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REVIEW

Advances in Indoor Environmental Engineering: Implications for Environmental Quality and Human Well-Being

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ABSTRACT

Indoor spaces are where most human exposure occurs, shaping health, comfort, and performance. Rapid advances in indoor environmental engineering are changing how buildings deliver indoor environmental quality (IEQ), driven by better ventilation and air distribution, high-efficiency filtration and air cleaning, source control through low-emitting materials and reduced combustion, and sensor-based monitoring and controls. This review summarizes these developments and evaluates their impacts on environmental quality and well-being within an integrated IEQ framework that also includes thermal, visual, and acoustic conditions. Evidence suggests layered strategies combining source reduction, strong pollutant removal, and measurement-informed operation can meaningfully cut particulate exposure, improve perceived air quality, and support risk management in shared-air settings, while also affecting comfort, noise, and lighting that determine real-world acceptance and sustained performance. Key challenges remain, including gaps between design intent and actual operation, uncertainty in low-cost sensors and proxy metrics, and difficulties balancing IEQ with energy, carbon, and resilience goals during extreme events such as heat waves and wildfire smoke. The review highlights priorities for standards and research, including performance-based verification, harmonized measurement protocols, longer field studies to better characterize exposure, and equity-focused implementation. Together, these advances position indoor environmental engineering to deliver healthier, more resilient, and lower-carbon indoor environments.

Keywords: Indoor Environmental Quality; Ventilation; Filtration; Smart Buildings; Human Well-Being

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1. Introduction

Most people spend the vast majority of their time in indoor environments, and the quality of the indoor conditions is a key determinant of population-scale exposure, comfort, and health [1]. Houses, schools, offices, hospitals, and transport spaces are major micro environments where airborne and surface-bound contaminants, thermal, lighting, and sound environments interplay and determine human well-being [2]. However, the indoor space is not a mere passive setting. It is designed, created with envelopes, heating, ventilation, and air-conditioning (HVAC) systems, filtration and air-cleaning systems, material selections, and operational controls, and its functionality is both designed and in practice. Due to increased airtightness and energy efficiency of buildings, the stakes of the field of indoor environmental engineering have risen: the plans aimed to minimize the energy consumption inevitably led to higher concentrations of indoor pollutants or worsening of the problem of moisture without proper management of ventilation and source control. Simultaneously, the increased interest in the spread of airborne infectious diseases, the intrusion of wildfire smoke, and the air quality of cities has broadened the scope of demand for indoor environmental systems, turning the primary compliance into a resilient and healthy performance [3,4].

The area of indoor environmental quality involves several areas, such as indoor air quality (IAQ), thermal comfort, quality of lighting, and acoustic environment, that together contribute to the effects on health, cognitive, and perceived well-being [5]. Traditionally, studies and applications have tended to consider such areas independently: ventilation engineering that focuses on odor control and carbon dioxide (CO_2) as measures of occupancy; thermal engineering that focuses on heat balance in steady-state conditions; lighting engineering that focuses on visual task performance; and acoustic engineering that focuses on noise control and speech privacy. Nevertheless, there is growing evidence to indicate that interactions can be overlooked in a compartmentalized approach. As an illustration, enhancing ventilation to reduce indoor pollutants can exert strain on energy consumption, inject external pollutants when the outdoor temperatures are elevated, or cause noise in well-ventilated areas. On the other hand, thermal efficiency may be enhanced through the use of energy-saving measures like minimal outdoor air intake or tighter envelopes, but increases occupant, cooking, cleaning products, furnishings, or combustion appliance-induced indoor exposure. The new paradigm can thus be described as one of integrated IEQ: the co-optimism of the environmental quality and human results within the limits of energy, carbon, cost, and climate variability [6].

The recent years were characterized by an avalanche of developments in the sphere of indoor environmental engineering due to the convergence of technological and social forces [7]. To begin with, sensing and computation have altered the way the indoor environment is measured and regulated. Near real-time monitoring and feedback have been made achievable by the use of low-cost sensors of particulate matter, CO_2, temperature, humidity, proxy volatile organic compounds (VOCs), and ubiquitous connections and building management systems. This has enabled control initiatives based on data, fault detection and diagnostics, and responsive operation that are able to react to occupancy trends, external environments, and changing interior hazards. Second, technologies of air cleaning and filtration methods have taken on increased visibility as supplements to ventilation, such as high-efficiency in-duct filtration, portable air cleaners, and, in certain environments, ultraviolet germicidal irradiation and sophisticated gaseous pollutant sorbent medium. Third, there has been an advancement in material science and product stewardship, as more low-emitting building materials are available and more people have realized that source control, the reduction of emissions at the source, can be more effective and less energy-intensive than dilution. Fourth, the climate and health conditions of the people are different. Greater and more frequent heat waves demand thermal performance in structures; smoke events at wildfires demand controls on the infiltration of particulates; and renewed consideration of airborne transmission has reinvented ideas of ventilation and equivalent delivery of clean air in shared indoor facilities.

