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REVIEW

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Residential indoor air quality interventions through a social-ecological systems lens: A systematic review

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Abstract
Indoor air quality (IAQ) is an important consideration for health and well-being as people spend most of their time indoors. Multi-disciplinary interest in IAQ is growing, resulting in more empirical research, especially in affordable housing settings, given disproportionate impacts on vulnerable populations. Conceptually, there is little coherency among these case studies; they traverse diverse spatial scales, indoor and outdoor environments, and populations, making it difficult to implement research findings in any given setting. We employ a social-ecological systems (SES) framework to review and categorize existing interventions and other literature findings to elucidate relationships among spatially and otherwise diverse IAQ factors. This perspective is highly attentive to the role of agency, highlighting individual, household, and organizational behaviors and constraints in managing IAQ. When combined with scientific knowledge about the effectiveness of IAQ interventions, this approach favors actionable strategies for reducing the presence of indoor pollutants and personal exposures.

KEYWORDS
green infrastructure, healthy housing, IAQ interventions, indoor air quality, occupant behavior, social-ecological systems

Practical Implications

- IAQ literature from diverse literature pools was analyzed and organized according to a social-ecological systems (SES) framework in order to categorize and present existing action strategies across indoor and outdoor environments to improve IAQ.
- Summarized action strategies include behavioral and physical strategies, highlighting the role of both residents and organizations in managing IAQ.
- Researchers and practitioners will benefit from a more integrated view of IAQ and an associated set of actionable IAQ strategies that link human activities and the built environment across an indoor-outdoor air pollution continuum.

1 | INTRODUCTION

Indoor air quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.[1] The effect of IAQ on health is potentially outsized as people spend most of their time indoors,[2,3] a situation that is exacerbated during public health emergencies such as COVID-19. Research has identified many negative health and productivity impacts of poor IAQ, including allergy and respiratory symptoms, low worker productivity, and increased morbidity

This work was conducted while the corresponding author was still a PhD student at Rutgers University, but has since moved to University College London.

and mortality.[4-7] Researchers have investigated factors affecting the presence, concentration, and species of indoor air pollutants and the effectiveness of interventions to improve IAQ. Most of these efforts are case studies, addressing individual factors affecting outdoor or indoor pollution, such as the role of the physical environment or human behavior. Needed is an organizational framework for evaluating and categorizing existing literature on IAQ influences and interventions based on the totality of diverse pollution factors and intersecting physical settings, human actors, and scales. One possible approach is to apply a framework offered by social-ecological systems (SES); SES facilitates analysis of complex systems that involve interactions among humans, infrastructure, and the environment, with an emphasis on the role of human agency, that is, the capacity for human beings to make choices and to impose those choices on the world.[8] Thus, the goal of this paper was to perform a comprehensive and systematic review of published IAQ research findings and place it within an SES framework characterized as interventions. This perspective is highly attentive to the role of agency, highlighting individual, household, and organizational behaviors and constraints in managing IAQ. In this application, this paper leads toward a more integrated set of actionable IAQ interventions by individual and/or group actors across diverse domains.

2 | BACKGROUND

2.1 | Indoor air quality

Indoor air quality is recognized as one of the primary aspects of indoor environmental quality (IEQ), along with thermal comfort, lighting, and acoustics. The most common pollutants considered in the context of IAQ are particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and formaldehyde (HCHO).[9] A central aspect of IAQ is human health and comfort, which distinguishes it from indoor chemistry,[6] a branch of chemistry that describes the main chemical reactions that occur in indoor air. Several disciplines study various aspects of IAQ, including environmental health and epidemiology, engineering, architecture, environmental and atmospheric sciences, psychology, and sociology producing a rich and varied literature.

2.2 | Factors affecting IAQ

Until recently, many IAQ issues were attributed primarily to building characteristics and poor construction standards, especially by the building science and engineering community. For example, construction dating from the 1970s, which prioritized energy efficiency over fresh air exchange, resulted in a large population of buildings diagnosed with sick building syndrome (SBS) and occupant exposure to toxic black mold, VOCs, and excessive ozone.[10-12] While the trade-off between energy efficiency and IAQ remains a design and operational challenge, the relevance of additional characteristics and factors affecting IAQ (eg, outdoor conditions, ambient pollutant properties and concentrations, as well as indoor occupant behaviors) have received increasing focus.[13-16] As a result, field studies have become more abundant in an attempt to parse the relative influence of various IAQ factors and to improve IAQ in real-world settings.

2.2.1 | *Influence of outdoor air quality and ambient conditions on IAQ*

Studies have shown that indoor pollutant presence is strongly associated with the presence of pollutants in outdoor air (see Ref. [13,16-19] Typically, 40–60% of indoor pollutants originate outdoors.[20] These findings stress the importance of research investigating the influence of outdoor air pollution and its local or regional sources on IAQ. For instance, the ambient PM was found to be elevated near heavy traffic or in highly urbanized and industrialized areas,[21,22] which led to IAQ issues in nearby buildings via pollutant penetration through the building envelope.[17] In the United States, individuals with low socioeconomic status often reside near outdoor sources of pollution such as highways or industry and live in tighter living spaces with poor building envelopes at a higher density of occupancy. This resulting poor outdoor air quality leads to poor air quality indoors.[23]

Since outdoor air quality has a strong effect on IAQ, improvements in outdoor air pollution can improve IAQ. However, reducing outdoor air pollution through traditional (eg, source control) methods is complicated. On large spatial scales, it is addressed by federal and state air quality standards, but often that does not address local variability in pollution concentration or the presence of pollutants suspected of causing health effects for which there are no standards yet, for example, ultrafine particles.[24,25] Thus, researchers and practitioners have turned their efforts to potentially efficacious non-traditional methods, such as changes in landscape design and outdoor amenities (eg, vegetated building roofs and walls)[26-29] to improve outdoor air quality at localized spatial scales. These interventions might benefit IAQ in nearby residences as well.

2.2.2 | *Influence of occupant behaviors on IAQ*

Individual occupant behaviors have a significant impact on IAQ, which may be adaptive or maladaptive and are mediated by the built environment. Known behaviors that are significant for IAQ include smoking, use of incense and candles, and cooking combined with poor ventilation.[16,30-33] At times, these behaviors are predicated on the presence (or lack) of building and site affordances, as in the case of building ventilation. Other behaviors may be determined by a broader social context. For instance, perceived safety and privacy issues outdoors lead to a higher prevalence of smoking indoors and reluctance to open windows for natural ventilation. Additionally, greater use of gas stove (not only for cooking but also for winter heating) and use of ventilation fans and air-conditioning behaviors are affected by income constraints.[13,23,34-37]

The role of non-governmental organizations and other organizations on IAQ is less often remarked, though it is a potential area of opportunity to make a positive impact. While some research has sought to address poor IAQ and other housing factors by leveraging housing organizations as a platform for health in lower-income communities,[35,38,39] such efforts have not been widely published. Added inspiration may be found in studies that have shown the efficacy of healthy lifestyle interventions implemented through community centers[40] and in the workplace.[41,42] Russell et al[40] find that healthy behavioral changes are most often adopted when personal, interpersonal, and programmatic connections are integrated with community-level actions into an overall service delivery framework.

2.3 | IAQ interventions through the lens of social-ecological systems framework

Social-ecological systems framework is premised on the notion that phenomena driven by multiple and diverse causes are better understood when bringing together theories and practices from social and natural sciences.[43,44] Therefore, an SES framework refers to an organizing structure that characterizes interactions among humans and the natural/built environment in a specific location and scale.[45] Elinor Ostrom's framework has pushed the social-ecological metaphor beyond the conceptual level and diagrammatically represents a system comprising social and ecological components that interact with each other in a specific spatial context, with resulting outcomes.[46,47] SES framework has been applied to a wide range of research questions and topics, including cities, climate change, urban management and disaster recovery, adaptation and mitigation, and energy and water management.[8,48-50]

When applied to IAQ, the SES framework could help categorize the associated literature and draw unique insights from it. Ideally, SES-informed synthesis of the IAQ literature would help formulate comprehensive intervention strategies across outdoor and indoor environments while elucidating mediating ecological and social variables. In the SES approach, the social component includes users and governance systems that rely on the ecological component comprised of resource systems and units. This construct is suitable for focusing pathways of interest as "*the process of a person coming into contact with a pollutant*"[51] and corresponding resources and vectors for reducing exposure. Therefore, we applied the SES framework to describe the relationships between the systems and actors that influence and are influenced by IAQ (See Figure 1). By applying SES to IAQ, we further sought to review and categorize existing interventions and other literature findings for reducing the presence of indoor pollutants and personal exposures (see Section 4).

3 | REVIEW METHODS

3.1 | Search strategy

To identify relevant articles, an advanced manual search using Google Scholar was conducted employing the keywords of Table 1, as well as synonyms and modified versions of these keywords to best utilize each database and thesaurus. The search combined keywords from columns 1, 2, and 3 with either 4.1 or 4.2 in Table 1 to capture diverse literature focusing on IAQ and related interventions both indoors and outdoors.

3.2 | Eligibility criteria

The main criteria for inclusion in this study were peer-reviewed journal articles published in English in the last 20 years (2000–2020). The primary focus was on evidence-based studies of indoor (behavioral or physical environment) and outdoor (green infrastructure and landscape design) factors affecting indoor pollutants in residential environments. Bearing in mind socioeconomic disparities earlier noted, we were particularly eager to include studies that commented on the affordability of IAQ interventions. Our inclusion criteria did not pose restrictions for study location, sample size, duration, and methodology.

3.3 | Data abstraction

The search of the online databases yielded 173 citations that were stored on Mendeley bibliographic software (See Figure 2). Eighty-two articles were related to indoor environments and 91 to outdoor environments. Duplicates (34) were removed. We excluded 45 citations after reading the abstract because they did not meet the inclusion criteria. Of those remaining, 84 were retrieved in full text; after parsing the articles by our inclusion criteria, we excluded an additional 37. In summary, we retained 47 articles for this review, 24 focusing on indoor environments and 23 on outdoor environments (See Tables 2–5 for the final list of articles).

4 | FINDINGS AND DISCUSSION

The majority of works in the final list of articles are from North America, followed by Europe and Asia (see left chart in Figure 3). While most research interest on indoor-related determinants of IAQ is from the United States, outdoor-related works mainly come from Europe and Asia, specifically China. Only ten of them were published before 2010, and the rest were published thereafter, which indicates increasing interest in the topic of air quality from a variety of disciplines, especially from building science, urban planning and landscape architecture, and health and epidemiology.

