation-burst keywords (CiteSpace)	“Low-cost sensors” (burst 2020–2025); “environmental justice” (2021–2026); “wildfire smoke” (2020–2024); “HEPA filtration” (2021–2025)	Sensor/IoT publications from Asia and Europe; EJ literature from North America	Burst zones with sparse primary evidence classified as high-priority MGIF candidate gap zones
Geographic collaboration network	North America–Europe dyad dominates; China–Europe growing; Africa and South Asia largely isolated nodes	Africa: 1 empirical study; Latin America: 3; South Asia: limited	International collaboration network reflects and perpetuates Global South evidence gap
Citation-frequency analysis (core venues)	Zone 1 (core): Building and Environment, Indoor Air, Environ. Int., Sci. Total Environ.; Zone 2–3: public health and engineering journals; note: these designations are based on citation frequency within the 105-record corpus, not formal Bradford law computation	Building and Environment leads in citation-weighted output for IAQ intervention evidence	Engineering journals dominate core; health and equity literature distributed across zones 2–3, suggesting a silo effect

4.3. Major Pollutant and Source Patterns (Stage 4 Output)

The Open Coding and Category Formation stages produced a robust thematic cluster around pollutant sources and concentration patterns, supported by 26 primary empirical records and 15 systematic reviews. Evidence in this section is predominantly Tier 2 (non-randomized field and laboratory studies) and Tier 4 (prior systematic reviews); Tier 3 modeling studies contribute to VOC cancer risk estimation. No Tier 1 randomized evidence addresses pollutant source characterization in this corpus.

PM_{2.5} was the most extensively studied pollutant across the corpus. One eleven-year Boston mortality time series (single-city, single-study; Tier 2 [37]) found that PM_{2.5} from traffic and heating-oil combustion mixtures was associated with 3.7% higher total mortality per 10 µg/m³, compared with 1.1% for the all-day population average and effectively no excess risk for crustal dust profiles of equivalent PM_{2.5} mass. This finding illustrates the source-mixture dependency of PM_{2.5} toxicological potency, consistent with the broader pattern documented across multiple corpus records that particle composition, not mass alone, determines health risk [38,39]; however, the specific mortality coefficients should not be generalized beyond the Boston setting and study period. Residential indoor PM_{2.5} concentrations ranged from 3 to 202 µg/m³ across the reviewed field studies, depending on ventilation strategy, source activity, building type, and occupant behavior [22,71].

Cooking was the single most consistently documented residential PM_{2.5} source across the corpus. One controlled laboratory comparison of five cooking methods (single-study, laboratory setting; Tier 2 [62]) found that pan-frying generated peak PM_{2.5} of 92.9 µg/m³ compared with 0.6 µg/m³ for air-frying, a 155-fold difference within a controlled experimental context. The rank order of cooking methods by PM_{2.5} emission was further corroborated by an independent Canadian field study of 132 households [63] and a separate apartment monitoring study [72], supporting the direction of this finding across study designs and national contexts, though absolute concentrations varied by ventilation conditions and kitchen geometry. VOC co-emission rank orders partially diverged from PM_{2.5} rank orders across the same cooking methods: pan-frying (260 ppb) and deep-frying (230 ppb) were highest, while air-frying was lowest (20 ppb) [62]. In naturally ventilated apartments under controlled frying conditions, unmitigated cooking-related PM_{2.5} peaks reached 200–1400 µg/m³ with full decay times of 1–10 h depending on ventilation conditions and air cleaner placement [72]. In one laboratory measurement, bacon frying generated PM_{2.5} at a rate of approximately 2350 µg/min [73]. Controlled home chemistry studies have further characterized the size distribution and dynamics of cooking-related PM in occupied residences [74]. Beyond primary emissions, indoor chemical reactions can also transform pollutants and contribute to reactive oxygen species formation, adding further complexity to indoor pollutant behavior [75,76]. Figure 5 summarizes the contrasting peak PM_{2.5} and VOC concentrations observed across the five cooking methods under the controlled conditions reported by Tang et al. [62].

In one Canadian field study of 132 households, only 27% of cooking events used any form of added ventilation [63]. Cooking contributed approximately 22% of daily PM_{2.5} personal exposure in that study, and ventilation during cooking approximately halved the PM_{2.5} decay rate [63]. Figure 6 summarizes ventilation-use patterns during cooking and the associated PM_{2.5} exposure and decay-rate findings from the 132-household Canadian field study [63].

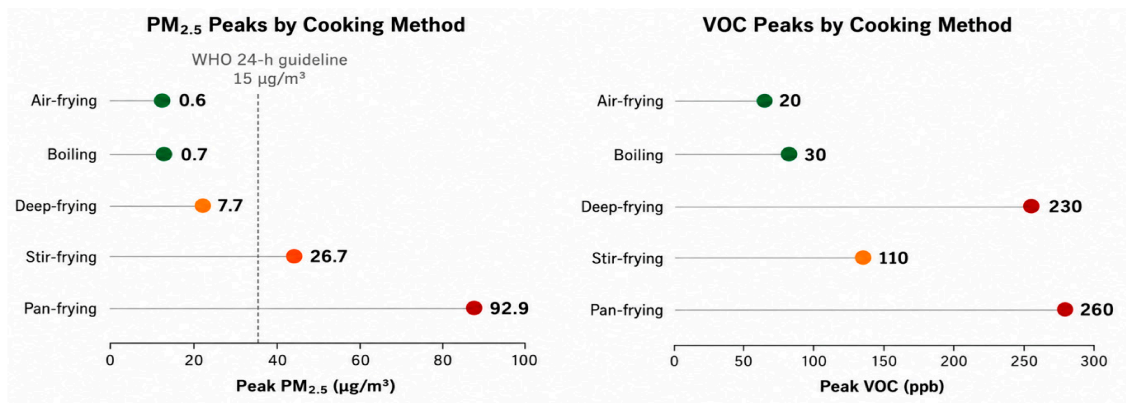


Figure 5. Peak PM_{2.5} and VOC concentrations by cooking method under controlled conditions. Extracted from Tang et al. [62]; single-study controlled measurements only. Green indicates lower measured concentrations, orange indicates intermediate concentrations, and red indicates the highest measured concentrations within each pollutant panel.

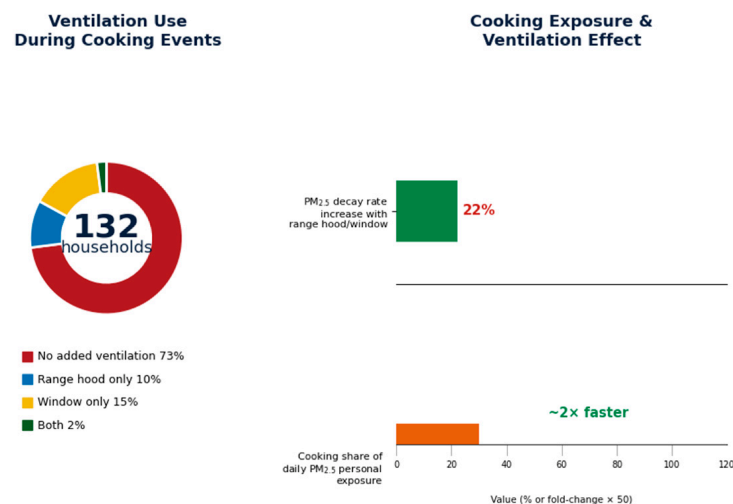


Figure 6. Ventilation behavior during cooking events across 132 Canadian households. Extracted from Sun and Wallace [63].

Beyond PM_{2.5} and VOCs, radon was identified as a persistently under-regulated residential carcinogen. One large observational study of 149,163 residential records in Ohio estimated a lifetime excess lung cancer risk of 2.29%, substantially above the 0.4% lifetime risk associated with the US EPA radon action level of 4 pCi/L [77]. Swiss field data showed radon concentrations of 251 Bq/m³ in naturally ventilated buildings compared with 96 Bq/m³ in mechanically ventilated ones [27]. VOC cancer risk thresholds were exceeded in 35–50% of simulated scenarios across 99 US homes, with 12 VOCs detectable in the majority of dwellings [78,79]. In office environments, VOC concentrations, CO₂, and thermal parameters interact to determine occupant comfort and cognitive performance [80]. One field measurement study of a single LEED-certified office building (single-study; Tier 2 [69]) found that the building functioned as a net VOC source (0.75 ± 0.71 mg/h/m²) while simultaneously acting as an ozone sink (0.457 mg/h/m²) and a PM_{2.5} sink (0.023 mg/h/m²). This finding should not be generalized to LEED-certified buildings as a class; it illustrates the source–sink duality of modern buildings in this single study and suggests that green energy certification does not automatically confer IAQ co-benefits, a hypothesis warranting systematic multi-building investigation. Emerging contaminants (microplastics [49], magnetic nanoparticles [48], and endocrine-disrupting chemicals [47]) were increasingly

identified in indoor environments across the corpus but remained absent from monitoring frameworks and regulatory standards in all reviewed jurisdictions.

4.4. Indoor–Outdoor Coupling and Source Dominance

PM_{2.5} indoor/outdoor (I/O) concentration ratios varied substantially across building and source conditions. I/O ratio evidence in this section draws on one Tier 4 systematic review [9], two Tier 2 field monitoring studies [28,67], and two Tier 3 CFD modeling studies [57,58]; where Tier 2 and Tier 3 findings converge on the same directional conclusion, this is noted as the strongest available form of support in this section. One systematic review reported ratios of 0.77 under mechanical ventilation with no indoor source, 0.95 under natural ventilation with no indoor source, 0.98 under mechanical ventilation with an indoor source, and 1.81 under natural ventilation with an active indoor combustion source [9]. Field monitoring of 88 naturally ventilated households in Kigali, Rwanda, recorded a near-complete outdoor PM_{2.5} penetration ratio (I/O = 0.94), while CO₂ accumulated substantially indoors (I/O = 1.47) in the same buildings under the same ventilation conditions [67].