The implications of these shifts are beyond the customary comfort and the idea of acceptable air. There is an increase in the perception of the indoor environment as an upstream determinant of performance and health. There is evidence that fine particulate matter and some VOCs have respiratory and cardiovascular effects; dampness and mold have asthma and allergy effects; and uncontrolled ventilation and filtration can lead to exposure to more infectious diseases in high-occupancy buildings. Meanwhile, thermal stress has an influence on morbidity and mortality in extreme heat, particularly in older adults and those with a low adaptive capacity. Lighting has an effect on the circadian entrainment and the quality of sleep, which subsequently determines mental health and cognitive performance. The stress, annoyance, and performance are influenced by acoustic environments in both learning and office settings. Notably, these risks and benefits are not well-balanced. The quality of housing, the condition of the buildings, and the availability of mitigation technologies vary according to different socioeconomic categories, and certain groups of people, such as children, aged persons, the chronically ill, and residents of crowded or inadequately-resourced buildings, have a disproportionate exposure burden. The equity aspect of indoor environmental engineering, as well, is that improving IEQ will help reduce health disparities, and poorly designed or maintained systems may increase them[8–10].

Nevertheless, there are still enormous hurdles on the way to the process of engineering advancements into the uniform and practical benefits. The prevalent problem is the so-called performance gap between specifications and performance. The occupation of a building by its occupants can significantly change the levels of indoor pollutants and comforts due to commissioning deficiencies, misconfigurations in controls, lapses in maintenance (e.g., failure to replace filters in time), and occupant behaviors (e.g., window opening, application of cleaning chemicals, cooking habits)[11]. The sensors are cheap, but may be noisy and drift long-term, and there is a need to carefully calibrate, quality assure, and understand sources and airflow to interpolate their signals. Most interventions have trade-offs, too: more efficient filters will boost fan power unless the system is designed to operate at pressure drop, more outdoor air will boost heating/cooling loads, and some air-cleaning systems may produce unwanted byproducts when used or installed inappropriately. Further, although epidemiological and experimental research has solidified the evidence of a number of exposure-outcome associations, causality has been challenging in multifaceted structures where various exposures covary. The field, therefore, has a two-fold responsibility to put in place viable measures to curb perceived risks today, in addition to enhancing processes and standards to provide a more accurate way of quantifying the benefits, managing trade-offs, and influencing sound decision-making.

Standards and guidelines are historically known to be the backbone of the indoor environmental engineering practice, but they are also pressured to change. Most of the ventilation and comfort standards are made on common conditions and assumptions, which may not be true in light of the rapid climate change, extreme weather, and greater demands on infection control and resilience. Increasing attention is being given to performance-based strategies focusing on the achievement of quantifiable results, in terms of contaminant levels, exposure indices, or some other comparable clean air delivery, as opposed to prescriptive minimum rates in isolation. On the same note, the rise of smart building technologies makes one wonder about data governance, privacy, cybersecurity, and transparency: as the buildings gather more data about the environment and occupancy level, the engineering community should guarantee that such data are utilized ethically and efficiently to enhance well-being[12,13]. A frontier that is important is aligning standards with emerging technologies, evidence of health and equity priorities.

It is against this background that this review summarizes the developments in the field of indoor environmental engineering and researches the developments on the same with reference to the quality and well-being of humans. Four pillars of the engineering practice that are connected are ventilation and air distribution, including demand-controlled, personalized, and hybrid approaches; filtration and air cleaning, including in-duct and in-room approaches to air cleaning and the evidence base of their effectiveness; source control and materials engineering, including low-emitting products, combustion mitigation, and moisture management, and sensing, monitoring, and control, including sensor performance considerations, data-driven operation, and smart building frameworks[14]. It is important to note that IEQ is not limited to air, so we place these advances in a multi-domain view, which also applies to thermal comfort, lighting, and acoustics, with an emphasis on both trade-offs and synergies. We highlight throughout the ways that engineering interventions can be converted into exposure reductions and human outcomes, focusing on vulnerable populations and the distributional consequences of indoor environmental enhancements.