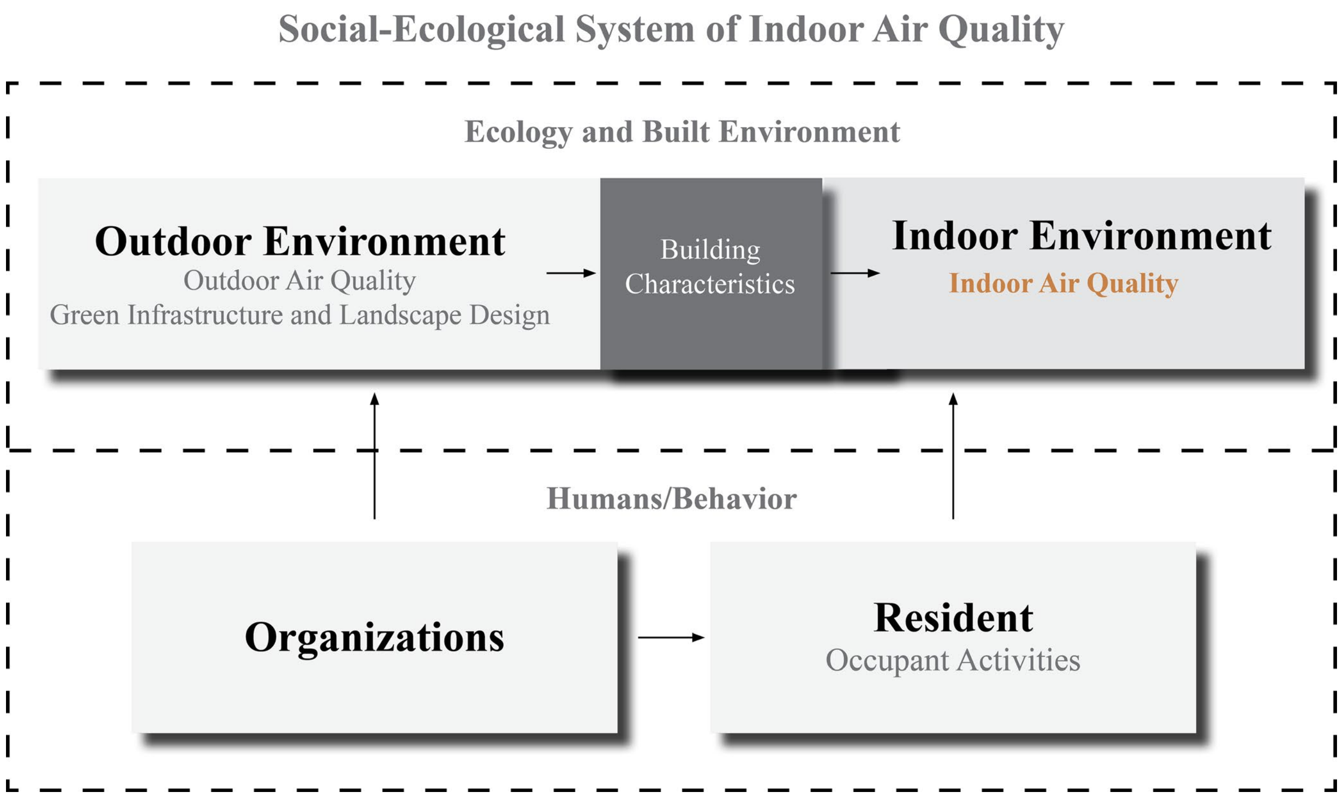

FIGURE 1 Application of social-ecological system (SES) approach to IAQ (adapted from refs. 46 and 47). IAQ is influenced by outdoor air, built environment characteristics, and occupant activities; local organizations can collaborate with residents to improve physical features indoors and outdoors and to educate occupants about altering their behaviors to support improved IAQ and reduced pollution exposures

TABLE 1 Keywords for literature review search by categories

			4. Building and environment	
1. Air quality	2. Interventions	3. Socioeconomic factors	4.1 Indoors	4.2 Outdoors
Indoor air	Interventions	Low income	Homes	Urban homes
Indoor air quality	Strategies	Cost-effective	Residential housing	Urban environments
Indoor air concentrations	Factors	Low cost	Sustainable housing	Built environment
Indoor environmental quality	Determinants	Affordable	Green homes	Residential neighborhoods
Indoor exposure(s)	Predictors	Public	Green buildings	Neighborhoods
Personal exposure(s)	Behavioral determinants	Accessible	Buildings	Sites
Human exposure(s)	Impacts		Sustainable buildings	Cities
Indoor air pollution	Control strategies		Households	Outdoor spaces
Indoor pollutants			Residential buildings	Green spaces
Particulate pollution			Single-family houses	Outdoor landscaping
Indoor pollutant exposure(s)			Single-family homes	Landscaping
Particulate matter			Multi-family buildings	Green infrastructure
Particles				Urban trees
				Urban greening
				Microclimate
				Local

Guided by the SES framework (see Figure 1), we classified the identified studies into two groups. The first group focuses on factors directly affecting IAQ within indoor environments that address changes in occupants' behaviors and/or physical alterations of housing characteristics. The second group focuses on outdoor environments, factors affecting ambient air quality, and related built environment strategies such as site design, vegetation applied to the building envelope, and landscape modifications that can reduce outdoor air pollution and consequently improve IAQ.

4.1 | Indoor environments: behavioral and physical strategies

Of the 24 articles focusing on indoor environments, 18 are evidence-based, and six are literature reviews. Six of the evidence-based papers and all six review papers address indoor interventions to improve IAQ, while the remaining 12 studies focus on factors affecting indoor pollutant levels. The interventions are either addressed directly or drawn indirectly from the studies, as outlined in Tables 2 and 3. All of the evidence-based papers discuss direct links to indoor pollutants, such as PM, allergens, VOCs, CO, CO_2, black smoke (BS), NO_2, Radon, HCHO, with PM dominating the majority of research due to its greater impacts on human health.[52]

Regarding the scale and location of the described studies, one paper undertook a large-scale project that made cross-cultural comparisons among different countries, while the remaining articles conducted smaller case studies that compared several dwellings or buildings within the same location. Among the latter group, 12 articles focused on low-income or public housing and otherwise vulnerable populations (eg, seniors, children, and pregnant women). And, three of the small-scale studies addressed individual exposures to indoor pollutants rather than pollutant concentrations.

Regarding data collection, published studies used sensors and data loggers to measure air quality variables and interviews or questionnaires to collect information about physical dwelling characteristics and resident activities. Articles that sought to identify IAQ determinants utilized regression, statistical testing and correlations,

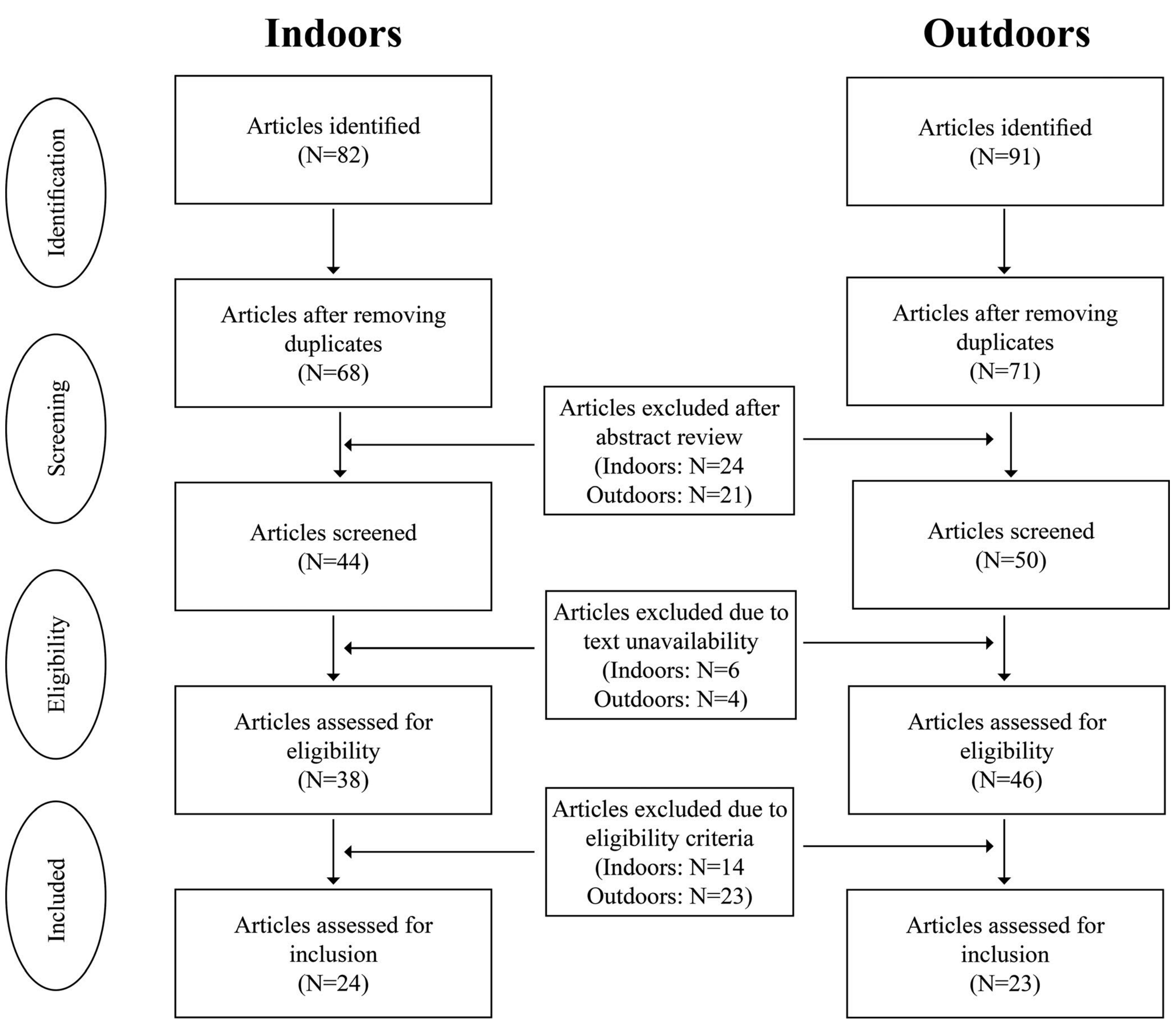

FIGURE 2 A PRISMA flow diagram for the review process[92]

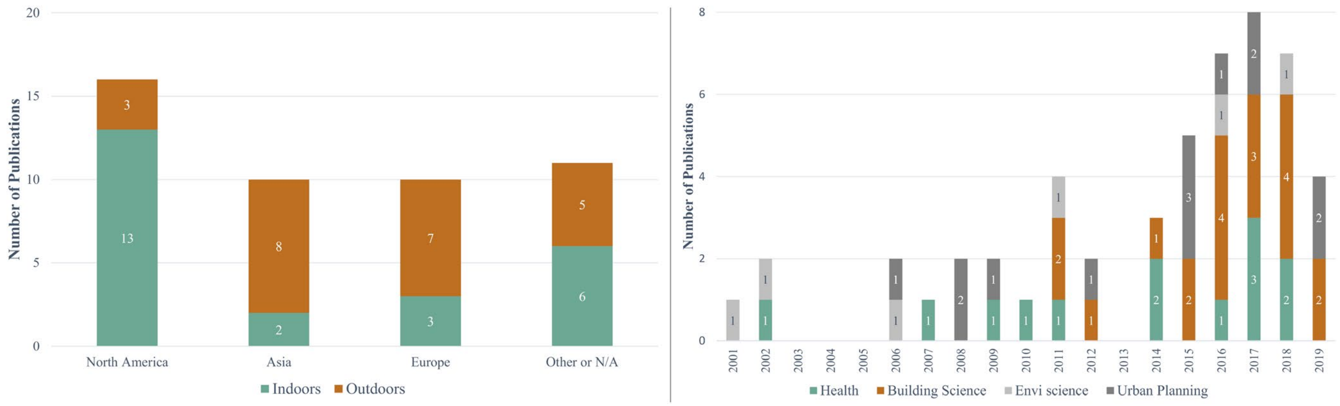

FIGURE 3 The number of reviewed articles by their geographical origin (left) and publication date and discipline (right)

indoor-outdoor ratios of pollutant concentrations, and IAQ simulations through computational fluid dynamics (CFD). Those directly addressing IAQ interventions utilized pre- and post-intervention statistical comparisons. In both cases, findings offer strategies to improve IAQ. However, none of the studies described in detail how these strategies could be implemented, such as by providing simple protocols with lists of actions that could be taken by involved stakeholders.