CFD modeling of a standard urban building produced a mean PM_{2.5} I/O ratio of 0.56 ± 0.24 , with specific room–floor–window configurations reaching up to 1.4 depending on wind direction, façade aperture pattern, and floor level [57]. One modeling study found that a naturally ventilated building positioned 10 m from a roadway sustained indoor PM_{2.5} concentrations 16–21% higher than at the road edge itself [58]. Closing roadside-facing windows reduced indoor particle concentrations by 22.5%; closing both roadside and side windows achieved a 50% reduction [58]. The magnitude and direction of outdoor–indoor coupling vary substantially across building typology and occupant demographics. In naturally ventilated residential buildings, the dominant typology in low- and middle-income urban contexts, I/O ratios approaching unity indicate near-complete outdoor PM_{2.5} penetration [67], making ambient pollution trends directly determinative of indoor exposure. In airtight, mechanically ventilated office and commercial buildings, envelope integrity and filtration efficiency mediate outdoor pollutant entry, but as the WHMV audit evidence confirms [26], design performance is not reliably achieved in practice. School buildings present a distinctive profile: high occupancy density combined with resuspension from occupant activity produces indoor PM₁₀ sources that are largely independent of outdoor pollution [68], while PM₁ and PM_{2.5} in classrooms remain primarily of outdoor origin [68]. Age-related factors further modulate the health significance of outdoor–indoor coupling: children have higher ventilatory rates relative to body mass than adults and spend prolonged continuous time in high-occupancy environments such as classrooms, increasing their dose per unit concentration [4,31]; older adults who spend the majority of waking hours at home in poorly ventilated dwellings face extended exposure to infiltrating outdoor PM_{2.5} in addition to indoor combustion and material emissions [81]. These typology- and age-specific coupling profiles argue against uniform IAQ standards and in favor of building-type-differentiated and demographic-sensitive regulatory frameworks, an approach absent from any reviewed jurisdiction. Figure 7 compares the PM_{2.5} indoor/outdoor concentration ratios across ventilation modes and indoor-source conditions, illustrating the transition from predominantly outdoor-driven to indoor-source-dominated exposure.

One source attribution study of low-income urban housing in Boston found that indoor sources contributed 37% of PM_{2.5} in the lowest-exposure quartile and 90% in the highest-exposure quartile [28].

Figure 8 shows the relative contribution of outdoor versus indoor sources to residential PM_{2.5} by exposure quartile, extracted from Adamkiewicz et al. [28] (low-income urban housing, Boston; *n* = reported in source). Published values are shown for the lowest and highest exposure quartiles only; intermediate quartile values were not reported in

the source study and are not shown here. Indoor sources contributed 37% of $PM_{2.5}$ in the lowest-exposure quartile and 90% in the highest-exposure quartile, illustrating the exposure-burden inversion documented in low-income urban housing contexts.

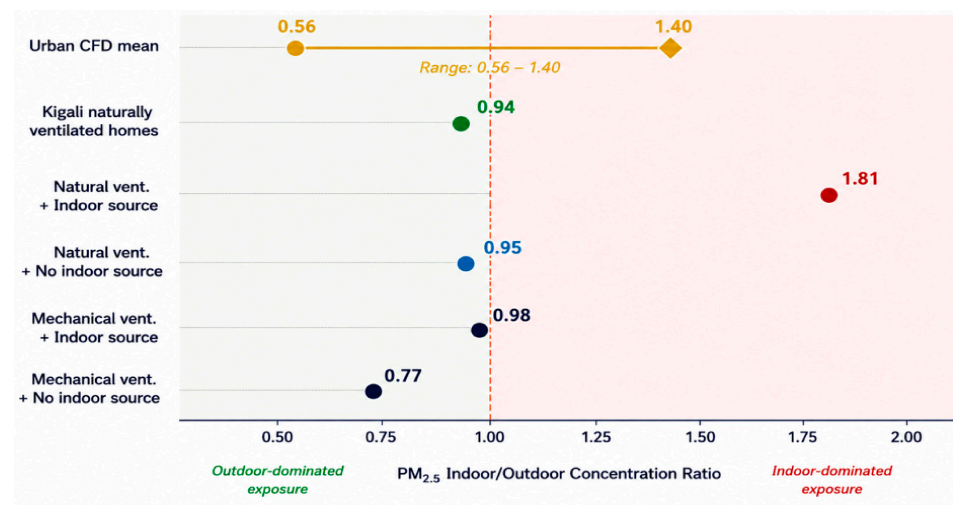
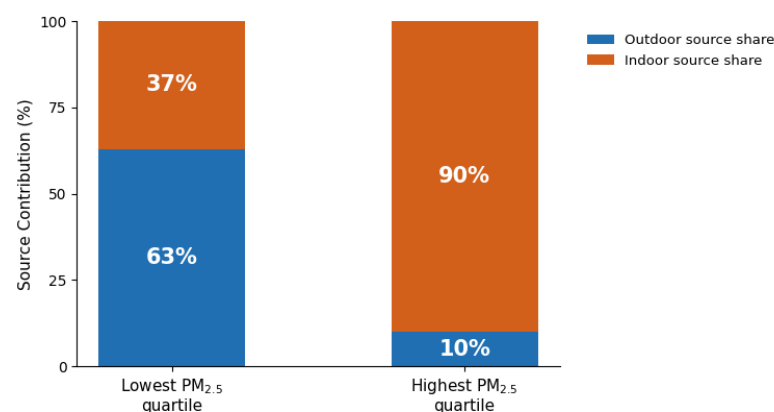


Figure 7. $PM_{2.5}$ I/O ratios across ventilation mode and source status combinations; authors' synthesis from data extracted from Nibagwire et al. [67] and Santiago et al. [57]. The shaded regions indicate outdoor-dominated and indoor-dominated exposure ranges, while point colors distinguish the ventilation and source-status scenarios.



Note: Only the lowest and highest $PM_{2.5}$ exposure quartiles were reported by the source; intermediate quartiles (Q2, Q3) were not reported.

Figure 8. Relative contribution of outdoor versus indoor sources to residential $PM_{2.5}$ by exposure quartile.

Winter-season $PM_{2.5}$ haze events in Chinese cities drive indoor concentrations in naturally ventilated residences far above WHO guideline thresholds [82]. At the global scale, household air pollution from solid fuel combustion contributed approximately 20% of total ambient $PM_{2.5}$ exposure globally, rising to approximately 30% in South Asia and approximately 50% in parts of India [30]. In European contexts, residential biomass and coal burning accounted for 46% of total primary $PM_{2.5}$ emissions, approximately twice the contribution of road transport [30].

4.5. Residential Intervention Effectiveness and Implementation Limitations

The intervention evidence cluster was the most extensively field-validated domain in the corpus, with nine distinct intervention types documented across multiple national contexts. Table 6 presents the complete intervention matrix.

Table 6. Residential IAQ intervention effectiveness matrix: study settings, measured effects, and key caveats.

Intervention	Setting/Study	Target Pollutant	Measured Effectiveness	Key Limitation/Caveat
Portable HEPA air cleaner (PAC)	29 homes; RCT crossover [8]	PM _{2.5} , PM ₁₀	PM _{2.5} : −78.8% primary room; −57.9% secondary room; PM ₁₀ : −63.9%/−60.4% [8]	Performance contingent on source proximity, room volume, filter CADR, and sustained operation; secondary-room benefit diminishes >10 m from device [8]
HEPA air cleaner (household, real-world)	Taiwan field study [64]	PM _{2.5}	33.5 → 17.2 µg/m ³ (−49%); I/O ratio 76.3% → 38.6%; $p < 0.001$ [64]	Single-country deployment; three-device configuration; generalizability to larger or higher-pollution dwellings requires further validation [64]
Positive-pressure mechanical ventilation (PPMV)	24 NZ homes; before/after [59]	PM _{2.5}	PM _{2.5} −38% to −62%; majority of homes shifted from I/O > 1.0 to <1.0 post-installation [59]	New Zealand temperate climate; no long-term follow-up; occupant behavior and seasonal variation untracked [59]
Whole-house mechanical ventilation (WHMV)	55 new US homes; crossover [26]	HCHO, radon, CO ₂ , PM _{2.5} , NO	Overnight CO ₂ < 800 ppm (vs. >1000 ppm without); HCHO, radon, NO significantly reduced [26]	35% of systems non-compliant with ASHRAE 62.2-2010; 46% lacked compliant labeling; 76% of users could not operate; HCHO still exceeded occupational threshold [26]
Mechanical ventilation retrofit	Chicago multi-family homes [65]	NO ₂ , PM ₁ , PM _{2.5} , PM ₁₀	I/O ratios: PM ₁ −42%; PM _{2.5} −39%; PM ₁₀ −33%; NO ₂ −10% [65]	Urban Chicago context; no occupant behavioral component; limited monitoring duration post-retrofit; seasonal effects not captured [65]
Range hood + window during cooking	132 Canadian households [63]	Cooking PM _{2.5}	~2× faster PM _{2.5} decay; cooking contributes ~22% of daily PM _{2.5} personal exposure [63]	Only 27% of cooking events used any added ventilation; thermal comfort and cooking style more determinant than IAQ awareness [63]
Window opening + PAC near source	Naturally ventilated apartment [72]	Cooking PM _{2.5}	Peak PM _{2.5} substantially reduced; decay time halved; without intervention: peaks 200–1400 µg/m ³ [72]	Single-apartment controlled experiment; specific cooking type (frying); limited generalizability to multi-room dwellings [72]

Table 6. *Cont.*

Intervention	Setting/Study	Target Pollutant	Measured Effectiveness	Key Limitation/Caveat
Building envelope retrofit (air sealing + windows)	Review of 51 publications [61]	Radon, CO ₂ , HCHO, thermal	Improved thermal comfort and respiratory outcomes in most studies; acoustic comfort gains consistent; IAQ findings mixed [61]	Envelope tightening without compensatory mechanical ventilation exacerbates radon, VOC, and CO ₂ accumulation [27,61]; summertime overheating risk increased
Low-cost MERV-13 box-fan filter (Corsi–Rosenthal box)	42 sites during wildfire smoke [83]	Wildfire PM _{2.5}	Highly effective for single-room PM reduction; residential buildings showed lower baseline infiltration than commercial/school buildings [83]	Acute episodic use only; not validated for chronic urban IAQ management or multi-pollutant environments [83]
Natural ventilation (strategy comparison)	Simulation across 5 Chinese climate zones [42]	PM _{2.5} , HCHO, TVOC	Natural ventilation exceeded PM _{2.5} 35 µg/m ³ guideline for 24–46% of occupied hours in polluted cities; mechanical ventilation maintained guidelines 100% of the time [42]	Simulation-based evidence only; real-world occupant override behavior not modeled; no health outcome validation [42]

Portable HEPA air cleaners showed the strongest and most consistent field evidence. One single-blinded randomized crossover trial in 29 occupied homes found PM_{2.5} reductions of 78.8% in the primary room and 57.9% in secondary rooms [8]. One Taiwan field study found that three-device HEPA deployment reduced indoor PM_{2.5} from 33.5 ± 10.3 to 17.2 ± 10.7 µg/m³, halving the I/O ratio from 76.3% to 38.6% ($p < 0.001$) [64].