This article has triple objectives. To begin with, we present a comprehensive framework that can be used to structure the design of indoor environmental engineering efforts in line with the pathways that lead to building design and operation in terms of exposure and well-being. Second, we provide a summary of the current state of the art in technologies and operation practices with a focus on what is already mature to be implemented and what is still emergent and uncertain. Third, we formulate challenges and future directions, such as the necessity of improved field evidence, protocols of standardized measurement, sound metrics of linking engineering performance to health endpoints, and decision frameworks of co-optimization of IEQ and energy and carbon objectives. This review, by synthesizing knowledge on disciplines, including building science, exposure assessment, environmental health, and control engineering, can help researchers, designers, facility managers, and policymakers to enhance not only energy-efficient but also healthy, strong, and conducive to human thriving indoor environments.

The rest of the article is arranged in the following way. Section 2 provides the conceptual framework and review methodology with which the interventions were classified and evidence synthesized. Section 3 is a review of the major technological advances in ventilation, filtration and air cleaning, source control, and sensing and control systems. Section 4 continues the discussion on multi-domain IEQ integration, which is concerned with the thermal, visual, and acoustic environments and their interactions with air-centered strategies. Section 5 summarizes the discussion about the effects of indoor environmental engineering on health, comfort, cognition, and well-being with references to susceptibility and equity. Section 6 addresses implementation issues, standards, and future research directions. Section 7 ends with the conclusion and major implications for practice and policy that can be adopted to ensure healthy and low-carbon indoor environments.

2. Conceptual Framework and Review Methodology

2.1. Framing Indoor Environmental Engineering as an Exposure Response System

The structure of this review is based on the assumption that indoor environmental engineering affects human well-being through the changing exposure conditions with time. There are various sources of pollutants, thermal and moisture causes, and sources that are present in buildings, and occupants circulate in areas of different activities and vulnerabilities. The indoor environment is, therefore, more of a dynamic exposure system as opposed to a fixed condition. In order to capture this dynamic, we embrace a pathway-based model that connects indoor sources and stressors to transport and transformation processes, thereby creating indoor concentrations and comfort states, individual exposure patterns, and downstream health and well-being outcomes[15]. In this framework, the engineering intervention is perceived as the effect of varying one or more links in the pathway by decreasing the source of emissions, altering transport and mixing, hastening elimination, or modifying the environment in reaction to occupancy and outside circumstances.

One of the implications of this framing is that the indoor environmental quality is to be considered as an integrated construct[16]. In actual buildings, airborne pollutants, temperature, humidity, lighting, and acoustics are co-occurring factors, and any interventions in one area often cause a change in another. The ventilation measures have the capacity to dilute the indoor-generated contaminants as well as enhance the heating or cooling loads, and they can impact acoustic conditions. Filtration can eliminate the exposure to particulate matter, but can increase the fan energy or noise unless it is properly designed. Moisture control has the potential to reduce the risk of mold, but is likely to have an interaction with thermal comfort and sensation of air dryness. As a result, the review is more focused on multi-domain interactions and aims at determining not only what works, but under which boundary conditions and at what trade-offs. The conceptual framework in this review (**Figure 1**) is based on the connection between engineering interventions and exposure pathways and final human outcomes.

2.2. Review Objectives, Questions, and Scope Boundaries

The review is intended to bring together progress in indoor environmental engineering, which has a direct relation to the quality of the environment and human health, where the focus is placed on the intervention that is applicable to building design, retrofit, and operation[17]. The main goals are to describe the state of the art in engineering strategies to enhance the performance of the indoor environment, to evaluate the quality of evidence relating strategies with the reduction of exposure and human outcomes, and to find out gaps that hinder implementation or generalization due to building type and climate. The objectives are operationalized by using the following questions: How do the recent advances in ventilation and air distribution, filtration and air cleaning, source control and material selection, and sensing and control systems influence the concentrations in the indoor environment, distribution of exposure, and well-being endpoints?