Regarding occupant behavior and its effect on IAQ, several factors that are associated with an increased presence of indoor pollutants were reported, including indoor smoking, reduced natural ventilation (closed windows), cooking with gas, frying food, burning candles or incense, using non-HEPA[1] vacuum cleaners, dusting or sweeping, and having pets and a large number of plants (See Tables 2 and 3).

Among the most prevalent strategies to improve IAQ was the avoidance of smoking indoors (13 articles), which, as suggested by Jacobs et al[31] has sufficient evidence for effectiveness in removing exposure to chemical agents and improving adverse health outcomes. Indeed, Lai et al[53] showed that the number of people smoking at home was a significant determinant for elevated indoor $PM_{2.5}$ levels within European households and Koistinen et al[22] found that mean indoor concentrations of $PM_{2.5}$ in Finish dwellings when a household member smoked indoors were approximately 2.5x higher compared to non-smoking households. The presence of $PM_{0.5}$ (particles smaller than 0.5 µm) was also increased because of environmental tobacco smoke in Italian living rooms.[54]

Studies of multi-family residences in the United States reported similar findings. High $PM_{2.5}$ concentration indoors were attributed to indoor smoking in Adamkiewicz et al[13] and Patton et al.[32] The nicotine concentration was significantly positively associated with the number of smokers in the household and the number of cigarettes smoked at home,nicotine levels were also high in non-smoking households, indicating infiltration through interior partitions from neighboring smoking apartments in Kraev et al.[55] Lastly, several studies found higher airborne particle levels,[16,20,36] as well as higher benzene, toluene, and m,p-xylene concentrations[56] in households where occupants smoke.

The next group of frequently reported strategies for improving IAQ in the reviewed literature increased natural ventilation through the window(s) or exterior door opening, as well as reduced cooking with gas (nine and seven articles, respectively). Clark et al[57] found that more than 50% of the variation in $PM_{2.5}$ and 85% of the variation in CO within Honduran households were explained by the state of the stove (4-level subjective scale ranging from poorly functioning traditional stoves to well-functioning improved stoves), the age of the stove, and ventilation factors. In multi-unit buildings of Boston, USA, cooking time and gas stove usage were further shown to contribute to higher indoor levels of NO_2 and $PM_{2.5}$ pollutants,[34] while reduced window opening resulted in an increase of formaldehyde potentially due to indoor sources in Cincinnati's houses.[58] The use of liquefied petroleum gas stove had a more significant negative impact on elevated indoor VOCs than the use of cooking stoves with natural gas as cooking fuel in Hong Kong's homes.[56] Overall, Barnes[30] recommend that interventions such as increased ventilation during cooking can reduce indoor air pollution by 20–98% in laboratory settings and 31%–94% in field settings, while Quansah et al[59] suggested that interventions to reduce air pollution in households (eg, changes in stove heating apparatus, changes in ventilation arrangements, and smoke control in cooking) that used solid fuel for cooking could substantially reduce indoor PM and CO.

In the reviewed studies, additional behavioral interventions to improve IAQ, such as changes in cleaning activities, decreased use of candles or incense, and increased ventilation if having pets, were less frequently identified. One study found that certain cleaning practices (vacuuming, dusting, or sweeping) resulted in higher indoor $PM_{2.5\text{–}10}$ levels,[54] and three studies [16,32,36] showed links of higher indoor particle counts and $PM_{2.5}$ and the use of candles/incense. Lastly, Doll et al[20] found correlations of pet presence with higher particle levels inside homes.

Effectiveness in reducing exposures to indoor pollutants via behavior also depends on whether these actions are employed singularly or in combination, consistently or inconsistently, and their interaction with ecological and built environment factors (see Figure 1). For example, the use of natural ventilation by opening windows could be detrimental to IAQ if outdoor pollution levels are high. This was the case

TABLE 2 Summary of indoor interventions to improve IAQ from evidence-based individual studies

Author	Year	Location	Sample	Pollutant	Recommended Intervention(s)
Koistinen et al	2001	Helsinki, Finland	201 adults	$PM_{2.5}$	No indoor smoking, better building envelope to counter proximity to high traffic density and infiltration from associated pollutants
Krieger et al	2002	Seattle, WA, USA	274 low-income children (4–12 y) with asthma-related health	Asbestos, lead, pesticides, toxic/hazardous chemicals, and combustion products (CO and NOx)	No indoor smoking, changes in cleaning practices (more frequent cleaning), increased/more frequent natural ventilation, removal of carpets
Lee et al	2002	Hong Kong, China	6 homes	CO_2, PM_{10}, HCHO, VOCs, airborne bacteria	No indoor smoking, use of natural gas stove instead of liquefied petroleum gas
Lai et al	2006	Europe: Athens, Basel, Helsinki, Milan, Oxford, Prague	N/A	$PM_{2.5}$, BS, NO_2	No indoor smoking/fewer cigarettes/day, reduced use of gas stove if practical, decreased heating from combustible fuels (eg, fuel switching)
Baxter et al	2007	Boston, MA, USA	43 low socioeconomic status households within multi-unit buildings	NO_2, $PM_{2.5}$	Reduced cooking time and reduced use of the gas stove
Kraev et al	2009	Boston, MA, USA	49 low-income multi-unit residences	Nicotine	No indoor smoking, fewer cigarettes/day
Clark et al	2010	Santa Lucia and Suyapa, Honduras	59 non-smoking houses	$PM_{2.5}$, CO	Improved cookstove quality and increased natural ventilation (open windows)
Adamkiewicz et al	2011	Boston, MA, USA	1 multi-family public housing building	NO_2, $PM_{2.5}$	No indoor smoking, reduced use of gas stove, reduced air leaks via weatherization (eg, sealing, replacing missing insulation) to reduce outdoor pollutant infiltration
Sharmin et al	2012	Fort McMurray, Alberta, Canada	12 apartments	CO_2	Use of energy recovery ventilation (ERV) (even though this is a proxy for better building envelope)
Urso et al	2015	Lodi, River Po Valley, Italy	60 living rooms	PM	Increased use of exhaust ventilation in kitchens, better-sealed windows and doors (ie, weatherization), change in cleaning practices (less frequent cleaning by vacuuming, dusting, or sweeping), no indoor smoking, no open fireplaces (or less use)
Coombs et al	2016	Cincinnati, Ohio, USA	42 low-income green and non-green multi-family houses	Formaldehyde, Black carbon	Increased natural ventilation (open windows)
Doll et al	2016	NC, USA	69 low-income single-family homes	CO, CO_2, NO_2, HCHO, Radon, $PM_{2.5}$, PM_{10}, Particle counts	Implementation of weatherization measures, increased ventilation, no indoor smoking, removal of pets if health affected

(Continues)

TABLE 2 (Continued)

Author	Year	Location	Sample	Pollutant	Recommended Intervention(s)
Patton et al	2016	Northeast, USA	16 low-income households in 2 multi-family green buildings	PM_1, $PM_{2.5}$, PM_4, PM_{10}, PMTotal	Reduced use of the gas stove and avoidance of cooking with oil, less use of candles/incense, no indoor smoking, increased natural ventilation (open windows)
Klepeis et al	2017	San Diego, CA, USA	262 low-income households with at least 1 child and 1 smoker	Fine particles (0.5 to 2.5 microns)	No indoor smoking, reduced frying of food, decreased use of candles/incense, change in cleaning practices (less frequent cleaning by vacuuming, dusting, or sweeping)
Ziemba et al	2017	Detroit, MI, USA	39 seniors in a low-income apartment building	$PM_{2.5}$	Use of indoor air filtration (either low or high efficiency)
Morishita et al	2018	Detroit, MI, USA	40 nonsmoking seniors in a low-income residential building	$PM_{2.5}$	Use of portable air filtration
Rice et al	2018	Baltimore, MD, USA	50 pregnant women or women with infants living with a smoker	$PM_{2.5}$, cotinine, nicotine	Use of air purifier, secondhand smoke education
Thomas et al	2019	Bronx, NY, USA	20 apartments in 2 high-rise affordable housing buildings	PM, ultrafine particle concentration	No indoor smoking, decreased use of candles/incense, improved insulation

in Patton et al,[32] who found that opening windows resulted in higher indoor PM concentrations in multi-family buildings in the Northeast USA, as well as in Urso et al,[54] who showed links of nearby road traffic to higher indoor PM in Italian living rooms. Reversely, Coombs et al[58] found that reduced window opening potentially reduced black carbon coming from outdoors to indoors.

In some instances, the existing physical infrastructure could limit behavioral actions that could be taken: For example, while cooking with gas elevates CO and PM,[13,56,57] it may be the only option available for daily meal preparation. In such cases, occupants could be conditioned to mitigate the harmful IAQ impacts of cooking by employing natural ventilation (eg, opening windows) in the absence of safety concerns[37] or utilizing local exhaust, if present.[30,54] Community-based organizations can further help enhance such practices through educational interventions for IAQ improvement, as illustrated in Krieger et al[37] and Rice et al.[33]

Regarding physical strategies, the reviewed articles suggest that poor building characteristics, such as insufficient ventilation and air filtration, limited insulation, and, thus, excessive building envelope infiltration when combined with poor outdoor air quality, contribute to deteriorated IAQ. In Thomas et al,[16] New York apartments that were missing more than 5% of insulation in their exterior wall had a significantly higher ultrafine particle concentration and their indoor/outdoor ratio. Adamkiewicz et al[13] found that at low $PM_{2.5}$ levels inside multi-family housing in Boston, outdoor sources contributed a higher fraction of indoor concentrations than indoor sources (63% versus 37%) due to house leakiness/infiltration. Reversely, Doll et al[20] and Urso et al[54] showed that reducing air leaks via weatherization can highly improve overall IAQ. Lastly, several studies illustrated that sufficient ventilation through ERV or DCV can lower indoor CO_2, VOCs, and radon,[60-62] and proper air filtration systems can significantly reduce indoor and personal exposures to $PM_{2.5}$.[63,64]

Additional built environment elements, such as gas stoves combined with the absence of (or insufficient) exhaust ventilation, heating with fossil fuels, open fireplaces, and carpeted floors, have all been shown to elevate the concentration of indoor pollutants, although they were less frequently reported in the reviewed literature (see Tables 2 and 3). For instance, Lai et al[53] showed a significant effect of fuel heating on elevated indoor NO_2. Urso et al[54] found links between open fireplaces and increased presence of $PM_{0.5\text{-}1}$ and identified protective factors to reduce this presence, such as the use of exhaust ventilation in kitchens. Lastly, Becher et al[65] suggested that carpets may act as a repository sink for indoor air pollutants, including particles, allergens, and other biological contamination, which in turn lead to adverse health effects, such as increased respiratory infections that can worsen asthma symptoms and earlier age of asthma onset. Therefore, more attention should be paid to carpeted floors, especially the rug design/construction, cleaning procedures, type of maintenance, and carpet age, while taking ventilation systems and rates into account.