Figure 9 shows PM_{2.5} reduction across residential IAQ intervention types, with authors' synthesis from effect estimates extracted from five included primary studies: Lu et al. [8], Chen et al. [64], Hernandez et al. [59], Kang et al. [65], Niculita-Hirzel [27]; cross-study effect-size comparison should be interpreted cautiously.

Mechanical ventilation produced broader multi-pollutant reductions. Positive-pressure mechanical ventilation in 24 New Zealand homes reduced PM_{2.5} by 38–62%, shifting most homes from I/O ratios above 1.0 to below 1.0 [59]. Whole-house mechanical ventilation (WHMV) in 55 newly constructed US homes maintained overnight CO₂ below 800 ppm (compared with above 1000 ppm without ventilation) and reduced formaldehyde, radon, and NO concentrations [26]. Mechanical ventilation retrofit in Chicago multi-family housing reduced I/O ratios for PM₁ by 42%, PM_{2.5} by 39%, PM₁₀ by 33%, and NO₂ by 10% [65]. Comparative ventilation strategy studies in humid subtropical climates confirm IAQ–energy trade-offs with hybrid mechanical systems outperforming natural ventilation [84]. Simulation across five Chinese climate zones found that mechanical ventilation with filtration maintained PM_{2.5} within guideline thresholds 100% of occupied hours, while natural ventilation exceeded 35 µg/m³ for 24–46% of occupied hours in polluted cities [42,85]. The relationship between natural ventilation adequacy, IAQ, and occupant thermal comfort is a central tension for building designers. Window-opening monitoring in 17 UK low-energy apartments found that indoor temperature, not PM_{2.5}, CO₂, or TVOC concentrations, was the primary driver of occupant ventilation behavior [86], indicating that thermal comfort governs ventilation decisions even among occupants with IAQ aware-

ness. This behavioral pattern has direct design implications: passive and near-zero-energy buildings optimized for airtightness may systematically underperform on IAQ unless mechanical ventilation with heat recovery is integrated from the design stage. Adaptive thermal comfort frameworks offer a partial resolution by permitting wider acceptable temperature ranges in naturally ventilated buildings, potentially extending periods during which windows can remain open, but this approach is climate-zone-dependent and cannot substitute for mechanical ventilation in urban environments with persistently elevated outdoor PM_{2.5} [42]. Building systems that integrate real-time IAQ monitoring with demand-controlled ventilation represent an emerging solution balancing IAQ performance, energy efficiency, and occupant comfort, but field validation across diverse residential typologies remains limited [68,86]. This IAQ–energy–comfort integration challenge is a priority research direction for the building science community.

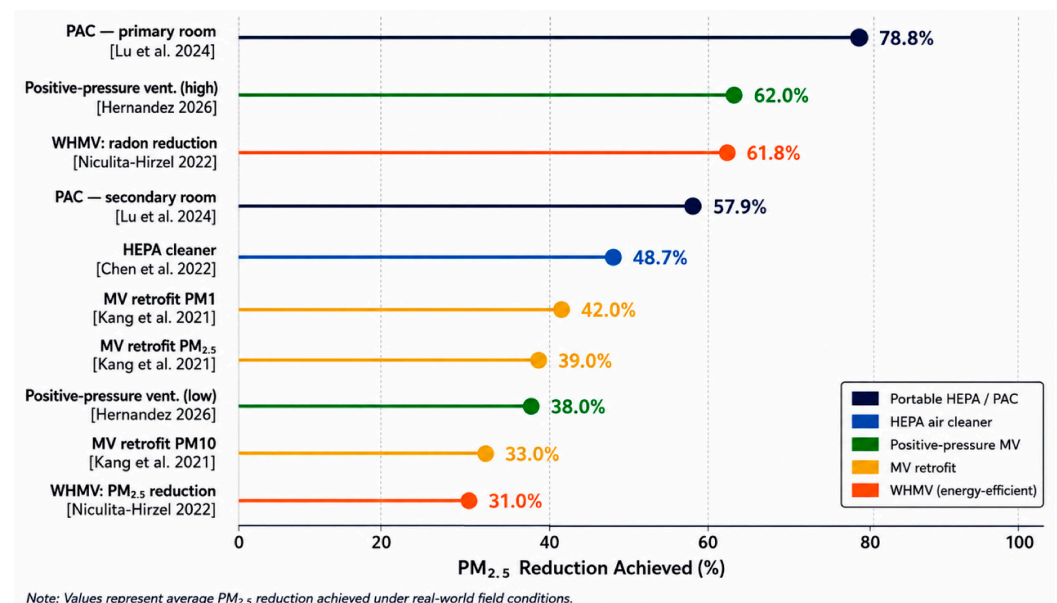


Figure 9. PM_{2.5} reduction achieved across residential IAQ intervention types, ranked by effectiveness. Authors’ synthesis based on effect estimates from Lu et al. [8], Chen et al. [64], Hernandez et al. [59], Kang et al. [65], and Niculita-Hirzel [27].

The multidisciplinary evidence that inadequate ventilation raises symptom rates, sick building syndrome incidence, and indoor pollutant concentrations is well established [87]. Despite measured technical effectiveness, compliance failures were documented across multiple field studies. In one audit of 55 newly constructed US homes in marine and cold-dry climates (single-study; Tier 2 [26]), 35% of code-required WHMV systems failed minimum airflow requirements under ASHRAE 62.2-2010, 46% lacked compliant labeling, and 35 of 46 occupants were unable to operate their installed systems correctly. While this study represents a single national context and specific climate zones, its findings are directionally consistent with the broader pattern documented across the corpus that real-world ventilation performance systematically falls short of laboratory-validated or code-assumed levels [59,61,87], a gap that is structural, arising from the absence of mandatory post-installation commissioning verification requirements. Formaldehyde persistently exceeded occupational reference levels across all ventilation conditions in the same study [26]. Window-opening monitoring in 17 UK low-energy apartments found that indoor temperature, not PM_{2.5}, CO₂, or TVOC concentrations, was the primary driver of occupant ventilation behavior [86]. Building envelope retrofits reduced outdoor particle infiltration but were associated with increased accumulation of radon (251 vs. 96 Bq/m³ under natural vs. mechanical ventilation) [27], VOCs, and CO₂ when compensatory mechanical

ventilation was not installed simultaneously [61]. Related evidence from hospitals and energy-efficient buildings also suggests that seasonal indoor air quality variation and the lack of standardized mold assessment can complicate interpretation of post-retrofit indoor environmental performance [88,89].

4.6. Child, School, and Vulnerable Population Evidence

The child and school evidence cluster spanned umbrella reviews, field monitoring with source apportionment, and biomarker studies. One umbrella review of 95 systematic reviews and meta-analyses found consistent evidence that air pollution adversely affects children's cognitive development, respiratory health, and learning performance [4]. The same review reported that approximately 93% of children under 15 globally breathe outdoor air at concentrations sufficient to affect health [4].

Field monitoring with low-cost sensors in UK urban school classrooms documented peak $PM_{2.5}$ concentrations of $14.4 \mu\text{g}/\text{m}^3$ and PM_{10} of $51 \mu\text{g}/\text{m}^3$ during school hours [68]. Source apportionment showed that outdoor air contributed 93–98% of classroom PM_1 and 74–89% of $PM_{2.5}$, but only 19–40% of PM_{10} , with the remaining 60–81% of PM_{10} originating from indoor sources including floor resuspension, chalk dust, occupant movement, and cleaning activities [68]. Earlier school and residential studies likewise indicate that indoor air quality varies with building operation, ventilation, and season, reinforcing the importance of context-specific interpretation of classroom and apartment monitoring results [90–92]. Figure 10 shows outdoor versus indoor source contributions to classroom PM concentrations by particle size fraction, extracted from Rose et al. [68], representing a single UK study context.

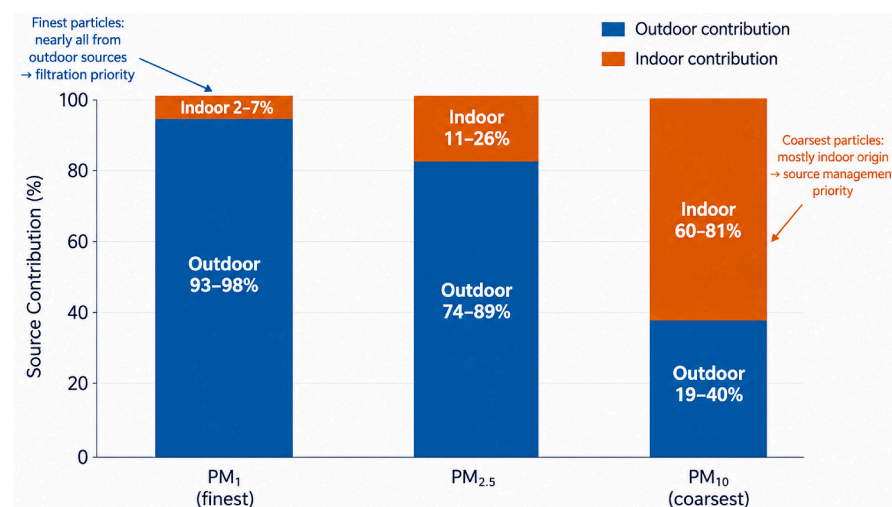


Figure 10. Outdoor versus indoor source contributions to classroom PM concentrations by particle size fraction.

One direct biomarker study of 1001 Nigerian preschool children with indoor combustion exposure found mean blood carboxyhemoglobin (COHb) of 1.652%. Developmental assessment revealed fine motor pass rates of 46%, gross motor 62%, problem-solving 53%, and personal–social 69% [66]. Higher blood CO concentrations were significantly associated with worse gross motor, fine motor, and problem-solving outcomes after covariate adjustment [66].

Figure 11 shows the developmental milestone pass rates across five domains in 1001 Nigerian preschool children, extracted from Nduka and Jimoh [66] as part of the systematic data extraction procedure applied to child health primary empirical studies in the corpus. Mean blood carboxyhemoglobin (COHb) was 1.652%, reflecting measurable

indoor CO exposure from household combustion sources. Domain pass rates ranged from 46% (fine motor) to 69% (personal–social). Higher blood CO concentrations were significantly associated with worse gross motor, fine motor, and problem-solving outcomes after covariate adjustment in the source study.