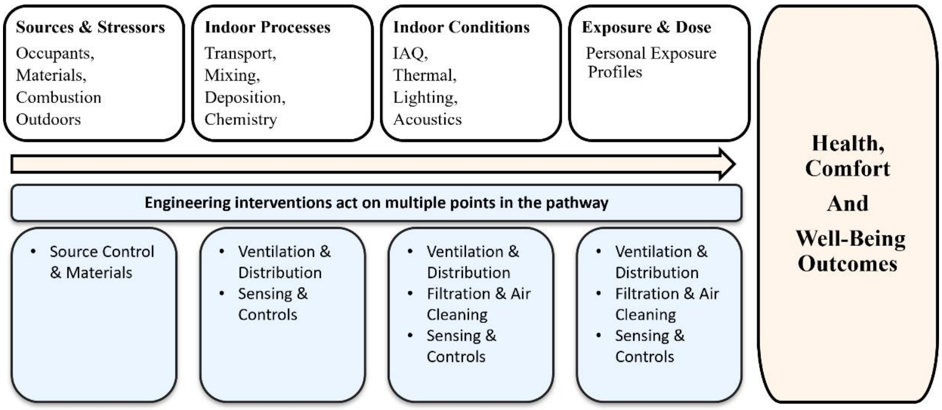

Figure 1. Conceptual framework illustrating pathways from indoor environmental engineering interventions through indoor processes and exposures to health, comfort, and well-being outcomes.

To continue to have coherence and comparability among the literature, the scope is limited in a number of ways. It is reviewed in the non-industrial indoor environment, which predominates the population exposure, i.e., residential, common non-residential (schools, offices, healthcare-related space) categories. It is also more focused on engineering strategies that can be applied at the building or room level, acknowledging that neighborhood-scale interventions (e.g., outdoor air quality policy) are still significant, but are not the main priority. The environmental quality aspect is perceived in a loose sense to incorporate IAQ and the IEQ, yet the engineering perspective is maintained throughout, with the focus of leveraging controllable aspects, quantifiable performance, and operationality [10]. Lastly, the review considers health and well-being as multi-dimensional outcomes, which include respiratory and cardiovascular endpoints, the risk of infectious disease in shared air, symptoms of poor indoor conditions, and functional outcomes, which include the quality of sleep, comfort, cognition, and productivity, but adds that the maturity of the evidence varies by endpoint [18].

2.3. Literature Identification and Search Strategy

A systematic search strategy was used to combine the literature base to include both the foundational and recent literature in the field of building science, exposure assessment, environmental health, and controls engineering [19]. Major bibliographic databases that are regularly used in SCI-indexed studies in the built environment and public health were searched. Search strings were a combination of the terms of indoor environmental engineering intervention, with terms of environmental quality measures and human outcome. The terms of intervention included ventilation, air distribution, demand-controlled and personalized ventilation, filtration, portable air cleaners, ultraviolet disinfection, sorbent-based removal, source control, low-emitting materials, moisture management, commissioning, and building automation. The outcome and metric terms were the concentration of indoor pollutants, PM, VOCs, CO_2 as an occupancy variable, humidity and dampness, thermal comfort, lighting quality, acoustics, exposure, dose, symptom, cognition, productivity, sleep, and risk of infection.

Since the terms used in one discipline are not necessarily the ones used in another, synonyms and neighboring concepts were considered, specifically in the smart building literature, where labels are not explicitly IEQ-related, such as indoor environmental control, digital twins, fault detection, and model predictive control. A reference list screening of the highly cited review papers and methodological seminal articles was employed to have major conceptual and measurement frameworks represented. Selective forward citation searching was done to find more recent studies that extend on the impactful early work, especially in these fast-moving fields, such as low-cost sensing and mobile air cleaning.

2.4. Study Screening, Eligibility Criteria, and Domain Classification

The eligibility was based on a staged screening process, which focused on the relevance of the study on the level of controllable indoor environmental engineering and the availability of interpretable performance or outcome measures. Participation in the studies was limited to those who reported quantifiable effects of an intervention or operational strategy on indoor environmental conditions, exposure-related measures, or health and well-being outcomes. Taking into consideration the interdisciplinary character of the field, a wider variety of study designs was incorporated, including laboratory experiments, controlled chamber studies, field interventions, observational monitoring campaigns, building simulation and computational fluid dynamics studies, and epidemiological studies in which indoor conditions were measured or highly speculated. Nevertheless, conceptual articles that lacked a substantive connection to engineering levers or research that dealt only with outdoor pollution, but with no indoor performance element, were considered to be out of scope.