Evident in most of the reviewed articles is that IAQ has both behavioral and physical determinants that often interact (see Figure 4).

TABLE 3 Summary of indoor interventions to improve IAQ based on literature reviews

Author	Year	Location	Sample	Pollutant	Recommended Intervention(s)
Barnes	2014	Developing Countries	N/A	PM, TSP, CO, SO_2	Increased natural ventilation (open windows or doors) during cooking
Jacobs et al	2014	N/A	N/A	N/A	Increased active ventilation, no indoor smoking
Quansah et al	2017	N/A	N/A	PM, CO	Improved cookstove quality through stove ventilation (eg, having a chimney and cleaner burning)
Ye et al	2017	China	7,000 dwellings	VOCs, Radon, CO_2	Increased natural ventilation (windows) combined with an air cleaner or increased mechanical ventilation combined with an air filtration unit
Becher et al	2018	N/A	N/A	Dust, Allergens, VOCs	No (or remove) carpeted floors
Guyot et al	2018	N/A	N/A	CO_2, TVOCs	Ventilation through demand control (DCV)

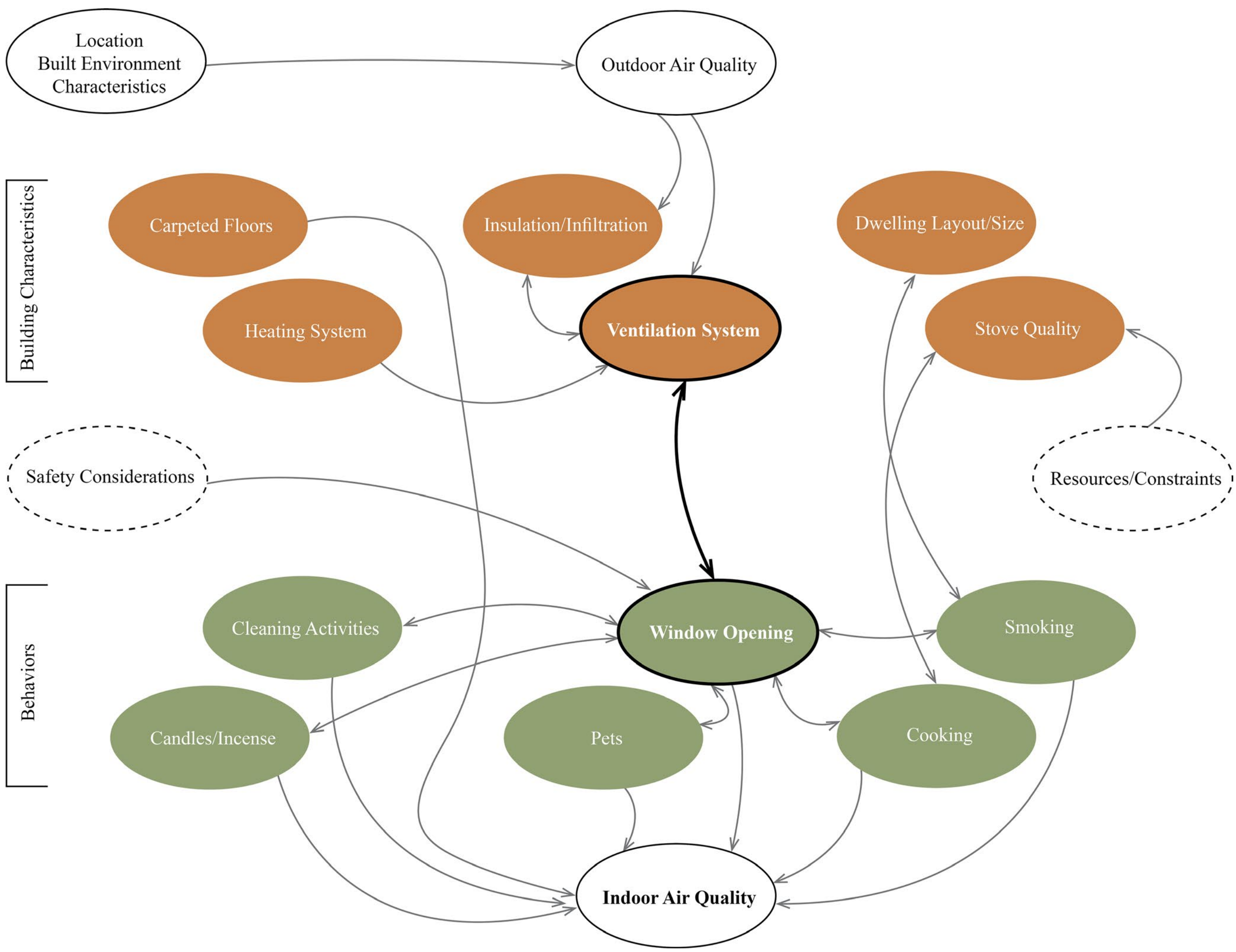

FIGURE 4 A diagram based on SES and Figure 1 representing the review findings regarding the indoor behavioral and physical (building characteristics) determinants of IAQ in dwellings and their interactions

For instance, indoor smoking was found to be consistently linked to elevated PM concentrations, but the increase is inversely proportional to the size of the space due to the amount of air volume.[36] Also, the effect of residential activities on indoor PM has been found to depend on dwelling layout, ventilation rates, and the availability of kitchen exhaust systems.[54] Koistinen et al[22] and Lai

TABLE 4 Summary of outdoor interventions to improve IAQ from evidence-based studies

Author	Year	Location	Sample	Pollutant	Recommended Intervention(s)
Nowak, Crane, and Stevens	2006	USA	55 cities across 48 states	CO, NO_2, O_3, PM_{10}, SO_2	Increased/retained/maintained trees (urban areas)
Currie and Bass	2008	Toronto, Canada	1 midtown urban neighborhood	NO_2, SO_2, CO, PM_{10}, O_3	Use of green walls and green roofs to achieve partial benefits of trees (urban)
Escobedo et al	2008	Santiago, Chile	36 municipalities	PM_{10}	Retained/managed urban forests
Jim and Chen	2008	Guangzhou, China	7 central city districts	SO_2, NO_2	Increased/retained/maintained trees (urban areas)
Yang, Yu, and Gong	2008	Chicago, Illinois, USA	170 green roofs	O_3, NO_2, PM_{10}, SO_2	Construction of green roofs (urban)
Dzierżanowski and Gawroński	2011	Warsaw, Poland	1 central district	PM	Increased/retained/maintained trees (urban areas, with specific species recommended for regional application)
Yin et al	2011	Shanghai, China	Pudong district	TSP, SO_2, NO_2	Increased/retained/maintained vegetation (trees and shrubs) in parks (urban)
Islam et al	2012	Khulna, Bangladesh	2 streets (one central/ one on the periphery)	TSP	Increased/retained/ maintained greenbelts, especially trees
Fantozzi et al	2015	Siena, Italy	1 urban area	O_3, NO_2	Increased/retained/maintained trees (specific species recommended for regional/urban application)
Kiss et al	2015	Szeged, Hungary	4 downtown street areas	CO, NO_2, PM_{10}, SO_2, O_3	Increased/retained trees, especially species with large leaf area
Pandey et al	2015	Varanasi, India	29 plant species	NO_2, SO_2, PM_{10}	Increased tree plantings for urban forest (specific species
Chen et al	2016	Beijing, China	21 urban blocks	$PM_{2.5}$	Increased planting of trees and shrubs (urban)
Liang et al	2016	Beijing and Chongqing, China	25 tree species along main urban roads with traffic pollution	$PM_{2.5}$	Increased/retained/maintained trees (urban areas, with specific species recommended for regional application)
Selmi et al	2016	Strasbourg, France	All public green spaces	CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, SO_2	Increased/retained/maintained trees
Jayasooriya et al	2017	Victoria, Australia	1 industrial area	O_3, SO_2, NO_2, CO, PM_{10}, $PM_{2.5}$	Increased/retained/maintained trees (industrial area)
Jeanjean et al	2017	London, UK	1 central neighborhood	NOx, $PM_{2.5}$	Increased/retained/maintained trees (urban)
Weerakkody et al	2017	Birmingham, UK	1 living wall in New Street Railway Station	PM_1, $PM_{2.5}$, PM_{10}	Construction of living walls (specific species recommended)
Viippola et al	2018	Lahti, Finland	8 sites	NO_2, $PM_{2.5}$	Increased roadside vegetation
Chen et al	2019	China: megacities	37 neighborhoods	$PM_{2.5}$	Increased/maintained neighborhood green space, especially trees (urban)
Qin et al	2019	Xi'an, China	1 urban park	PM	Increased/retained/maintained specifically located tree cover (urban)

et al[53] associated the increased levels of indoor PM and BS with a building's proximity to traffic, in addition to occupant behaviors and physical dwelling characteristics. It is also apparent that physical characteristics of indoor space (eg, apartment size), outdoor attributes (eg, location), and occupant behaviors (eg, indoor smoking and use(s) of the gas stove) depend on socioeconomic and institutional

TABLE 5 Summary of outdoor interventions to improve IAQ from literature reviews

Author	Year	Location	Sample	Pollutant	Recommended Intervention(s)
Rowe	2011	N/A	N/A	CO_2	Construction of green roofs with specific species and substrate/technology recommendations
Janhäll	2015	N/A	N/A	N/A	Construction of urban vegetation with specific species and design recommendations
Abhijith et al	2017	N/A	N/A	N/A	Green infrastructure for street canyon environments (specific height and porosity recommendations by location); construction of green walls and roofs on buildings

factors.[13,34] Collectively, these studies suggest that stand-alone actions may not be sufficient to improve IAQ and that future research and intervention plans would benefit from an integrated view of IAQ linking human activities and the built environment along an indoor-outdoor continuum.

4.2 | Outdoor environments: green infrastructure and landscape design

Of the reviewed articles, 20 evidence-based studies and three literature reviews focused on outdoor environments, as outlined in Tables 4 and 5. Most evidence-based papers focused on outdoor strategies related to green infrastructure elements and linkages to ambient air quality, while literature reviews collected evidence on the same relationship. While all articles targeted multiple pollutants such as NO_2, SO_2, CO, PM, and O_3, PM was of greatest interest.