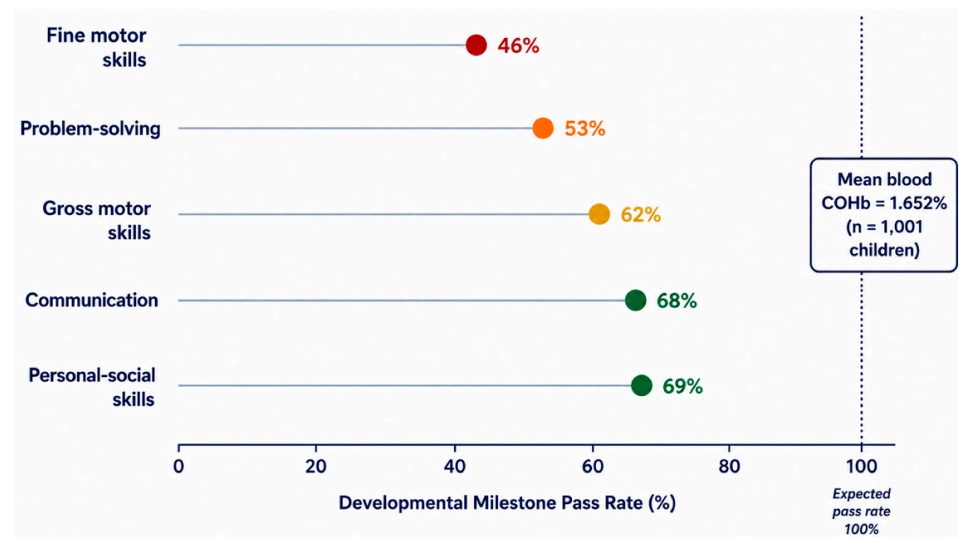


Figure 11. Developmental milestone pass rates across five domains in 1001 Nigerian preschool children, extracted from Nduka and Jimoh [66].

One systematic review of 38 studies identified from 20,914 records found repeated associations between indoor air pollutant exposure and mortality, myocardial infarction, stroke, emergency hospitalization, and emergency-room visits in older adults [81]. One ecological cross-sectional study of adults over 50 documented positive population-level correlations between household air pollution exposure and high LDL cholesterol ($r = 0.70$), elevated systolic blood pressure ($r = 0.63$), elevated BMI ($r = 0.57$), and type 2 diabetes ($r = 0.38$) [93]; these are ecological correlations and should not be interpreted as individual-level causal estimates. Figure 12 shows the percentage increase in total mortality per $10 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ by pollution source cluster, extracted from Zanobetti et al. [37]; only directly reported values are shown.

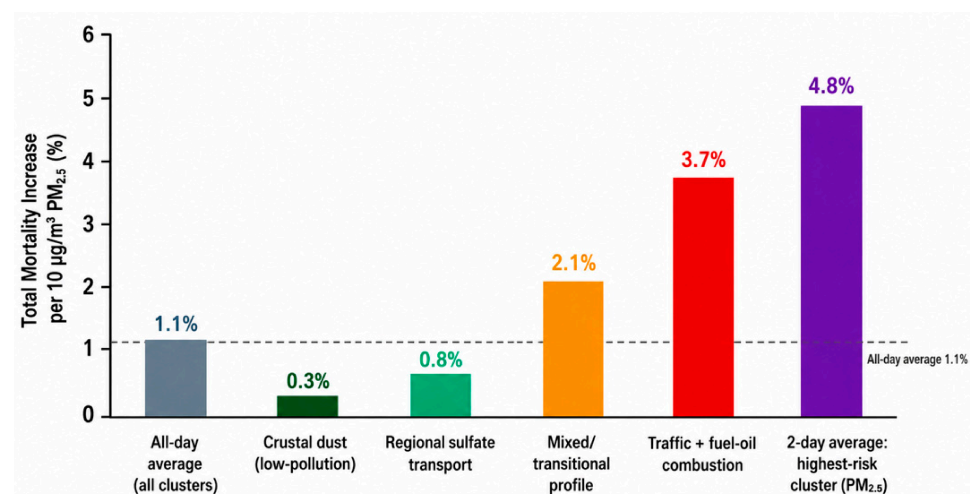


Figure 12. Percentage increase in total mortality per $10 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ increase, stratified by pollution source cluster.

4.7. Equity, Housing, and Global South Evidence

One source attribution study of low-income urban Boston housing (single-city, cross-sectional; Tier 2 [28]) found that indoor sources contributed approximately 90% of PM_{2.5} in the highest-exposure quartile and 37% in the lowest-exposure quartile, a pattern suggesting that in high-burden urban housing, ambient air quality improvements alone may be insufficient without simultaneous indoor source control. This exposure gradient has not been replicated across other cities or housing types in the present corpus and is noted as an illustrative finding rather than a general relationship; it is corroborated directionally by a related study documenting disproportionate indoor-source PM_{2.5} burden in low-income communities [94]. One review of 46 empirical studies found consistent evidence that multi-family homes had higher average outdoor pollution exposure, smaller unit volumes, and ventilation characteristics (including shared corridors and stack effects in high-rise buildings) that transferred pollutants between units [2]. In one study of low-income residents in Los Angeles, 82.5% of participants reported physical or mental health symptoms during poor-air-quality days while also reporting severely limited capacity to take protective action, including inability to afford air purifiers and inability to stay home during high-pollution episodes [95].

Socioeconomic inequalities in cooking-related PM_{2.5} exposure within Chinese urban households demonstrate within-city equity gradients driven by fuel type, stove technology, and ventilation access [96]. In social housing in low- and middle-income country contexts, one study recorded indoor PM_{2.5} of 1360 µg/m³ during cooking, CO peaks of 150 ppm, and formaldehyde concentrations of up to 4.802 ppm [97].

The Maung et al. systematic review of 69 studies included 23 from Asia, 22 from Europe, and 20 from North America, but only three from South and Central America and one from Africa [53]. Household air pollution contributes approximately 30% of ambient PM_{2.5} in South Asia compared with approximately 7% in high-income North America [30].

4.8. Policy, Standards, and Implementation Fragmentation

One international database analysis documented more than 840 IAQ limit values across 40+ countries, of which 33% were classified as enforceable government regulations, 50% as governmental guidelines without binding force, and 12% as non-governmental standards [51]. One review of 26 IAQ standards across six countries plus the WHO found that formaldehyde and PM_{2.5} were the most widely addressed pollutants, while biological contaminants, airborne-transmission criteria, and mixture effects were largely absent [50]. No standard reviewed in that analysis incorporated epidemic-prevention or airborne-transmission criteria [50,98–100]. TVOC concentration thresholds varied by a factor of ten across green-level standards (0.3–3 mg/m³) [50]. CO₂, the most widely used proxy for ventilation adequacy in real-time building management, currently has no WHO guideline value [101].

In contrast to indoor standards, PM_{2.5}, NO₂, and O₃ are subject to nationally enforceable ambient standards in most high-income countries, while enforceable indoor PM_{2.5} limits were absent from nearly all reviewed jurisdictions [60]. PM_{2.5} concentrations were rising in 65% of cities globally in the reviewed monitoring data, NO₂ was increasing at 71% of cities, and surface ozone was growing at 89% of monitoring stations [33]. Figure 13 shows IAQ governance fragmentation and outdoor pollutant trends, using authors' synthesis from Haverinen-Shaughnessy et al. [51], Sicard et al. [33], and Wei et al. [50].

Field evidence confirmed systematic gaps between statutory requirements and in-use performance: 35% of code-required WHMV systems failed minimum airflow requirements, 46% lacked compliant labeling, and three-quarters of occupants could not operate installed systems correctly [26]. Morawska et al. called explicitly for mandatory enforceable IAQ

standards in public buildings as an immediate public health priority [60]. The nature of legal and regulatory responses to IAQ exceedances varies substantially across jurisdictions. In the United States, indoor air quality in non-occupational settings is not governed by a unified federal statute; the EPA provides voluntary guidance while occupational settings fall under OSHA limits that do not apply to residences or schools. The European Union’s revised Ambient Air Quality Directive (2024) [102] tightens outdoor standards but does not establish binding indoor limits, leaving member states with discretion over residential IAQ enforcement. China’s GB/T 18883-2022 standard [103] specifies requirements for 22 indoor air quality indicators, including PM_{2.5}, formaldehyde, and TVOC, but enforcement in residential settings relies primarily on voluntary compliance rather than mandatory inspection. WHO Air Quality Guidelines provide a global reference baseline without enforcement authority in any jurisdiction. The consequence of this jurisdictional patchwork is that exceeding documented harmful indoor concentration thresholds triggers no mandatory regulatory response in most residential settings globally [50,51]. Translating existing technical evidence into legally enforceable indoor exposure limits, with mandatory post-occupancy verification and remediation pathways, is both technically feasible and absent from current policy design in the majority of reviewed jurisdictions.

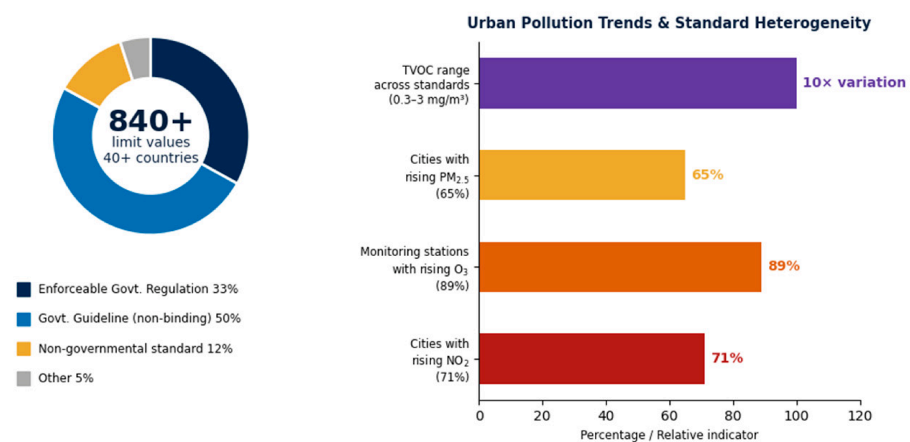


Figure 13. IAQ governance fragmentation and outdoor pollutant trends. Left panel: enforceability breakdown of more than 840 IAQ limit values across more than 40 countries in the global IEQ database. Right panel: variation in TVOC limits across standards and the proportions of monitored cities or stations reporting increasing PM_{2.5}, NO₂, and O₃ trends. Authors’ synthesis from Haverinen-Shaughnessy et al. [51], Sicard et al. [33], and Wei et al. [50].

4.9. The MGIF: Five Gap Dimension Matrices (Stages 5–7 Output)

Figure 14 presents the MGIF as an integrated system diagram showing the five gap dimensions surrounding the central Urban Indoor Air Quality System and their interconnections. The five dimensions are not independent silos: knowledge gaps limit methodological progress, which constrains technology validation, which weakens the evidence base for policy, which perpetuates equity disparities. Tables 7–11 present the detailed sub-category matrices for each dimension, derived directly from the seven-stage procedure described in Section 3.6. Each matrix entry includes a sub-category label, specific gaps identified through open coding, the primary literature anchor from which the gap was derived, and the recommended research or policy direction. These tables are the direct, traceable output of the MGIF derivation procedure and constitute the central analytical contribution of the review.