Included studies were categorized to facilitate synthesis using two overlapping axes. The first axis was a classification of the interventions according to the primary engineering mechanism, such as ventilation and air distribution, filtration and air cleaning, source control and materials selection, moisture and envelope-related controls, and sensing and control systems. The second axis classified the results based on their nearness to human well-being, with studies that reported mainly on indoor concentrations or comfort parameters as opposed to results that reported exposure proxies, biomarkers, clinical outcomes, or functional outcomes like cognition and productivity [20,21]. This two-category classification is used because the evidence chain is frequently partial in any individual study; many engineering articles measure environmental shifts without quantitatively measuring health, whereas many health articles fail to describe the engineered indoor environment in a very detailed manner.

2.5. Data Extraction and Harmonization of Performance Metrics

In every qualified study, the descriptive and quantitative data were mined to enable comparison between interventions and settings. Features that were extracted were building type, climate or season, occupancy characteristics, description of interventions and settings of operation, baseline conditions, method of measurements, and duration of sampling and reported changes in the environmental parameters. In cases where applicable, engineering constraints and co-impacts, such as energy use, pressure drop, noise, maintenance requirements, and user acceptability, were also obtained during extraction. Since the study of the indoor environment is heterogeneous, a particular focus was put on the units and definitions of key measures because differences in the averaging time of averaged metrics, the type of instruments, or their spatial location have a significant impact on the results reported [22].

The interpretation of performance measures was done using harmonized concepts, where feasible, to enhance comparability. On studies that involved air cleaning and ventilation, the results were superimposed on the removal interpretation, which may be in terms of indoor particle accumulation relative to the outdoor, or decay, or clean air delivery equivalents. In the case of ventilation studies, in which direct ventilation rate data were available, they were retained; the review reported the use of proxies, like CO_2 dynamics, and indicated the uncertainties associated with them. To achieve thermal comfort, the review identified variation between steady-state indices and adaptive models and determined the capacity of the studies to capture transient conditions or spatially non-uniform conditions. In the sensing studies, the extraction contained calibration methods, error reported, drift behavior, and context-dependent limitations, as the sensor reliability determines the ability of the improvements measured to be maintained in the realistic operation [23].

2.6. Evidence Synthesis Approach and Assessment of Certainty

The synthesis methodology was intended to be stringent yet realistic, with the fact that a single statistical meta-analysis may not be possible in highly diverse studies of indoor environmental conditions. Based on this, the review follows a structured narrative analysis based on the type of interventions and the proximity of outcomes, comprising evidence of controlled experiments, field studies, and modeling. In cases where several studies documented similar measures when similar conditions were observed, the review focuses on convergence and provides possible causes of variance, including the tightness of the building, the type of ventilation system, the frequency of filter replacement, occupant behavior, or the outdoor pollutant regime [14,24].

Evaluation of the evidence strength is based on the internal validity, the quality of exposure characterization, and applicability to a real-world deployment. In the case of engineering performance studies, certainty is affected by the measurement fidelity, length of observation, and whether or not the intervention was conducted within the usual operating conditions. Certainty would affect health and well-being outcomes in terms of the study design, control of confounding factors, sample size, and the plausibility of the exposure-response pathway, given measured indoor conditions [25]. In fields, the review differentiates evidence of efficacy in controlled settings and evidence of effectiveness in occupied buildings since the latter is frequently constrained by irregular functionality and imperfect reporting.

2.7. Methodological Challenges Specific to Indoor Environmental Research

The research of indoor environmental engineering has challenges that define the manner in which results ought to be understood and generalized [26]. The exposures that are considered indoors are intermittent and behavioral; events that are high in emittance, like cooking, cleaning, or when people are present in their maximum numbers, may not be captured with short windows of monitoring. The variability in space within rooms and across zones makes it difficult to infer using a few monitors and assumptions of well-mixed spaces when stratified or poorly mixed spaces are taken into consideration. Outdoor settings bring about time-dependent boundary limitations, such as pollution bursts, humidity spikes, and changes in temperature that impact indoor concentrations and system functioning. Such features can generate seeming inconsistencies among studies, which are actually consistent on the condition of considering the bounding conditions.