Compared to the articles that focus on indoor spaces in individual housing units (eg, in buildings or apartments), articles that investigated outdoor factors reported significant variation in the spatial unit of analysis, spanning building sites, blocks, neighborhoods, and city infrastructure (eg, green roofs/walls, parks, urban forests, greenbelts, and highway bioswales/corridors). Six large-scale studies provided comparisons between neighborhoods or cities across different states or countries, while the remaining articles focused on a small number of units (eg, one neighborhood) within the same location. The former group provides an overview of greening benefits at the macroscale, while the latter provides information on the types and characteristics of trees, vegetation, and plant species that are tied to the local ecology and IAQ. Seven studies utilized sensors and passive samplers to collect data on ambient air pollutants, while the rest relied on national air monitoring networks. Studies employed dry deposition models, urban forest effects models, statistical correlations, CFD simulations, and various forms of regression and GIS analysis to identify associations between outdoor pollutant reduction and type and percent of green infrastructure/space coverage.

Most articles concerning urban environments recommended investing in the urban tree canopy (17 articles). Large-scale studies provided evidence of the benefits of high green space coverage in lowering ambient pollutant concentrations. Jim and Chen[66] found that all urban trees from seven districts in downtown Guangzhou, China, removed in total more than 300 mg of SO_2, NO_2, and TSP within a year and that the majority of removal happened during winter. Nowak, Crane, and Stevens[67] found that the magnitude of pollutant (CO, NO_2, O_3, PM_{10}, SO_2) removal by urban trees, although different among 55 US cities, was significant and estimated to be 711,000 metric tons annually. Likewise, Selmi et al[68] found that within a year (with seasonal variations), trees in public spaces in Strasbourg, France, removed about 88 tons of pollutants: 1 ton of CO, 14 tons of NO_2, 56 tons of O_3, 12 tons for PM_{10}, 5 tons of $PM_{2.5}$, and 1 ton of SO_2.

These studies suggest that outdoor air quality can be improved by increasing urban tree canopy cover, but the type of coverage plays an important role. Several additional works have investigated this further. Chen et al[26] identified lower $PM_{2.5}$ concentrations with higher green space coverage in Chinese megacities, specifically with higher tree coverage (height > 1 m) compared to ground cover, such as grass; a similar idea was also suggested by Jeanjean et al[69] in a study in downtown London, UK, for trees over 3 m tall. Similarly, Jim and Chen[66] concluded that ecosystem services can be improved by planting more trees beyond shrubs and grass. Lastly, Chen et al[70] provided further evidence of different vegetation types and their ability to reduce $PM_{2.5}$ concentrations, suggesting that, overall, trees (height = 11 m, length = 53 m, width = 1 m) had the highest $PM_{2.5}$ deposition and therefore the most benefits for reducing $PM_{2.5}$ exposures, followed by shrubs (height = 0.3 m, length = 52 m, width = 1 m), which had a moderate performance in $PM_{2.5}$ removal. In a more detailed investigation of urban tree coverage, several works have further stressed the importance of examining particular species, concluding that characteristics such as groove proportion, stomata size, and leaf surface area can highly affect air pollution removal (see Ref. [71-75

Despite the many benefits of tall trees, lower vegetation with grass and shrubs can still improve ambient air quality. For instance, Yin et al[76] showed that a combination of urban vegetation (trees of approx. 4 m height and diameter and shrubs of approx. 0.3 m_3 volume) contributed to removing 9.1% of TSP, 5.3% of SO_2, and 2.6% of NO_2 in downtown Shanghai, China. Islam et al[77] found that greenbelts near streets contribute to TSP pollution reduction up to 65%, especially during the summer, and Viippola et al[78] found that peri-urban forests may have a smaller effect on reducing fine PM near roads compared to lower roadside vegetation. Therefore, low vegetation close to pollution sources, such as open roads, can be more effective in reducing air pollution compared to high vegetation,[79] but, as suggested by Janhäll,[27] vegetation barriers need to be dense and porous to improve air penetration and substantial particle deposition.

The last group of outdoor strategies to improve air quality identified in this review concerns investing in green roofs and green/living walls. In a large study of 170 green roofs in Chicago, USA, Yang, Yu, and Gong[80] found that 1675 kg of air pollutants were removed by 19.8 ha of green roofs within a year. By mass, O_3 accounted for 52% of the total removal, NO_2 for 27%, PM_{10} for 14%, and SO_2 for 7%. In midtown Toronto, Canada, Currie and Bass[81] further found that green roofs, particularly intensive roof-shrubs-based roofs, had a more significant pollutant reduction effect, especially for PM_{10}. Results showed that green walls had a higher benefit than the 20% coverage of extensive green roofs, concluding that combining 20% coverage of extensive green roofs with some coverage of green walls can have an impact of approximately equal to 20% coverage by trees. A combination of urban green coverage was also recommended by Jayasooriya et al,[28] who suggested that while trees can provide the highest pollutant removal capability, combining scenarios (eg, trees with green walls or trees with green roofs) can present additional benefits for building energy savings. Nevertheless, besides air pollution abatement benefits, investing in green roofs and green/living walls should consider long-term analysis to justify initial costs,[80] as well as careful plant selection, rooftop and wall agriculture, the development of improved growing substrates, and related complementary technologies.[29,82]

4.3 | Residents and organizations

Guided by the SES framework and its attention to human agency, we combined the findings in Sections 4.1 and 4.2 into practical strategies to improve IAQ by both individuals and supportive organizations/communities, shown in Figure 5. Three groups of potential interventions are presented, prioritized based on their prevalence in literature, and demonstrated effectiveness and cost-effectiveness levels. A further description of each group is provided in Tables 6–8. The first group is indoor interventions related to resident activities and behaviors, which may be enhanced via educational inputs delivered by community-based organizations; the second group is building alterations, which requires organizational intervention; the third is physical site modifications where both organizations and residents can take action based on dwelling ownership and maintenance roles.

Most articles (see Table 6) suggested avoiding indoor smoking, reduced use of the gas stove, or a combination of these behaviors with increased natural ventilation (eg, window opening), examples of IAQ strategies that are cost-effective and often can be implemented by individual residents even if some behavior change may be difficult (eg, smoking cessation). Other articles emphasize avoidance or reduction in candle and incense use and alternative cleaning methods as behavior (modifications) that are protective of IAQ.

The next group of interventions (see Table 7) is related to building retrofits and aims to protect indoor environments from ambient air pollution or improve IAQ via greater indoor-outdoor air exchange. Examples include reducing air leaks and infiltration via sealing windows and doors, improving cookstove quality along with installing local exhaust ventilation in kitchens, and employing natural (eg, opening windows and doors) and/or mechanical (eg, ERV, DCV strategies as per Tables 2–3) ventilation to increase fresh air intake and air filtration/purification practices. Some of these strategies have reasonable costs, while others could be prohibitively expensive, especially for low-income residents and/or affordable housing operators.

The last and more speculative group of interventions (see Table 8), due to the lack of concrete measurement data across the outdoor-indoor continuum and in relation to personal exposures, is focused on the addition of protective buffers to indoor environments through the use of appropriate site landscaping features that can reduce outdoor pollutant concentrations. Most urban-level studies indicate that greening strategies, such as increasing tree canopy, shrubs, and other vegetation, and building roof and wall greening, can be effective in ambient PM, SO_2, and NO_2 reduction. Such strategies are especially important in highly urbanized sites in close proximity to pollution sources. While the cost may be high in a large-scale implementation, greening the immediate building surroundings with smaller shrubs and trees can be cost-effective and still lower the level of outdoor air pollution.[70,76]

Consistent with an integrated SES approach to IAQ research and practice, the majority of interventions shown in Figure 5 and Tables 6–8 either require or benefit from collaboration among local organizations and residents.

5 | LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

In our attempt to collect evidence from diverse literature on indoor air quality, we recognize that our search strategy (and keywords) was not exhaustive and therefore limited in its ability to locate all relevant papers. Although Google Scholar's advanced search enables one to identify keywords throughout a publication's title, abstract, and main text, the use of additional search engines could have resulted in a wider collection of studies for our review. Nevertheless, we attempted to overcome this issue by presenting a wide range of key intervention strategies indoors and outdoors based on the works included. Therefore, we do not expect a significant change in our conclusions, even if additional search engines were used. Lastly, we recognize that we presented only summaries of the papers we reviewed, which inevitably resulted in a loss of details.

Despite these drawbacks, our work suggests several areas that will benefit future research and assist community-based

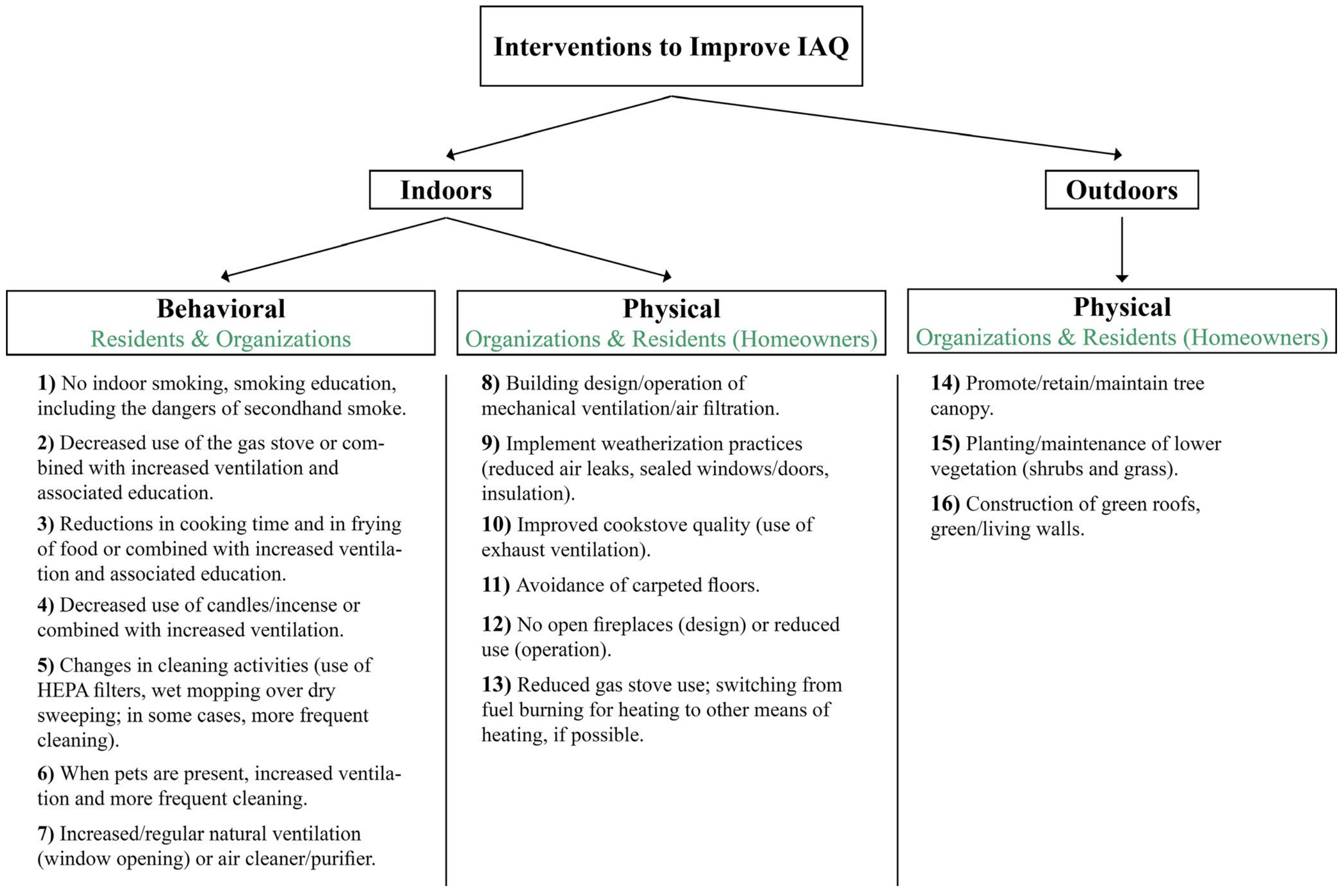

FIGURE 5 Suggested strategies and actionable interventions to improve IAQ. They are organized according to the SES framework and highlight the environment of action (eg, indoors and outdoors), the type (eg, behavioral and physical), and the role of actors involved