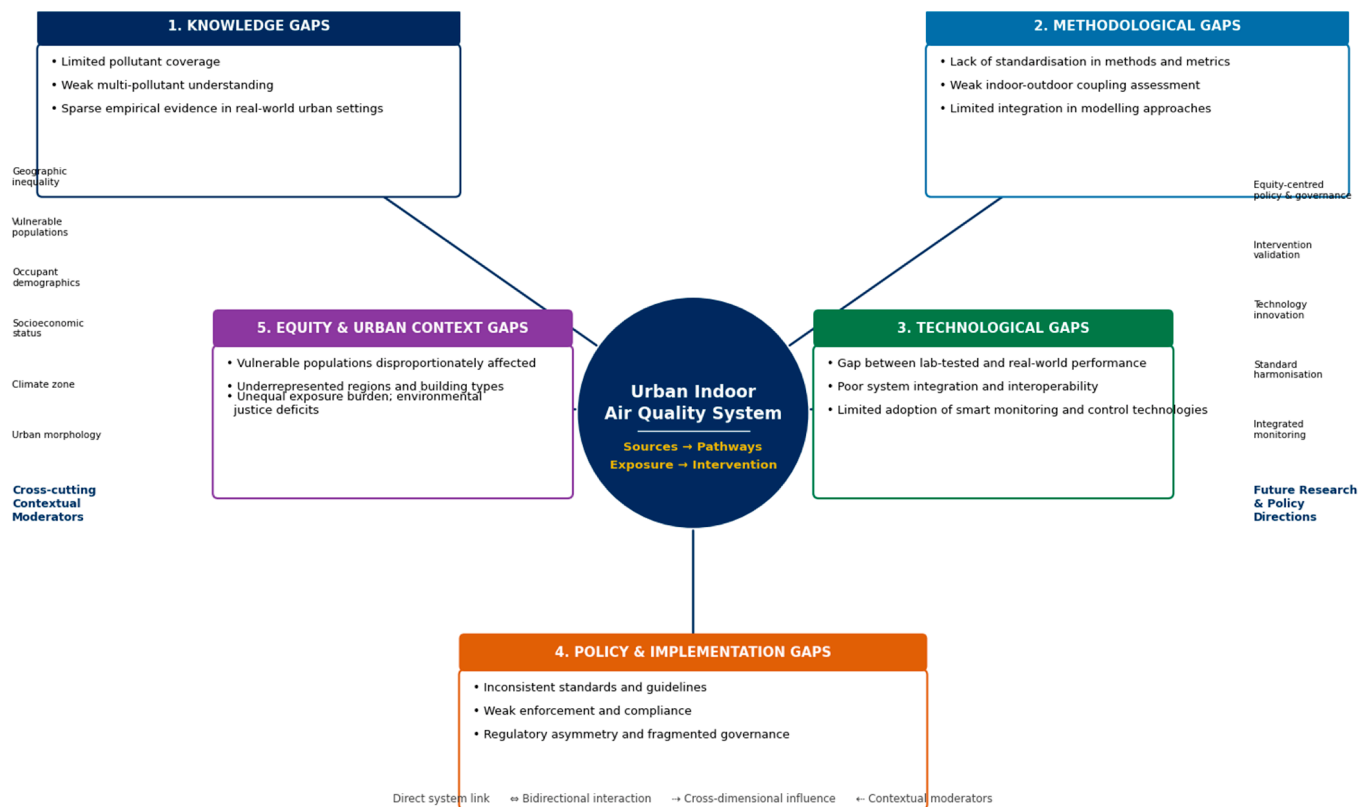


Figure 14. Multi-Dimensional Gap Identification Framework (MGIF) for urban indoor air quality.

Table 7. MGIF Dimension 1: Knowledge gaps in urban indoor air quality research.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Pollutant coverage	Over-focus on PM _{2.5} and a narrow VOC list; UFPs, SVOCs, biological contaminants, magnetic nanoparticles, microplastics, and PFAS under-studied in indoor environments; standards and monitoring frameworks lag behind this broader pollutant reality	Wei et al. [50]: biological and emerging contaminants absent from 26 reviewed standards; TVOC limits vary 10-fold across green-level standards. Aguilera et al. [48]: magnetic susceptibility significantly higher in schools than houses ($p = 0.01$), but health effects poorly characterized. Wang et al. [47]: EDCs, OPEs, and microplastics increasingly detected indoors without regulatory response.	Expand monitoring to multi-pollutant assessment frameworks; develop standardized indoor sampling protocols for emerging contaminants; integrate sensors for UFPs, SVOCs, and biological agents into longitudinal IAQ campaigns; prioritize toxicological characterization of indoor emerging contaminants
Exposure science	Reliance on single-pollutant exposure models; weak linkage between fixed-site concentration and personal exposure; insufficient longitudinal data; outdoor ambient monitoring used as indoor exposure proxy despite fundamental mismatch	Zanobetti et al. [37]: PM _{2.5} mixture composition changes mortality risk by $>3\times$ across source clusters in the same city. Pillarisetti & Ye [3]: 80–90% of time spent indoors, yet exposure is still primarily measured outdoors. Liu et al. [21]: systematic review of 210 PM _{2.5} studies found activity pattern, microenvironment, and season critical, but rarely measured simultaneously.	Deploy wearable sensors with time-activity tracking in longitudinal cohort studies; develop multi-pollutant personal exposure models validated against direct biomarker measures; prioritize panel study designs with ≥ 12 -month monitoring periods in occupied dwellings

Table 7. *Cont.*

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Multi-pollutant interactions	Synergistic and antagonistic toxicity of co-occurring indoor pollutant mixtures unstudied; mixture effects absent from risk assessment frameworks, IAQ monitoring design, and standard-setting processes	Austin et al. [38]: five distinct multi-pollutant profiles identified in urban air data with different source attributions and health implications. Zanobetti et al. [37]: traffic–oil mixture PM _{2.5} produces 3.7% mortality increase vs. 1.1% for clean-day equivalent mass, proving mixture composition is a primary risk determinant.	Adopt mixture modeling and exposome-level IAQ study designs; develop source-specific indoor PM _{2.5} exposure profiles for major urban dwelling types; incorporate chemical fingerprinting into routine IAQ monitoring protocols
Indoor source taxonomy	Cooking, cleaning product use, and material off-gassing poorly characterized in combination and over time; temporal emission dynamics under-resolved; cultural and behavioral drivers of source intensity rarely quantified	Tang et al. [62]: pan-frying peaks at 92.9 µg/m ³ vs. 0.6 µg/m ³ for air-frying, 155-fold range within a single domestic activity type. Sun & Wallace [63]: only 27% of cooking events used any added ventilation despite 22% contribution to daily PM _{2.5} personal exposure. Baeza-Romero et al. [104]: ~180 reviewed studies systematically under-report behavioral, occupancy, and source-timing metadata.	Conduct high-frequency multi-source simultaneous monitoring in occupied urban dwellings across diverse cultural and demographic contexts; link real-time source activity logs to IAQ sensor data; characterize emission factors for culturally specific cooking methods

The evidence patterns documented in Sections 4.3–4.8 (pollutant source heterogeneity, intervention compliance failures, regulatory fragmentation, and equity disparities) are the empirical substrate from which the five MGIF gap dimensions in Section 4.9 are directly derived. Each sub-category in Tables 7–11 is anchored to at least one finding from these sections; the cross-references embedded in the evidence anchor column of each table provide the specific traceability links.

4.9.1. Dimension 1: Knowledge Gaps

The knowledge gap dimension draws primarily on the pollutant source and exposure patterns documented in Sections 4.3 and 4.4, where multi-pollutant complexity and personal exposure measurement limitations were the most recurrent evidence-class findings across the corpus.

4.9.2. Dimension 2: Methodological Gaps

The methodological gap dimension draws primarily on the measurement inconsistencies and study design limitations surfaced across Sections 4.3 and 4.4, where cross-study comparability failures were the most frequently cited limitation in the included records.

4.9.3. Dimension 3: Technological Gaps

The technological gap dimension draws primarily on the intervention effectiveness and compliance findings in Section 4.5, where the systematic distance between laboratory-validated and field-measured performance was the defining cross-study pattern.

Table 8. MGIF Dimension 2: Methodological gaps in urban indoor air quality research.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Measurement standardization	No universal IAQ measurement protocol exists; instrument choice, averaging periods, detection limits, ventilation state during sampling, and contextual metadata reporting vary so widely across studies that cross-study comparison and meta-analysis are severely limited	Bo et al. [34]: I/O ratios span near-zero to >10 in the reviewed literature, depending on measurement method and ventilation context, making meta-analytic synthesis of “the” I/O ratio uninformative. Baeza-Romero et al. [104]: 180 reviewed studies systematically under-report building parameters critical for interpreting IAQ measurements. Mannan & Al-Ghamdi [23]: absence of standardized metrics limits reproducibility across the field.	Develop ISO/WHO-aligned unified indoor IAQ monitoring protocols specifying minimum contextual metadata, averaging periods, co-located reference measurement requirements, and QA/QC reporting standards; establish inter-laboratory comparison programs for indoor monitoring equipment
Low-cost sensor validation	Consumer- and research-grade low-cost sensors (LCS) show acceptable correlation for PM _{2.5} but significantly lower agreement for CO ₂ , CO, O ₃ , VOCs, and NO ₂ ; cross-sensitivity, humidity interference, calibration drift, and site-to-site transferability are inadequately characterized for indoor deployment	Chojer et al. [18]: PM _{2.5} $r = 0.97$ vs. reference; CO ₂ $r = 0.81$ – 0.89 ; O ₃ $r = 0.80$ – 0.85 , revealing significant pollutant-specific performance divergence. Lopes et al. [19] and Bagkis et al. [20]: documented calibration transferability failures, humidity cross-sensitivity, and drift patterns across sensor networks; absence of standardized performance metrics across manufacturer platforms.	Establish mandatory co-location protocols with reference-grade instruments for indoor LCS deployment; develop multi-sensor fusion algorithms with real-time drift correction; require manufacturers to provide indoor-specific calibration certificates; create open-access LCS performance benchmarking databases
Study design limitations	Predominance of short-duration cross-sectional designs; chronic exposure trajectories unknown; occupant behavior rarely quantified or modeled; most studies treat I/O relationship as static rather than time-varying	Liu et al. [21]: systematic review of 210 PM _{2.5} studies confirmed that exposure duration, activity patterns, and microenvironment are primary determinants of personal exposure, yet are rarely measured simultaneously. Wang et al. [86]: window-opening behavior driven by thermal comfort rather than IAQ awareness in 17 monitored UK apartments, demonstrating that occupant behavior is a primary exposure determinant that current designs miss.	Prioritize longitudinal panel and cohort study designs with ≥ 12 -month repeated IAQ measurement; integrate occupancy sensors, time–activity diaries, and wearable monitors with fixed IAQ instrumentation; develop activity-based exposure models that treat occupant behavior as a dynamic variable
Indoor–outdoor coupled modeling	Models treating the building as a permeable interface within an urban flow field, rather than as a sealed or perfectly mixed box, remain rare; room-level concentration heterogeneity driven by wind direction, window configuration, and indoor flow recirculation is systematically under-modeled	Santiago et al. [57]: CFD simulation found mean I/O ratio of 0.56 ± 0.24 with room-level values reaching 1.4 under specific window configurations, demonstrating that a single building-level I/O ratio conceals multiple-fold room-level variability. Tong et al. [58]: near-road building at 10 m showed indoor concentrations 16–21% higher than road edge, reversing the protective effect of moving indoors.	Develop and validate coupled indoor–outdoor CFD models for standard urban canyon geometries; link real-time ambient monitoring with building-scale IAQ sensors for model-in-the-loop adaptive ventilation control; develop validated particle penetration models for urban-specific façade and infiltration conditions