The other difficulty is related to the conversion of the environmental measurements to well-being outcomes [27,28]. Most studies provide reports of change in indoor concentrations with no individual exposure measured, and fewer of them measure dose or clinical endpoints. On the other hand, reports of health relationships can use simplified proxies of indoor conditions, which restrict causal interpretation. These gaps are addressed explicitly through the review, and the areas of strong evidence chain are highlighted, while those that are inferential are not. Lastly, the emergence of relying upon data-driven controls and interconnected sensors creates a problem of data completeness, privacy, and transparency of algorithms, whose impacts on research reproducibility and adoption into practice. The solution to these methodological limitations is necessary to establish norms and working practices that can provide healthy indoor environments, and not formal compliance.

2.8. Organization of the Review Based on the Framework

The above-described conceptual and methodological choices dictate the structure of the rest of the sections. The progress of engineering is assessed in advance with the perspective of controllable levers that alter the indoor exposures and conditions, and subsequently, synergies and trade-offs appear in the domains of IEQ [29]. The evidence connecting these interventions with health and well-being is then synthesized through the perspective of susceptibility and equity, and lastly interpreted in the light of the implementation, standards, and future research requirements. This organization will be meant to close disciplinary silos and offer a coherent narrative between engineering design and operation on one hand, and human-centered outcomes.

3. Advances in Indoor Environmental Engineering Technologies

To structure the discussion of technological advances, the principal indoor environmental engineering interventions reviewed in this article are summarized by mechanism, scale, and practical constraints in **Table 1**.

Table 1. Overview of major indoor environmental engineering intervention categories, their primary mechanisms of action, typical spatial scales, and key implementation constraints.

Engineering Domain	Intervention Type	Primary Mechanism	Typical Scale	Key Constraints
Ventilation	Mechanical outdoor air ventilation	Dilution and removal of indoor-generated contaminants	Building/zone	Energy use, outdoor air quality
Ventilation	Demand-controlled ventilation	Occupancy-responsive air exchange	Building/zone	Sensor accuracy, control logic
Air distribution	Displacement/underfloor systems	Stratification-based contaminant removal	Room/zone	Sensitivity to heat gains
Filtration	In-duct high-efficiency filtration	Particle removal from recirculated air	Building	Pressure drop, fan capacity
Air cleaning	Portable air cleaners	Localized particle removal	Room	Noise, placement, maintenance
Source control	Low-emitting materials	Emission reduction at origin	Material/building	Availability, cost
Source control	Combustion mitigation	Removal or isolation of combustion byproducts	Appliance/unit	Retrofit feasibility
Controls	Sensor-driven automation	Adaptive operation based on real-time data	Building	Data quality, cyber security

3.1. Ventilation Paradigms and the Evolution of Air Distribution Design

Ventilation is a cornerstone of indoor environmental engineering as it is the controlling element of dilution of the indoor-generated contaminants and the exchange of indoor and outdoor air [30]. In the past 20 years, there has been a change in practice where relatively homogeneous delivery of outdoor air to buildings has been replaced with more responsive approaches to occupancy, spatial heterogeneity, and outside boundary conditions. Demand-controlled ventilation is a relatively modern trend in most commercial properties and has employed occupancy-related proxies, such as carbon dioxide or occupancy counting, to adjust the amount of outdoor air intake. The engineering rationale behind this is to ensure decent contaminant dilution during different occupancy and to decrease unneeded conditioning of the outdoor air. This change has, however, also helped to explain the difference between applying CO_2 as an indicator of ventilation adequacy and applying it as a hazardous agent, and has added impetus to the focus on sensor placement, calibration, and control logic capable of preventing chronic under-ventilation.

In line with demand control, interest in ventilation practices that directly control the places of air delivery and the transportation of contaminants in a space has been revived. The potential of displacement ventilation and underfloor air distribution has undergone research and application as an alternative to traditional overhead mixing, the objective of which is to apply buoyancy-driven stratification to more effectively remove heat and contaminants in the occupied area. Practically, the functioning of such systems is greatly dependent on internal heat gains, diffuser design, and on occupant activity that may disrupt stratification. Personalized ventilation. An even more specific development is that of personalized ventilation, which delivers clean air to the breathing area. The method is consistent with exposure science, as it focuses on reducing inhalation exposure as opposed to concentrations in the whole room. However, individualized systems add complexity to design, need special attention to integration with thermal comfort and occupants' control preferences, and can be questioned with regard to maintenance and fair access in the selective deployment [31,32].