practitioners. First, it is a limitation of the existing literature that studies on air quality tend to focus either on the indoor or outdoor environment and pay little attention to the continuous nature of personal exposures across these scales. Correspondingly, while some of the literature pertaining to IAQ is intervention-based and includes a discussion of occupant behaviors in a passive sense, generally it does not emphasize the role of human agency in affecting and even controlling IAQ and the resulting personal exposures. Nor does this literature parse the roles of varying human agents (eg, individuals, organizations) to produce a roadmap of collaborative IAQ actions.

Among the benefits of applying the SES framework to the IAQ literature review is a shift in unit of analysis from places to people, or rather to people living in and moving from place to place. However, this approach requires attendant knowledge of how environmental-physical, socioeconomic, and demographic variables mediate outcomes,[51,83] making it difficult to generalize findings for which this information is limited or not available. The SES framework is inherently action-oriented; however, it is not a foregone conclusion that IAQ interventions are transformed into action, especially at an infrastructural scale (eg, building, site) requiring organizational and/or community participation.[35,37,38] This is especially the case in communities where resources are limited and poorer residents suffer lower-quality built environments and elevated ambient pollutant concentrations.[13,23,34,84]

A noteworthy intervention that has been deployed in some low-income communities and fits well with the SES framework is the US EPA's AirNow Flag Program.[85] This program was developed to engage school-aged children to hoist flags which are color-coded according to the EPA air quality index (AQI) scale in schools in environmental justice communities to promote the awareness of regional air quality.[86-88] Future research should emphasize not only the indoor-outdoor continuum of air pollution exposures but also the very real mediating impact of organizational-based actions in low resource communities, whatever their nature. The US EPA AirNow program was not located through our literature review, most likely due to its prevalence in school-based settings wherein the facilitating organization of note is a school.

A second example wherein educational institutions play a propitiating role in helping to overcome limitations concerns the continuous measurement of personal exposures. The smart cities ubiquitous mobile computing research movement is supported by teams of computer, environmental, and behavioral scientists. Within this paradigm, research subjects (aka, citizen scientists) carry wearable air quality sensors while going about both their daily indoor and outdoor routines to monitor and report air quality

TABLE 6 Description of suggested indoor behavioral strategies and actionable interventions to improve IAQ

	Intervention	Pollutant	Level of Effectiveness	Source(s)
1	No indoor smoking, smoking education, including on the dangers of secondhand smoke	$PM_{2.5}$, fine particles (0.5 to 2.5 microns), BS, NO_2, nicotine, cotinine	Smoking, the number of occupants smoking, and the number of cigarettes smoked indoors have all been connected to significant indoor PM, BS, and NO_2 pollution. In smoking households, smoking dominates the contribution to indoor PM compared to other activities. Educating residents about the consequences of indoor smoking and secondhand/passive smoke is important in reducing indoor PM levels	Adamkiewicz et al (2011)[13], Doll et al (2016)[20], Jacobs et al (2010)[31], Klepeis et al (2017)[36], Koistinen et al (2001)[22], Kraev et al (2009)[55], Krieger et al (2002)[37], Lai et al (2006)[53], Lee et al (2002)[56], Patton et al (2016)[32], Rice et al (2018)[33], Thomas et al (2019)[16], Urso et al (2015)[54]
2	Decreased use of the gas stove or combined with increased ventilation and associated education	NO_2, VOCs, $PM_{2.5}$, BS	Many studies have shown a strong connection between cooking with gas and BS, NO_2, $PM_{2.5,}$ and VOCs. In addition, the duration of using the gas stove may explain approximately 1.5% of indoor PM. Educating residents to open windows when cooking is a low cost yet effective strategy. This may be accomplished via traditional educational inputs and/or with the aid of installed IAQ sensor(s). While sometimes there are barriers to window opening (eg, outdoor pollution, safety perceptions, privacy), these too may be addressable via organizational involvement	Adamkiewicz et al (2011)[13], Baxter et al (2007)[34], Lai et al (2006)[53], Lee et al (2002)[56], Patton et al (2016)[32]
3	Reductions in cooking time and in frying of food or combined with increased ventilation and associated education	Fine particles (0.5 to 2.5 microns), $PM_{2.5}$, NO_2	Cooking time and frying food have been shown to increase indoor PM and NO_2 levels, especially when combined with poor ventilation, cooking with gas, and smoking. Educating the residents on being more cognizant of cooking time and frying food while increasing ventilation of their homes can be beneficial to IAQ	Baxter et al (2007)[34], Klepeis et al (2017)[36]
4	Decreased use of candles/incense or combined with increased ventilation	(0.5 to 2.5 microns), PM	Lighting candles/incense indoors can have a small but significant negative impact on indoor PM. Educating the residents about reducing the use of such products can be beneficial	Klepeis et al (2017)[36], Patton et al (2016)[32], Thomas et al (2019)[16]
5	Changes in cleaning activities (use of HEPA filters, wet mopping over dry sweeping; in some cases, more frequent cleaning)	Fine particles (0.5 to 2.5 microns), PM	House cleaning practices can affect indoor PM levels; alternative ways of cleaning the house can be beneficial in the long term, and resident education can help towards that goal	Klepeis et al (2017)[36], Krieger et al (2002)[37]; Urso et al (2015)[54]
6	When pets are present, increased ventilation and more frequent cleaning	PM	Having pets indoors can increase CO2 and PM levels, but this also depends on the frequency of cleaning and ventilation. Educating the residents about improving ventilation and increasing cleaning when having pets can be beneficial	Doll et al (2016)[20], Krieger et al (2002)[37]
7	Increased/regular natural ventilation (window opening) or air cleaner/purifier	$PM_{2.5}$, VOCs, Radon, CO, CO_2, Formaldehyde, Black carbon, TSP, SO_2	Assuming good outdoor air quality, it has been shown that ventilation at certain times of day can improve indoor air quality, even in households with smokers. Several studies have used the apartment volume (products of area and height) and the number of occupants as primary determinants of ventilation rates. An alternative is air purification, which can be particularly effective in reducing $PM_{2.5}$ levels in non-smoking households	Barnes (2014)[30], Clark et al (2010)[57], Coombs et al (2016)[58], Doll et al (2016)[20], Jacobs et al (2010)[31], Krieger et al (2002)[37], Patton et al (2016)[32], Rice et al (2018)[33], Ye et al (2017)[62]

TABLE 7 Description of suggested indoor physical strategies and actionable interventions to improve IAQ

	Intervention	Pollutant	Level of Effectiveness	Source(s)
8	Building design/ operation of mechanical ventilation/air filtration	$PM_{2.5}$, VOCs, Radon, CO_2, TVOCs	Both low- and high-efficiency indoor filtration has been shown to reduce indoor $PM_{2.5}$ concentrations and personal exposures by 35–51% in non-smoking households. It can also have significant health benefits for those suffering from cardiovascular disease. Apartments with higher energy recovery ventilation (ERV) usage can achieve lower CO_2 levels, while apartments with demand control ventilation (DCV) can achieve up to 60% energy savings without compromising IAQ	Doll et al (2016)[20], Guyot et al (2018)[60]; Morishita et al (2018)[63], Sharmin et al (2014)[61], Ye et al (2017)[62], Ziemba et al (2017)[64]
9	Implement weatherization practices (reduced air leaks, sealed windows/doors, insulation)	CO, CO_2, NO_2, HCHO, radon, $PM_{2.5}$, PM_{10}, particle counts	Overall, it has been shown that weatherization practices can significantly decrease CO, CO_2, radon, NO_2 levels, and PM in nonsmoking houses. In naturally ventilated non-smoking households, the outdoor air can explain about 65–70% of the indoor air. Therefore, reducing air leaks (infiltration) can be effective so that windows and doors can be closed/properly sealed to protect against PM during times of poor outdoor air	Adamkiewicz et al (2011)[13], Doll et al (2016)[20], Jacobs et al (2010)[31], Krieger et al (2002)[37], Thomas et al (2019)[16], Urso et al (2015)[54]
10	Improved cookstove quality (use of exhaust ventilation)	PM, CO	Exhaust ventilation/fan in kitchens can be a significant protective factor against PM, especially 0.5–1 µm particles	Clark et al (2010)[57], Quansah et al (2017)[59], Urso et al (2015)
11	Avoidance of carpeted floors	Dust, allergens, VOCs	Several studies have shown that although rug-design/construction, cleaning procedures, type of maintenance, age of carpet as well as ventilation rates tend to be important, overall, carpeted floors may absorb indoor air pollutants such as particles, allergens, and other biological contaminants, which may have adverse health outcomes related to the respiratory tract. Replacement methods should consider possible effects on IAQ and health	Becher et al (2018)[65], Krieger et al (2002)[37]
12	No open fireplaces (design) or reduced use (operation)	PM	The existence of open fireplaces has been shown to increase indoor $PM_{0.5\text{-}1}$	Urso et al (2015)[54]
13	Reduced gas stove use; switching from fuel burning for heating to other means of heating, if possible	NO_2	The usage of gas stove and fuel heating explained 10.7% and 6.5% of NO_2 concentrations in the investigated four cities	Lai et al (2006)[53]

in their surroundings. Corresponding human-computer intervention (HCI) approaches utilize these data, often via interactive devices,[89-91] as individualized behavioral inputs that can result in decreased pollution exposures.[91]

6 | CONCLUSION

While the importance of IAQ for human health is well recognized, there are no minimal standards and regulations for air quality in residential indoor spaces due, at least in part, to the difficulty of measuring and enforcing it.[9] Growing multi-disciplinary interest in reducing harmful exposures to air pollutants has led to an increasing number of IAQ studies, which nevertheless lack a coherent framework posing a barrier to the rapid translation of research findings into action. We employed the SES framework to organize identified IAQ variables and intervention strategies according to spatial scale (indoors/ building characteristics, and outdoors/ green infrastructure and landscape design) and by the individual and organizational agency. The final list of IAQ intervention strategies and actions in Figure 5 and Tables 6–8 features cost-effective strategies proven to reduce exposure to indoor air pollutants and improve IAQ. However, it is worth noting that, even with these interventions, stand-alone actions may not sufficiently improve air quality in residential environments. Future research should consider an integrated view of IAQ that links human activities with their environments across an indoor-outdoor continuum.