Table 9. MGIF Dimension 3: Technological gaps in urban indoor air quality research.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Real-world intervention performance gap	Technical efficacy established in laboratory or controlled conditions substantially overstates real-world IAQ improvement in occupied urban buildings; installation deficiencies, occupant misoperation, maintenance neglect, and HVAC system interactions consistently reduce in-use performance	Antonopoulos et al. [26]: 35% of code-required WHMV systems failed ASHRAE 62.2-2010 minimum airflow requirements; 46% lacked compliant labeling; 76% of occupants could not operate correctly; HCHO exceeded occupational thresholds even with ventilation operating. Niculita-Hirzel [27]: energy-efficient retrofit buildings showed radon 251 vs. 96 Bq/m ³ with natural vs. mechanical ventilation; tightening the building envelope without upgrading ventilation trades one risk for another.	Conduct pragmatic RCTs and natural experiments in occupied urban housing with long-term follow-up; mandate independent commissioning verification and occupant training as statutory requirements of installation compliance; establish IAQ performance certificates at point-of-occupancy linked to building permits
Integrated building-system approaches	Ventilation, filtration, envelope, and source control interventions studied almost exclusively in isolation; interactive effects, synergies, and trade-offs among systems remain uncharacterized at the whole-building scale; energy–IAQ trade-offs inadequately addressed	Lozinsky et al. [61]: review of 51 publications found envelope retrofits improve thermal comfort and acoustic outcomes but produce mixed IAQ results and increased summertime overheating risk when ventilation is not simultaneously upgraded. González-Martín et al. [11]: no single technology addresses all indoor pollutant classes; sequential or hybrid configurations needed, but energy, cost, and maintenance implications unstudied in real residential contexts.	Conduct whole-building-system trials combining ventilation, filtration, envelope improvements, and source control in randomized designs; develop integrated IAQ design frameworks with explicit trade-off mapping across pollutant classes, energy performance, and climate zones; assess lifecycle energy and IAQ performance simultaneously
Smart building integration	Real-time IAQ monitoring is available but rarely integrated into building management systems (BMS) for adaptive ventilation control; IoT-enabled demand-controlled ventilation based on IAQ rather than occupancy alone is nascent in residential contexts; interoperability between sensor platforms and HVAC control systems is poor	Ramadan et al. [70]: federated learning LSTM model achieved 90.8% prediction accuracy for HVAC optimization in healthcare, but residential IoT deployment remains rare and lacks validation. Chojer et al. [18] and Lopes et al. [19]: sensor performance sufficient for real-time control in some applications but CO ₂ and O ₃ accuracy gaps limit multi-pollutant BMS integration.	Embed validated multi-pollutant IAQ monitoring into residential BMS with adaptive ventilation control algorithms; develop open interoperability standards for IAQ-BMS integration; validate occupant-responsive IAQ control systems in diverse residential building types across climate zones; assess occupant privacy and data governance implications of continuous indoor monitoring
Multi-pollutant and hybrid filtration	Most commercial filtration technologies are optimized for particulate removal only; VOC and gaseous pollutant removal requires separate activated carbon or photocatalytic systems; no single device addresses all major indoor pollutant classes; energy penalty of hybrid systems is poorly characterized	González-Martín et al. [11]: HEPA achieves > 99.5% for 0.3–0.5 µm particles; activated carbon removes BTEX at 81.5–100%; biofilters achieve VOC removal > 95% under optimal conditions, but optimal conditions differ radically from real residential environments. Sequential or hybrid configurations introduce compounding energy, maintenance, and cost burdens that remain unvalidated in field conditions.	Develop and validate hybrid sequential filtration–adsorption units optimized for indoor residential multi-pollutant environments; characterize energy penalty, filter service life, and maintenance requirements under real urban conditions; develop low-cost biofilter and passive adsorption technologies scalable to residential and school settings

Table 10. MGIF Dimension 4: Policy and implementation gaps in urban indoor air quality research.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Standard fragmentation and weak enforceability	TVOC limits vary ten-fold across equivalent-level standards; biological contaminants, airborne-transmission criteria, and mixture effects absent from most frameworks; only 33% of 840+ global IAQ limit values are classified as enforceable government regulations; WHO guidelines not uniformly adopted	Haverinen-Shaughnessy et al. [51]: 840+ IAQ limit values across 40+ countries; 33% enforceable regulations, 50% governmental guidelines, 12% non-governmental standards. Wei et al. [50]: 26 standards across 6 countries, no standard included epidemic-prevention criteria; TVOC thresholds span 0.3–3 mg/m ³ across green-level standards. Dimitroulopoulou et al. [101]: CO ₂ lacks WHO guideline value despite being the most widely used ventilation adequacy proxy.	Harmonize indoor PM _{2.5} , VOC mixture, formaldehyde, biological contaminant, and CO ₂ limits internationally around WHO Air Quality Guidelines as binding reference standards; establish epidemic-prevention criteria in health-level IAQ certifications; close the CO ₂ guideline gap through WHO-led consultation process
Compliance failure and post-installation gap	Code-required systems systematically non-compliant in practice; post-installation performance verification not legally required; occupant education not mandated as part of installation compliance; labeling and commissioning standards poorly enforced	Antonopoulos et al. [26]: 35% of WHMV systems non-compliant with ASHRAE 62.2-2010; 46% lacked compliant labeling; 35 of 46 participants could not operate correctly; HCHO exceeded occupational thresholds even when systems were operational. This gap is structural, not incidental: installation is regulated but performance, commissioning, and education are not.	Mandate third-party commissioning verification for all residential IAQ systems at point of installation; require IAQ performance certificates linked to building occupancy permits; mandate occupant education and written operating instructions as statutory installation requirements; establish ongoing maintenance and inspection regimes for code-required ventilation systems
Indoor–outdoor regulatory asymmetry	Outdoor PM _{2.5} , NO ₂ , and O ₃ subject to nationally enforceable ambient standards in most high-income countries; enforceable indoor PM _{2.5} limits absent in nearly all jurisdictions; residents receive less health protection during the 80–90% of time spent indoors than during outdoor periods	Morawska et al. [60]: explicit call for mandatory enforceable IAQ standards in public buildings. Sicard et al. [33]: NO ₂ rising in 71% of cities, O ₃ at 89% of stations, outdoor pollution increasingly infiltrating indoors without any indoor regulatory backstop to protect building occupants. WHO [105]: outdoor PM _{2.5} guideline 5 µg/m ³ ; typical indoor PM _{2.5} in occupied residences commonly exceeds this without triggering any regulatory response.	Establish legally enforceable indoor PM _{2.5} and NO ₂ limits in residential, school, and public building codes; link indoor standards to local ambient air quality context so that urban buildings in high-pollution zones carry higher ventilation and filtration requirements; extend ambient monitoring equivalence to occupied indoor environments

Table 10. Cont.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Source control and product regulation	VOC content limits for building materials, interior finishes, and consumer products inconsistently enforced across jurisdictions; no systematic lifecycle tracking of indoor material emissions after installation; HCHO and SVOC emissions from installed materials inadequately regulated	Wickliffe et al. [78]: 12 VOCs detectable in majority of 99 US homes; cancer risk threshold exceeded in 35–50% of simulations for some VOC scenarios. Wimalasena et al. [106]: a systematic review identified housing risk factors associated with respiratory disease, reinforcing the importance of housing conditions for indoor environmental health. Wu et al. [69]: modern LEED-certified office building functions as net VOC source (0.75 mg/h/m ²) despite green certification, challenging assumptions about high-performance buildings. Salthammer et al. [43]: material emission decay times range from weeks to years depending on product quality.	Harmonize building product VOC and HCHO emission limits across jurisdictions aligned with EU REACH and California Title 24 standards; require Environmental Product Declarations (EPDs) for all interior finish materials with indoor emission test data; mandate post-occupancy emission testing for new residential construction; establish material performance warranties for IAQ-relevant emission levels
Cross-sector coordination and integration	IAQ, energy efficiency, health, and planning policies developed independently with limited coordination; building energy codes focus on thermal performance without IAQ co-performance requirements; urban planning rarely incorporates IAQ risk mapping into siting decisions	Niculita-Hirzel [27]: energy efficiency programs inadvertently worsened IAQ by mandating airtight building envelopes without compensatory ventilation requirements. Niza et al. [107]: reviewed 103 ventilation publications finding consistent IAQ–energy trade-offs inadequately addressed in current guidance. WHO [105]: IAQ guidelines exist in isolation from building energy directives in most national regulatory frameworks.	Integrate IAQ co-performance requirements into building energy codes; establish joint IAQ–energy rating systems for residential construction and major retrofit projects; require urban planners to use ambient air quality data in building siting decisions for schools, hospitals, and high-density housing; develop cross-ministry coordination frameworks for IAQ–health–energy policy alignment

4.9.4. Dimension 4: Policy and Implementation Gaps

The policy gap dimension draws primarily on the governance fragmentation findings in Section 4.8, where the enforceability deficit and indoor–outdoor regulatory asymmetry were documented across multiple independent analyses.