There has been a growing focus on the literature of ventilation about the significance of outdoor air quality and episodic events. In events of wildfire smoke, outdoor particulate concentrations can occur at a high level, so augmented ventilation can be counterproductive unless augmented with high-efficiency filtration and due consideration of pressure. In very polluted urban corridors, a policy of ventilation should not only be used to determine the volume of outdoor air that should be taken into the building, but also the time of the day when it should be taken and the efficiency of filtration of all pollutants, including gaseous ones. These factors have prompted a rush towards hybrid and mixed-mode solutions that integrate mechanical ventilation with operable windows and include controls that are responsive to outdoor air quality, thermal stress, and occupant comfort [33,34]. These systems have the potential to provide benefits of energy and comfort, but cannot withstand changes in occupant behavior and user interfaces that can inform them of when and how natural ventilation has to be employed.

3.2. From Ventilation Rates to Removal Capacity: Operational Metrics and Design Targets

The major conceptual development in the field of indoor environmental engineering that occurred is the progressive change in the meaning of nominal ventilation rates as the characteristic of the total removal capacity of contaminants [35]. Whereas the ventilation rates continue to be pivotal to most applications, removal-based interpretation can more appropriately serve the increasing role of filtration, air cleaning, and source control. Practically, removal capacity may be formulated using equivalent clean air delivery ideas, which put the various removal processes on a common platform. It can be applied practically to design and operation as it endorses flexible sets of interventions. An example is that a building can get a desired reduction of exposure by a combination of moderate outdoor air exchange, high-performance recirculated air filtration, and localized in-room cleaning instead of using outdoor air.

This development has also added the concern of the real-life airflow patterns and mixing conditions. Short-circuiting between supply and return diffusers, stratification, and imbalance between multi-zone pressures can lead to actual removal effectiveness that is not what is predicted by the ventilation rate in many buildings [36]. New developments in computational fluid dynamics, reduced-order airflow models, and tracer-gas diagnostics have enhanced the ability to capture these effects, but the discrepancy between research-level assessment and practice in general is still wide. Besides this, the appreciation of the fact that infectious aerosols and fine particles may act in different ways under some flow conditions has led to a re-examination of diffuser design, occupant density, and localized stagnation regions that may not be reflected by whole building ventilation indicators.

3.3. High-Efficiency Filtration and the Maturation of Particle Control Strategies

Filtration has also emerged as a focal point of indoor environmental engineering, especially regarding the control of particulate matter spanning a large size spectrum [37]. HVAC In-duct filtration has been utilized over time, though the focus has shifted to more efficient filters, both in residential and commercial applications. This change is motivated by the fact that the evidence of exposure to fine particles and negative health effects is now more serious, and that there is a higher understanding of sources of particles like cooking, infiltration of traffic pollution, and smoke events. Indoor particle concentrations can be significantly lowered by high-efficiency filtration in cases where the designed systems are capable of supporting the pressure drop associated with filtration, and where the filters are installed and properly maintained. The practical restriction is that a lot of existing systems have not been configured for higher resistance filters, and retrofit can necessitate upgrades of fans, cautious commissioning, or operational readjustment to retain airflow rates.

Portable air cleaners are a complementary intervention that is likely to be implemented faster, especially when central HVAC is unavailable or in under-ventilated rooms [38]. Their growing use has led to closer examination of clean air delivery performance under realistic conditions, such as the effect of location, geometries of rooms, air mixing, and occupant-induced resuspension. One common factor is that performance ratings of a device do not directly correspond to the amount of exposure reduction attained unless the device is sized to fit into the available space and is run at flow settings that the occupants can leave without hearing impairment. This practical limitation connects the efficacy of air cleaning with the human factor and fairness: noise, price, and serviceability can restrict continued application, particularly in less resourceful residences and schools.

3.4. Air Cleaning beyond Particles: Gaseous Pollutants, Byproducts, and Risk Management

As the control of particles has become mature, the engineering control of gaseous pollution is more difficult because there is a variety of compounds and sources [39,40]. VCs and ozone can be removed by activated carbon and other sorbent-based media, although performance varies depending on the type of media, pollutant mixture, humidity, and saturation behavior. Even the engineering solutions to indoor VOC chemistry are complicated: most indoor VOCs are produced by materials and consumer products over a long period, and not all interventions can effectively reduce exposure, as they may cause chemical changes. To illustrate, ozone reactions with terpenes and other VOCs may produce secondary pollutants, such as ultrafine particles and oxygenated compounds, which may have unintended effects if ozone is brought in or left unsuccessfully removed.