TABLE 8 Description of suggested outdoor physical strategies and actionable interventions to improve IAQ.

	Intervention	Pollutant	Level of Effectiveness	Source(s)
14	Promote/retain/maintain tree canopy	$PM_{2.5}$, PM_{10}, O_3, NO_2, CO, SO_2, NO_2, VOCs, TSP	Large healthy trees (with large leaf areas) can remove about 60 times more $PM_{2.5}$ pollutants on an annual basis than healthy but smaller trees. This is especially true if they function as protective belts against pollution sources (eg, streets). They can also decrease NO_2 levels in all seasons; O_3 is most successfully mitigated during the Fall. Certain tree species may yield higher benefits in the long term, but this is subject to the local context of an area and may vary highly between cities	Abhijith et al (2017)[79], Chen et al (2019)[26], Chen et al (2016)[70], Dzierżanowski and Gawroński (2011)[71], Fantozzi et al (2015)[72], Kiss et al (2015)[73], Jayasooriya et al (2017)[28], Islam et al (2012)[77], Jeanjean et al (2017)[69], Jim and Chen (2008)[66], Nowak, Crane and Stevens (2006)[67], Pandey et al (2015)[75], Qin et al (2019)[93], Liang et al (2016)[74], Selmi et al (2016)[68], Setälä et al (2013)[94], Viippola et al (2018)[78]
15	Planting/maintenance of lower vegetation (shrubs and grass)	$PM_{2.5}$, PM_{10}, TSP, SO_2, NO_2	Vegetation, particularly shrubs followed by grass, can reduce $PM_{2.5}$ and PM_1 levels. Design of planting configuration (a combination of trees, shrubs, and grass) is practically more effective than tree species selection in reducing the ambient PM concentrations in urban settings. Likewise, vegetation in urban parks and urban forests can remove large amounts of airborne pollutants, especially during summer, and be a cost-effective local pollution mitigation policy. Ground vegetation with dense and porous plants can be further valuable close to pollution sources	Abhijith et al (2017)[79], Chen et al (2016)[70], Escobedo et al (2008)[95], Janhäll (2015)[27], Yin et al (2011)[76]
16	Construction of green roofs, green/living walls	PM_1, $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3	Intensive green roofs have a more significant effect, but extensive green roofs are cheaper. A 20% coverage of extensive green roofs combined with some coverage of green walls can equal approximately to 20% of trees. Roof greening on leeward buildings has been shown to produce greater PM removal effects compared with windward buildings. Green roofs have further been shown to remove large amounts of O_3 followed by NO_2, PM_{10} and SO_2. While their installation can be initially costly, a long-term analysis of benefits can justify the cost. Likewise, living walls (esp. smaller-leaved plants with hairy/waxy leaf surfaces) can remove particulates	Abhijith et al (2017)[79], Currie and Bass (2008)[81], Jayasooriya et al (2017)[28], Qin et al (2019)[93], Rowe (2011)[29], Weerakkody et al (2017)[82], Yang et al (2008)[80]

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Ioanna Tsoulou contributed to conceptualization, methodology, data curation, formal analysis, original draft, review and editing. **Jennifer Senick** involved in methodology, original draft, review and editing. **Gediminas Mainelis** contributed to methodology, formal analysis, validation, original draft, review and editing. **Sunyoung Kim** involved in conceptualization, methodology, resources, supervision, project administration, review and editing.

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ENDNOTE

[1] HEPA stands for high efficiency particulate air filter.

REFERENCES

1. US Environmental Protection Agency (EPA). Green Infrastructure and Air Quality Impacts; 2019. https://www.epa.gov/green-infrastructure/green-infrastructure-and-air-quality-impacts. Accessed 1/16/2020.
2. Ashrae S. *Standard 62.1-2016. Ventilation for acceptable indoor air quality*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc; 2016.
3. Spalt EW, Curl CL, Allen RW, et al. Time–location patterns of a diverse population of older adults: the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). *J Eposure Sci Environ Epidemiol*. 2016;26(4):349.
4. Abdul-Wahab SA, En SCF, Elkamel A, Ahmadi L, Yetilmezsoy K. A review of standards and guidelines set by international bodies for the parameters of indoor air quality. *Atmos Pollut Res*. 2015;6(5):751-767.
5. Spengler JD, Chen Q. Indoor air quality factors in designing a healthy building. *Annu Rev Energy Env*. 2000;25(1):567-600.
6. Sundell J. Reflections on the history of indoor air science, focusing on the last 50 years. *Indoor Air*. 2017;27(4):708-724.
7. Sundell J. On the history of indoor air quality and health. *Indoor Air*. 2004;14(s 7):51-58.
8. Ramaswami A, Weible C, Main D, et al. A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems. *J Ind Ecol*. 2012;16(6):801-813.
9. Steinemann A, Wargocki P, Rismanchi B. Ten questions concerning green buildings and indoor air quality. *Build Environ*. 2017;112:351-358.
10. Straus DC. Molds, mycotoxins, and sick building syndrome. *Toxicol Ind Health*. 2009;25(9–10):617-635.
11. Terr AI. Sick Building Syndrome: is mould the cause? *Med Mycol*. 2009;47(Supplement_1):S217-S222.
12. US Environmental Protection Agency (EPA). Indoor Air Facts No. 4 Sick Building Syndrome. *EPA-Air Radiat (6609J), Res Dev*. 1991;1-4. https://www.epa.gov/sites/production/files/2014-08/documents/sick_building_factsheet.pdf
13. Adamkiewicz G, Zota AR, Fabian MP, et al. Moving environmental justice indoors: understanding structural influences on residential exposure patterns in low-income communities. *Am J Public Health*. 2011;101(S1):S238-S245.
14. Institute of Medicine (États-Unis). Committee on the Effect of Climate Change on Indoor Air Quality and Public Health. *Climate Change, the Indoor Environment, and Health*. Washington, DC: National Academies Press; 2011.
15. Luo N, Weng W, Xu X, Hong T, Fu M, Sun K. Assessment of occupant-behavior-based indoor air quality and its impacts on human exposure risk: A case study based on the wildfires in Northern California. *Sci Total Environ*. 2019;686:1251-1261.
16. Thomas NM, Calderón L, Senick J, et al. Investigation of indoor air quality determinants in a field study using three different data streams. *Build Environ*. 2019;154:281-295.
17. Challoner A, Gill L. Indoor/outdoor air pollution relationships in ten commercial buildings: PM2. 5 and NO2. *Build Environ*. 2014;80:159-173.
18. Myers NT, Calderón L, Pavilonis B, Wang Z, Xiong Y. Presence and variability of culturable bioaerosols in three multi-family apartment buildings with different ventilation systems in the Northeastern US. *Indoor Air*. 2021;31(2):502-523.
19. Mohammadyan M, Ashmore M, Shabankhani B. Indoor PM2. 5 concentrations in the office, café, and home. *Int J Occup Hyg*. 2010;2:57-62.
20. Doll SC, Davison EL, Painting BR. Weatherization impacts and baseline indoor environmental quality in low income single-family homes. *Build Environ*. 2016;107:181-190.
21. Kearney J, Wallace L, MacNeill M, Héroux ME, Kindzierski W, Wheeler A. Residential infiltration of fine and ultrafine particles in Edmonton. *Atmos Environ*. 2014;94:793-805.
22. Koistinen KJ, Hänninen O, Rotko T, Edwards RD, Moschandreas D, Jantunen MJ. Behavioral and environmental determinants of personal exposures to PM2. 5 in EXPOLIS–Helsinki, Finland. *Atmos Environ*. 2001;35(14):2473-2481.
23. Tessum CW, Apte JS, Goodkind AL, et al. Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proc Natl Acad Sci*. 2019;116(13):6001-6006.
24. Ibald-Mulli A, Wichmann HE, Kreyling W, Peters A. Epidemiological evidence on health effects of ultrafine particles. *J Aerosol Med*. 2002;15(2):189-201.
25. Karottki DG, Bekö G, Clausen G, et al. Cardiovascular and lung function in relation to outdoor and indoor exposure to fine and ultrafine particulate matter in middle-aged subjects. *Environ Int*. 2014;73:372-381.
26. Chen M, Dai F, Yang B, Zhu S. Effects of neighborhood green space on PM2. 5 mitigation: Evidence from five megacities in China. *Build Environ*. 2019;156:33-45.
27. Janhäll S. Review on urban vegetation and particle air pollution–Deposition and dispersion. *Atmos Environ*. 2015;105:130-137.
28. Jayasooriya VM, Ng AWM, Muthukumaran S, Perera BJC. Green infrastructure practices for improvement of urban air quality. *Urban Forest Urban Green*. 2017;21:34-47.
29. Rowe DB. Green roofs as a means of pollution abatement. *Environ Pollut*. 2011;159(8–9):2100-2110.
30. Barnes BR. Behavioural change, indoor air pollution and child respiratory health in developing countries: A review. *Int J Environ Res Public Health*. 2014;11(5):4607-4618.
31. Jacobs DE, Brown MJ, Baeder A, et al. A systematic review of housing interventions and health: introduction, methods, and summary findings. *J Public Health Manag Practi*. 2010;16(5):S5-S10.
32. Patton AP, Calderon L, Xiong Y, et al. Airborne particulate matter in two multi-family green buildings: Concentrations and effect of ventilation and occupant behavior. *Int J Environ Res Public Health*. 2016;13(1):144.
33. Rice JL, Brigham E, Dineen R, et al. The feasibility of an air purifier and secondhand smoke education intervention in homes of inner city pregnant women and infants living with a smoker. *Environ Res*. 2018;160:524-530.
34. Baxter LK, Clougherty JE, Laden F, Levy JI. Predictors of concentrations of nitrogen dioxide, fine particulate matter, and particle constituents inside of lower socio-economic status urban homes. *J Eposure Sci Environ Epidemiol*. 2007;17(5):433.
35. Chaudhuri N. Interventions to improve children's health by improving the housing environment. *Rev Environ Health*. 2004;19(3–4):197-222.
36. Klepeis NE, Bellettiere J, Hughes SC, et al. Fine particles in homes of predominantly low-income families with children and smokers: Key physical and behavioral determinants to inform indoor-air-quality interventions. *PLoS One*. 2017;12(5):e0177718.
37. Krieger JK, Takaro TK, Allen C, et al. The Seattle-King County healthy homes project: implementation of a comprehensive approach to improving indoor environmental quality for low-income children with asthma. *Environ Health Perspect*. 2002;110(suppl 2):311-322.
38. Ballard-Tremeer G, Mathee A. *Review of interventions to reduce the exposure of women and young children to indoor air pollution in developing countries*. Washington, DC: WHO/USAID Global Consultation; 2000. https://www.researchgate.net/profile/Grant-Ballard-Tremeer/publication/268273141_Review_of_interventions_to_reduce_the_exposure_of_women_and_young_children_to_indoor_air_pollution_in_developing_countries/links/54e35eba0cf201fe67ec96a7/Review-of-interventions-to-reduce-the-expos