4.9.5. Dimension 5: Equity and Urban Context Gaps

The equity gap dimension draws primarily on the evidence from Sections 4.6 and 4.7, where geographic concentration of primary evidence and disproportionate exposure burden among low-income and Global South populations were the most consistently under-addressed structural features of the corpus.

Table 11. MGIF Dimension 5: Equity and urban context gaps in urban indoor air quality research.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Low-income and multi-family housing	Structural disadvantage amplifies indoor exposures through smaller unit volumes, shared ventilation corridors, higher outdoor pollution proximity, and lower capacity to invest in mitigation; these mechanisms are documented but not yet translated into targeted policy instruments	Adamkiewicz et al. [28]: indoor sources contribute 90% of PM _{2.5} in highest-exposure quartile vs. 37% in lowest; outdoor air quality improvements will be least effective for highest-burden residents. Levy & Kibilko [2]: 46 empirical studies confirm multi-family homes have systematically higher indoor pollution. Palinkas et al. [95]: 82.5% of low-income LA residents reported health symptoms during poor-air-quality days with severely constrained adaptive capacity.	Equity-centered IAQ research with disaggregated exposure analysis by housing tenure, income decile, building type, and demographic group; targeted retrofit programs for social and rental housing with health co-benefit tracking; tenant-centered IAQ improvement standards that do not require owner permission for individual interventions
Global South underrepresentation	IAQ primary evidence base concentrated in high-income countries; populations with highest indoor exposure burden (South Asia, sub-Saharan Africa, Central America) minimally represented in primary empirical literature; standards designed for high-income building stock applied by default to LMIC contexts	Maung et al. [53]: 69-study systematic review includes 23 studies from Asia, 22 Europe, 20 North America, but only 3 South/Central Americas and 1 Africa. Chowdhury et al. [30]: HAP contributes ~30% of ambient PM _{2.5} in South Asia vs. ~7% in high-income North America, a four-fold burden disparity. Emeteri et al. [24]: IAQ challenges in African cities systematically different from European/North American contexts but almost entirely unstudied.	International capacity-building programs linking LMIC researchers with measurement technology and analysis support; open-access low-cost sensor deployment in LMIC cities with local data ownership; research funding criteria requiring geographic equity of study populations; LMIC-specific IAQ guidelines accounting for local fuel types, climate, and building stock
Children and school environments	School IAQ standards lag behind residential standards in most jurisdictions; developmental and neurocognitive consequences of school-hour exposure inadequately quantified outside high-income contexts; classroom-specific source profiles not incorporated into school IAQ policy	Valls Roche et al. [4]: 93% of children globally breathe air polluted enough to affect health; consistent evidence of effects on cognition, respiratory health, and learning performance from 95 systematic reviews. Nduka & Jimoh [66]: fine motor pass rate 46% in highest-CO-exposure preschool group (<i>n</i> = 1001) using direct biomarker. Caciara et al. [108]: comprehensive analysis of classroom microclimate standards found significant gaps between recommended and measured IAQ in schools globally.	Mandatory IAQ monitoring, reporting, and remediation standards for all school buildings; longitudinal cohort studies linking measured school-hour IAQ to academic performance, cognitive development, and respiratory health outcomes in diverse national contexts; integration of school IAQ requirements into national education infrastructure investment programs

Table 11. Cont.

Sub-Category	Specific Gaps Identified	Evidence Anchor from Literature	Priority Research/Policy Direction
Older adults and clinically vulnerable populations	Cardiovascular, metabolic, and neurodegenerative consequences of indoor air pollution in older adults systematically under-studied relative to respiratory outcomes; clinical vulnerability from pre-existing conditions poorly integrated into IAQ risk assessment frameworks	Ndlovu & Nkeh-Chungag [81]: systematic review (38 studies, 20,914 records): indoor pollution associated with mortality, MI, stroke, emergency hospitalization, and ER visits in older adults. Dehghani et al. [93]: HAP correlated with LDL cholesterol $r = 0.70$, systolic BP $r = 0.63$, BMI $r = 0.57$, DM2 $r = 0.38$, demonstrating metabolic as well as cardiovascular burden. Brauer et al. [109]: air pollution impact on cardiovascular outcomes systematically underestimated in indoor exposure studies.	Integrate cardiovascular, metabolic, and cognitive outcomes into IAQ burden assessment and standard justification; design dwelling-level IAQ interventions specifically for aging-in-place populations with clinical vulnerability; include IAQ assessment in standard clinical care pathways for patients with cardiovascular or respiratory disease
Cultural and behavioral factors	Cooking practices, incense use, solid fuel use patterns, cleaning product preferences, and window-opening habits vary substantially by culture and socioeconomic context; culturally specific exposure profiles absent from mainstream IAQ literature; most interventions are technology-centric and culturally decontextualized	Sun & Wallace [63]: only 27% of cooking events used added ventilation in Canadian households, behavioral norms override available technology. Tang et al. [62]: method-specific PM _{2.5} emissions span 155-fold range, meaning cultural cooking preferences alone can determine whether WHO guidelines are violated. Chowdhury et al. [30]: 3.8 billion people use solid fuels, exposure patterns fundamentally different from natural gas users studied in most intervention trials.	Design culturally stratified IAQ exposure studies across multicultural urban settings; co-design behavioral interventions with community partners, embedding IAQ actions within existing cultural practices rather than substituting them with technology-centric solutions; develop cooking-method-specific emission guidance for public health communication

5. Discussion

5.1. Cross-Cutting Patterns Across the MGIF Dimensions

Three cross-dimensional interactions emerged from the MGIF derivation that are consequential enough to warrant discussion as a group rather than within individual dimension matrices. The first involves Knowledge Dimension 1 and Methodological Dimension 2. The corpus showed that PM_{2.5} source-cluster composition modulates mortality risk by a factor exceeding three within the same urban environment [37], yet monitoring frameworks and study designs across the reviewed literature remained calibrated for single-pollutant mass measurement. The field cannot generate the evidence needed to validate mixture-based risk models if monitoring instruments and study protocols are not designed to capture mixture composition. These two gaps are therefore mutually reinforcing: poor measurement design prevents the knowledge generation needed to reform measurement standards.

The second interaction links Technological Dimension 3 and Policy Dimension 4. The reviewed literature showed that ventilation systems failed minimum performance requirements in 35% of audited cases [26], not because the technology was inadequate but because installation is regulated and post-installation performance is not. The technology itself is adequate; the regulatory architecture that would translate it into actual exposure

reduction is not. Improving technology without fixing enforcement, or tightening standards without improving commissioning requirements, will not close the health protection gap.

The third linkage connects Equity Dimension 5 to all four other dimensions. Geographic concentration of the evidence base in high-income settings means that measurement protocols, intervention technologies, and regulatory standards have all been designed around building stock, climate conditions, and occupant behavior that are not representative of the settings where indoor air pollution burden is highest. South Asian and sub-Saharan African populations, who carry a disproportionate share of the indoor pollution burden [30,53], are minimally represented in the evidence base from which standards and interventions are derived. This is not a peripheral limitation but a structural bias embedded in how the field has allocated research investment.

5.2. Interpretation of Key Evidence Patterns

Several patterns in the results warrant interpretive discussion that goes beyond describing what was found.

The inversion in PM_{2.5} source contributions across exposure quartiles (37% indoor-source dominance in the lowest quartile, 90% in the highest [28]) has a specific implication for policy design: improvements to outdoor ambient air quality, which are the primary regulatory instrument in most jurisdictions, will produce the least proportional health benefit precisely for the residents carrying the greatest total PM_{2.5} burden. This pattern, drawn from a single source-attribution study in low-income Boston housing [28], has not been replicated across other cities or income contexts. If generalizable, it would suggest that policy frameworks focused exclusively on outdoor emissions control may produce the least proportional health benefit for the residents carrying the greatest exposure burden, though this inference requires confirmation from multi-city replication studies.

The divergence in PM_{2.5} and VOC rank orders across cooking methods [62] suggests that single-pollutant assessment of cooking sources will misrepresent multi-pollutant exposure. Pan-frying dominates both PM_{2.5} and VOC emission rankings, but the relative magnitudes differ, reflecting different underlying emission mechanisms (oil chemistry and combustion temperature rather than overall emission intensity). Monitoring designs that measure only PM_{2.5} during cooking events will miss the VOC co-exposure that contributes to cancer and respiratory risk from the same activity.

The ventilation compliance audit findings [26] indicate a structural pattern rather than an isolated failure. Installation of code-required systems is regulated; performance after installation, commissioning quality, and occupant capability to operate systems correctly are not. The audit evidence from Antonopoulos et al. [26] (one study of 55 newly constructed US homes in specific climate zones) suggests this reflects a regulatory design gap rather than a technology limitation. This interpretation is consistent with but not confirmed by the broader corpus; it should be tested in diverse building regulatory contexts before being adopted as a general policy diagnosis.

The pattern of building envelope retrofits improving thermal performance while worsening IAQ in the absence of compensatory ventilation [27,61] illustrates a recurring trade-off in the evidence base: interventions designed to improve one dimension of building performance can create or worsen IAQ problems when they are not designed as integrated systems. Energy efficiency programs that mandate air sealing without requiring ventilation upgrades have inadvertently worsened radon, VOC, and CO₂ accumulation in several reviewed study populations.

The association between LEED green certification and net VOC source behavior [69] suggests that certification schemes calibrated primarily for energy performance do not guarantee IAQ co-benefits. This finding comes from a single field measurement study of

one LEED-certified office building [69] and cannot be generalized to green certification schemes as a class. It is noted here as a hypothesis warranting systematic investigation across certified building types and certification standards.

Window-opening behavior driven by thermal comfort rather than pollutant concentration [86] indicates that occupant responses to IAQ risk are primarily governed by comfort rather than health awareness, even among occupants in monitored buildings with available IAQ data. This pattern suggests that technology-centric interventions requiring sustained occupant engagement (such as range hood use during cooking or manual adjustment of ventilation settings) will underperform relative to passive or automated systems that do not depend on occupant action.

5.3. The UIAQN Framework: Structure, Comparison with Prior Frameworks, and Limitations

The UIAQN framework (Figure 3) proposed in this review is not the first attempt to organize urban IAQ evidence into a multi-level conceptual structure. Mannan and Al-Ghamdi [23] proposed a building-centered model linking indoor sources, occupant activities, and health outcomes. Vardoulakis et al. [10] organized residential exposure evidence around pollutant pathways. Tran et al. [5] structured their synthesis around pollutant–disease–technology triads. Table 12 provides a direct comparison of these frameworks with the UIAQN.