ure-of-women-and-young-children-to-indoor-air-pollution-in-developing-countries.pdf
39. Hood E. Dwelling disparities: How poor housing leads to poor health. *Environ Health Perspect*. 2005;113(5):310–317.
40. Russell HA, Rufus C, Fogarty CT, Fiscella K, Carroll J. 'You need a support. When you don't have that.. chocolate looks real good'. Barriers to and facilitators of behavioural changes among participants of a Healthy Living Program. *Fam Pract*. 2013;30(4):452-458.
41. Dubuy V, De Cocker K, De Bourdeaudhuij I, et al. Evaluation of a workplace intervention to promote commuter cycling: A RE-AIM analysis. *BMC Public Health*. 2013;13(1):587.
42. Niks IM, de Jonge J, Gevers JM, Houtman IL. Design of the DISCovery project: tailored work-oriented interventions to improve employee health, well-being, and performance-related outcomes in hospital care. *BMC Health Serv Res*. 2013;13(1):1-11.
43. Folke C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob Environ Change*. 2006;16(3):253-267.
44. Gadgil M, Olsson P, Berkes F, Folke C, Berkes F, Colding J, Folk C. Exploring the Role of Local Ecological Knowledge in Ecosystem Management: Three Case Studies. In: *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. 2003:189-209.
45. Halliday A, Glaser M. A management perspective on social ecological systems: A generic system model and its application to a case study from Peru. *Human Ecol Rev*. 2011;18(1):1-18.
46. McGinnis M, Ostrom E. Social-ecological system framework: initial changes and continuing challenges. *Ecol Soc*. 2014;19(2). https://www.jstor.org/stable/26269580?seq=1#metadata_info_tab_contents
47. Ostrom E. A general framework for analyzing sustainability of social-ecological systems. *Science*. 2009;325(5939):419-422.
48. McPhearson T, Pickett ST, Grimm NB, et al. Advancing urban ecology toward a science of cities. *Bioscience*. 2016;66(3):198-212.
49. Pickett ST, Cadenasso ML, Grove JM. Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landscape Urban Plan*. 2004;69(4):369-384.
50. Wilkinson C. Social-ecological resilience: Insights and issues for planning theory. *Planning Theory*. 2012;11(2):148-169.
51. Ott WR. Concepts of human exposure to air pollution. *Environ Int*. 1982;7(3):179-196.
52. World Health Organization. *Air quality guidelines for Europe* (2nd ed.). Copenhagen: WHO Regional Office for Europe; 2000. https://apps.who.int/iris/handle/10665/107335
53. Lai HK, Bayer-Oglesby L, Colvile R, et al. Determinants of indoor air concentrations of PM2. 5, black smoke and NO2 in six European cities (EXPOLIS study). *Atmos Environ*. 2006;40(7):1299-1313.
54. Urso P, Cattaneo A, Garramone G, Peruzzo C, Cavallo DM, Carrer P. Identification of particulate matter determinants in residential homes. *Build Environ*. 2015;86:61-69.
55. Kraev TA, Adamkiewicz G, Hammond SK, Spengler JD. Indoor concentrations of nicotine in low-income, multi-unit housing: associations with smoking behaviours and housing characteristics. *Tobacco Control*. 2009;18(6):438-444.
56. Lee SC, Li WM, Ao CH. Investigation of indoor air quality at residential homes in Hong Kong—case study. *Atmos Environ*. 2002;36(2):225-237.
57. Clark ML, Reynolds SJ, Burch JB, Conway S, Bachand AM, Peel JL. Indoor air pollution, cookstove quality, and housing characteristics in two Honduran communities. *Environ Res*. 2010;110(1):12-18.
58. Coombs KC, Chew GL, Schaffer C, et al. Indoor air quality in green-renovated vs. non-green low-income homes of children living in a temperate region of US (Ohio). *Sci Total Environ*. 2016;554:178-185.
59. Quansah R, Semple S, Ochieng CA, et al. Effectiveness of interventions to reduce household air pollution and/or improve health in homes using solid fuel in low-and-middle income countries: A systematic review and meta-analysis. *Environ Int*. 2017;103:73-90.
60. Guyot G, Sherman MH, Walker IS. Smart ventilation energy and indoor air quality performance in residential buildings: A review. *Energ Build*. 2018;165:416-430.
61. Sharmin T, Gül M, Li X, Ganev V, Nikolaidis I, Al-Hussein M. Monitoring building energy consumption, thermal performance, and indoor air quality in a cold climate region. *Sustain Cities Soc*. 2014;13:57-68.
62. Ye W, Zhang X, Gao J, Cao G, Zhou X, Su X. Indoor air pollutants, ventilation rate determinants and potential control strategies in Chinese dwellings: A literature review. *Sci Total Environ*. 2017;586:696-729.
63. Morishita M, Adar SD, D'Souza J, et al. Effect of portable air filtration systems on personal exposure to fine particulate matter and blood pressure among residents in a low-income senior facility: a randomized clinical trial. *JAMA Intern Med*. 2018;178(10):1350-1357.
64. Ziemba RA, Brook RD, Bard RL, Spino C, Adar S, Morishita M. Improving air quality and cardiovascular health for low-income elderly in detroit michigan. *Innovation in Aging*. 2017;1(Suppl 1):442.
65. Becher R, Øvrevik J, Schwarze P, Nilsen S, Hongslo J, Bakke J. Do carpets impair indoor air quality and cause adverse health outcomes: a review. *International J Environ Res Public Health*. 2018;15(2):184.
66. Jim CY, Chen WY. Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *J Environ Manage*. 2008;88(4):665-676.
67. Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. *Urban Forest Urban Green*. 2006;4(3–4):115-123.
68. Selmi W, Weber C, Rivière E, Blond N, Mehdi L, Nowak D. Air pollution removal by trees in public green spaces in Strasbourg city, France. *Urban Forest Urban Green*. 2016;17:192-201.
69. Jeanjean AP, Buccolieri R, Eddy J, Monks PS, Leigh RJ. Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London. *Urban Fores Urban Green*. 2017;22:41-53.
70. Chen L, Liu C, Zou R, Yang M, Zhang Z. Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. *Environ Pollut*. 2016;208:198-208.
71. Dzierżanowski K, Gawroński SW. Use of trees for reducing particulate matter pollution in air. *Challenge Mod Technol*. 2011;2.
72. Fantozzi F, Monaci F, Blanusa T, Bargagli R. Spatio-temporal variations of ozone and nitrogen dioxide concentrations under urban trees and in a nearby open area. *Urban Climate*. 2015;12:119-127.
73. Kiss M, Takács Á, Pogácsás R, Gulyás Á. The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary). *Moravian Geograp Rep*. 2015;23(3):36-46.
74. Liang D, Ma C, Wang YQ, Wang YJ, Chen-xi Z. Quantifying PM 2.5 capture capability of greening trees based on leaf factors analyzing. *Environ Sci Pollut Res*. 2016;23(21):21176-21186.
75. Pandey AK, Pandey M, Mishra A, Tiwary SM, Tripathi BD. Air pollution tolerance index and anticipated performance index of some plant species for development of urban forest. *Urban Forest Urban Green*. 2015;14(4):866-871.
76. Yin S, Shen Z, Zhou P, Zou X, Che S, Wang W. Quantifying air pollution attenuation within urban parks: An experimental approach in Shanghai, China. *Environ Pollut*. 2011;159(8–9):2155-2163.
77. Islam MN, Rahman KS, Bahar MM, Habib MA, Ando K, Hattori N. Pollution attenuation by roadside greenbelt in and around urban areas. *Urban Forest Urban Green*. 2012;11(4):460-464.
78. Viippola V, Whitlow TH, Zhao W, et al. The effects of trees on air pollutant levels in peri-urban near-road environments. *Urban Forest Urban Green*. 2018;30:62-71.

79. Abhijith KV, Kumar P, Gallagher J, et al. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments–A review. *Atmos Environ*. 2017;162:71-86.
80. Yang J, Yu Q, Gong P. Quantifying air pollution removal by green roofs in Chicago. *Atmos Environ*. 2008;42(31):7266-7273.
81. Currie BA, Bass B. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosyst*. 2008;11(4):409-422.
82. Weerakkody U, Dover JW, Mitchell P, Reiling K. Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. *Urban Forest Urban Green*. 2017;27:173-186.
83. Kuras ER, Richardson MB, Calkins MM, et al. Opportunities and challenges for personal heat exposure research. *Environ Health Perspect*. 2017;125(8):085001.
84. Steinle S, Reis S, Sabel CE. Quantifying human exposure to air pollution—Moving from static monitoring to spatio-temporally resolved personal exposure assessment. *Sci Total Environ*. 2013;443:184-193.
85. US Environmental Protection Agency (EPA). Air Quality Flag Program; 2020. https://cfpub.epa.gov/airnow/index.cfm?action=flag_program.index. Accessed 1/16/2020.
86. Dorevitch S, Karandikar A, Washington GF, Walton GP, Anderson R, Nickels L. Efficacy of an outdoor air pollution education program in a community at risk for asthma morbidity. *J Asthma*. 2008;45(9):839-844.
87. Loh P, Sugerman-Brozan J, Wiggins S, Noiles D, Archibald C. From asthma to AirBeat: community-driven monitoring of fine particles and black carbon in Roxbury, Massachusetts. *Environ Health Perspect*. 2002;110(suppl 2):297-301.
88. Shendell DG, Rawling MM, Foster C, et al. The outdoor air quality flag program in central california: a school-based educational intervention to potentially help reduce children's exposure to environmental asthma triggers. *J Environ Health*. 2007;70(3):28-31.
89. Kim S, Li M, Senick J, Mainelis G. Designing to engage children in monitoring indoor air quality: a participatory approach. In: *Proceedings of the Interaction Design and Children Conference*, London, UK; New York, NY: Association of Computing Machinery; 2020:323-334.
90. Kim S, Paulos E, Mankoff J. inAir: a longitudinal study of indoor air quality measurements and visualizations. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Paris, France; New York, NY: Association for Computing Machinery; 2013:2745-2754.
91. Kim S, Senick JA, Mainelis G. Sensing the invisible: Understanding the perception of indoor air quality among children in low-income families. *Int J Child-comput Interact*. 2019;19:79-88.
92. Moher D, Shamseer L, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev*. 2015;4(1):1.
93. Qin H, Hong B, Jiang R, Yan S, Zhou Y. The Effect of Vegetation Enhancement on Particulate Pollution Reduction: CFD Simulations in an Urban Park. *Forests*. 2019;10(5):373.
94. Setälä H, Viippola V, Rantalainen AL, Pennanen A, Yli-Pelkonen V. Does urban vegetation mitigate air pollution in northern conditions? *Environ Pollut*. 2013;183:104-112.
95. Escobedo FJ, Wagner JE, Nowak DJ, De la Maza CL, Rodriguez M, Crane DE. Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *J Environ Manage*. 2008;86(1):148-157.

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