The UIAQN extends these prior structures in three specific ways. First, governance and policy mechanisms are elevated from background context to a co-equal fourth level, reflecting the finding that policy and implementation gaps are as consequential as knowledge and technological gaps in determining real-world exposure outcomes. Second, the five MGIF gap dimensions are embedded as structural components of the framework architecture rather than listed as a separate gap section, with knowledge and methodological gaps mapping to Level 1 and Level 3 deficiencies; technological gaps to Level 2 failures; policy gaps to Level 4 deficiencies; and equity gaps to the contextual moderators operating across all levels. Third, bidirectional feedback pathways connect all four levels explicitly, reflecting the evidence reviewed here: governance decisions constrain building system options; system performance shapes personal exposure; and exposure burden data should in principle feed back into regulatory design, though in current practice this feedback loop is largely absent.

The framework’s primary limitation is that it is conceptual. Its internal structure is grounded in the MGIF gap analysis, but it has not been empirically validated against field data. Validation would require multi-site, multi-pollutant, multi-scale studies of the type identified as high priorities in the MGIF matrices, studies that do not yet exist in sufficient number or geographic diversity. The UIAQN is therefore best understood as an organizing architecture for future research and policy design rather than a tested predictive model.

Table 12. Comparison of UIAQN with selected prior IAQ conceptual frameworks.

Feature	Mannan & Al-Ghamdi [23]	Vardoulakis et al. [10]	Tran et al. [5]	UIAQN (This Review)
Levels or dimensions	Sources → building factors → occupant health	Pollutant sources → pathways → exposure	Pollutants → diseases → technologies	Pollutant dynamics → building systems → personal exposure → governance
Governance as integral level	No; regulatory context treated as external	No; policy discussed but not a framework level	No; technology-focused; governance peripheral	Yes; governance and policy mechanisms is Level 4

Table 12. *Cont.*

Feature	Mannan & Al-Ghamdi [23]	Vardoulakis et al. [10]	Tran et al. [5]	UIAQN (This Review)
Gap dimensions embedded in framework	No	No	No	Yes; five MGIF dimensions mapped onto framework levels
Bidirectional feedback pathways	No; linear source-to-health logic	No; pathway model is unidirectional	No	Yes; all four levels connected by bidirectional feedback
Equity moderators across all levels	No; equity not addressed	Partially; vulnerable populations noted	No	Yes; urban morphology, socioeconomic stratum, climate zone, and occupant demographics operate across all levels
Evidence base	Narrative review	Systematic review	Narrative review	PRISMA 2020 systematic review with bibliometric mapping
Gap identification procedure	Narrative	Narrative	Narrative	Seven-stage hybrid deductive–inductive derivation

5.4. Priority Research and Policy Directions

Seven cross-cutting priorities emerge from the five MGIF dimension matrices and the cross-dimensional interactions described above.

First, transition from single-pollutant to multi-pollutant monitoring and exposure assessment, incorporating wearable personal sensors, time–activity modeling, and mixture-based risk methods, addressing Knowledge Gaps 1 and 2 together.

Second, develop and mandate universal IAQ measurement protocols specifying minimum contextual metadata, averaging periods, sensor co-location requirements, and quality assurance standards, addressing Methodological Gap 1 and enabling meaningful cross-study synthesis for the first time.

Third, conduct field trials of integrated building-system interventions in occupied urban housing with mandated commissioning verification and occupant training as statutory components, addressing Technological Gap 1, Technological Gap 2, and Policy Gap 2 simultaneously.

Fourth, establish enforceable indoor PM_{2.5}, VOC mixture, and formaldehyde limits in residential and public building codes, explicitly linked to local outdoor air quality context, addressing Policy Gaps 1 and 3.

Fifth, mandate equity-centered research designs with disaggregated exposure analysis by housing tenure, income level, and geographic region, and direct research funding toward Global South primary evidence generation, addressing Equity Gaps 1 and 2.

Sixth, develop and deploy open-access, low-cost sensor networks in Global South urban settings with local data ownership and capacity-building support, addressing the intersection of Methodological Gap 2, Technological Gap 3, and Equity Gap 2.

Seventh, integrate geospatial AI and spatial inequality analysis into urban IAQ research and governance. The current evidence base is dominated by point-measurement studies and building-scale interventions; it lacks the spatial resolution needed to identify within-city IAQ inequality gradients or to target mitigation resources geographically. Emerging GeoAI methods, including satellite-based PM_{2.5} downscaling, machine learning-assisted source apportionment, digital twin building simulation, and street-network-

integrated exposure mapping, offer the potential to transform IAQ governance from a building-by-building problem to a neighborhood- and city-scale equity challenge. Spatial clustering of co-exposure vulnerability (overlapping poor ventilation, high outdoor PM_{2.5}, low-income housing density, and medically vulnerable populations) can identify intervention priority zones with far greater precision than current monitoring networks allow. Developing, validating, and openly sharing GeoAI-based indoor exposure estimation tools, particularly for contexts where building-level measurement campaigns are not feasible, is a high-priority technical direction for IAQ research in the coming decade.

From a building engineering and HVAC perspective, the findings across Sections 4.5 and 4.8 converge on a structural implementation challenge that transcends technology performance. Existing HVAC and ventilation technologies, including whole-house mechanical ventilation, energy recovery ventilators, HEPA and MERV-13 filtration, demand-controlled ventilation, and source-specific exhaust systems, are demonstrably effective under controlled or laboratory conditions. The gap is not technological but commissioning and regulatory: installed systems fail to deliver design performance at rates that constitute a public health problem [26], and post-installation performance verification is not a mandatory component of building code compliance in any reviewed jurisdiction. HVAC engineers and building commissioning professionals therefore occupy a critical position in the IAQ improvement pathway, one that current regulatory frameworks underutilize. Future research should evaluate whether mandatory commissioning protocols, occupant education requirements, and post-occupancy IAQ performance certificates tied to occupancy permits can systematically close the gap between design-level and in-use ventilation performance.

5.5. Limitations

This review has several limitations that require explicit acknowledgment.

Review-heavy evidence base. Fifty-one percent of included records are themselves systematic reviews or meta-analyses rather than primary empirical studies. A substantial portion of the quantitative findings reported in Section 4 therefore reflects prior synthesis rather than new primary observations. This review does not attempt statistical pooling of effect sizes across included syntheses, and quantitative values are attributed to the primary empirical studies within those syntheses wherever traceable. Nevertheless, readers should interpret findings drawn from Tier 4 sources as characterizations of the existing evidence landscape rather than as independent empirical contributions of this review.

Geographic concentration. Primary empirical evidence is concentrated in North America, Europe, and East Asia. Sub-Saharan Africa is represented by one primary field study; Latin America by three records within included reviews; and South Asia by limited primary evidence despite carrying a disproportionate share of the global indoor air pollution burden. The MGIF gap matrices for Equity Dimension 5 partly reflect this concentration directly: the identified gaps are not only knowledge gaps in the abstract but gaps in the evidence base itself. Framework outputs, intervention effectiveness estimates, and policy recommendations derived from this corpus are most directly applicable to high-income urban building contexts and should be interpreted cautiously for other settings.

Language restriction. The review is restricted to English-language full-text records. Substantial IAQ research published in Chinese, Spanish, Portuguese, Arabic, and other languages was not retrievable under the eligibility criteria. This restriction may introduce systematic publication bias toward findings from English-language research environments, compounding the geographic concentration limitation.

MGIF interpretive subjectivity. The derivation procedure involves interpretive judgment at Stages 3 through 5. Dual-reviewer coding and inter-coder reliability reporting

($\kappa = 0.81$) reduce but do not eliminate this subjectivity. A different coding team applying the same procedure to the same corpus might produce a different dimension structure or a different distribution of intermediate categories across dimensions. The five-dimension MGIF should be understood as one defensible analytical outcome among plausible alternatives, not as a uniquely correct organization of the gap space.

Conceptual status of the UIAQN framework. The UIAQN is a conceptual organizing architecture derived from the MGIF gap output. It has not been empirically validated: no field data exist that could confirm or disconfirm its four-level structure as an accurate representation of how pollutant dynamics, building systems, personal exposure, and governance mechanisms interact in practice. Its value is as a reference architecture for designing future research and coordinating policy investment, not as a predictive or explanatory model. Empirical validation would require multi-site, multi-pollutant, multi-scale prospective studies that do not yet exist at the required geographic and contextual diversity.

Bibliometric sensitivity. The bibliometric component relied on citation and keyword patterns within indexed literature. Citation-frequency zone distributions and collaboration network structures are sensitive to database coverage and citation practices that vary across disciplines and languages. The disciplinary silo identified between engineering and public health literature may partly reflect differential database indexing rather than purely intellectual fragmentation.

6. Conclusions

This review set out to answer a specific research question: what are the critical, multi-dimensional gaps in urban indoor air quality science, and how can they be systematically derived and translated into an actionable framework? The answer consists of two parts. The MGIF derivation procedure identified 20 specific gaps across five dimensions (knowledge, methodological, technological, policy and implementation, and equity and urban context), each traceable to the coded literature corpus and linked to priority research and governance directions. The UIAQN framework organizes these gaps into a four-level conceptual architecture designed as a shared reference for the research and policy communities working on urban indoor environments.

The most urgent cross-dimensional priorities are: (1) transitioning from single-pollutant to multi-pollutant monitoring and exposure assessment; (2) closing the real-world ventilation compliance gap through mandated commissioning verification and occupant education; (3) establishing enforceable indoor $PM_{2.5}$ limits to end the regulatory asymmetry between indoor and outdoor air quality governance; (4) mandating equity-centered research designs with Global South primary evidence generation; and (5) developing and validating integrated building-system interventions that address ventilation, filtration, envelope, and source control simultaneously rather than in isolation.

The UIAQN framework offers a four-level conceptual organizing architecture—pollutant dynamics, building systems and occupant behavior, personal exposure and health outcomes, and governance and policy mechanisms—as a structured reference for the next phase of urban IAQ research and policy investment. Both the MGIF and UIAQN are evidence-derived organizing tools, not externally validated predictive models; their value lies in structuring research programs and policy coordination conversations across disciplinary boundaries. For building scientists and HVAC engineers specifically, the framework highlights that the most urgent priority is not new technology development but the governance infrastructure that ensures installed ventilation systems perform as designed, mandatory commissioning verification, post-occupancy IAQ performance certification, and occupant training requirements are all technically feasible and currently absent from most building codes. Addressing urban indoor air quality at the scale of the problem

requires coordinated investment across technical, governance, and equity dimensions simultaneously. The MGIF matrices and UIAQN framework provide a structured architecture for organizing that investment, subject to the limitations of the evidence base, the methodological constraints of the hybrid synthesis approach, and the absence of external framework validation.

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