Microbial control with ultraviolet germicidal irradiation type of technology has attracted attention in special situations [41]. The upper-room UV and in-duct UV can eliminate viable airborne pathogens with proper design and installation, and their effectiveness is influenced by the delivery of the dose, air mixing, lamp shielding, and maintenance of the lamp output. Other electronic or reactive technologies in the market are used to clean the air, and these need to be scrutinized since some of them produce ozone and other reactive species that raise concerns over the formation of byproducts and possible health hazards. The general lesson in engineering is that air cleaning ought to be approached as a performance-validated intervention in which side effects are explicitly considered, but not as a generic add-on. This has encouraged a greater focus on third-party testing, standardized performance measures, and a precautionary stance in case of incomplete evidence.

3.5. Source Control and Materials Engineering as Upstream Interventions

The use of source control has also become a more economical and energy-efficient way of enhancing the quality of the indoor environment [42]. Instead of diluting or eliminating pollutants once they get into the air inside the building, source control attempts to curb emissions by selecting materials, designing products, and designing using behavioral knowledge. Advancements in low-emitting building materials, furnishing, and coatings have increased the range of tools that designers have to use, especially in new buildings and major remodeling. Simultaneously, it is increasingly being acknowledged that the occupant activities (cooking, cleaning, use of fragranced products, smoking, and hobby-related emissions) can occupy a majority of the indoor pollutant profiles in residential buildings, given that engineering interventions are likely to often have to go beyond the building fabric itself to include the effectiveness of kitchen ventilation, local capture, and occupant instructions.

Combustion source mitigation has gained a specifically provocative theme, as the evidence of interior combustion of gas stoves and unvented appliances has increased. The engineering reactions involve better local exhaust format, verification of the capture proficiency, and wider electrification approaches, which eliminate the origins of combustion. The interventions will interact with the tightness and pressure balance of building envelopes because the back-drafting risks and migration of pollutants in connected garages or in the neighboring units of multi-family buildings can negate local changes. The hybridization of source control and building physics is characterized by moisture control, in which envelope design, ventilation, and dehumidification should be balanced in such a way that they do not cause dampness or mold growth and related health effects without causing undue energy use or unpleasing conditions [43,44].

3.6. Sensing, Monitoring, and the Transition to Data-Driven Indoor Environmental Management

The development of sensing has transformed indoor environmental engineering since it is now possible to continuously or nearly continuously monitor the conditions that used to be measured at intervals [45]. It has become commonplace to use low-cost CO_2, particle, temperature, and humidity sensors, and proxy-based VOC sensing, which has to be used with caution. The value of these sensors as an engineering tool is not just in measurement, but in that such sensors can be combined with controls to give the systems the ability to react to occupancy dynamics and the outdoors. Meanwhile, the shortcomings of low-cost sensing, drift, cross-sensitivities, and unit-to-unit variability have been understood to a greater extent. This has prompted methodological progress in methods of calibration, such as field co-location with reference measurements, algorithmic correction, and sensor fusion, which uses multiple measurements to estimate latent variables (ventilation rates or source events).

It has also moved to a more adaptive style of control instead of a rule-based type of scheduling with building automation systems. By explicitly adding energy and comfort limitations, weather prediction and occupancy prediction, model predictive control, and optimization-based methods can achieve trade-offs between ventilation, thermal comfort, and energy usage. The concept of digital twins, combining a physics-informed model of the behavior of a building with live data streams, is gaining interest as a tool to assist in the fault detection and predictive maintenance, as well as scenario testing of indoor environmental interventions. Such developments are especially important in terms of long-term maintenance of IEQ, as most failures in the indoor environment are not due to poor design criteria, but to drift in operation or equipment malfunctions, or control maladaptation [46].

3.7. Operational Reliability: Commissioning, Fault Detection, and Maintenance as Technology Enablers

One of the common lessons of recent developments is the observation that the efficacy of technology is determined by the reliability of operations. Commissioning and re-commissioning have expanded to incorporate not just energy performance but also ventilation delivery checking, pressure balance checking, quality of filtration installation, and checking that control responses to occupancy. Common failures that may be detected using fault detection and diagnostics methods may include stuck dampers, sensor bias, leaking filters, and fan performance that may be degraded, and all these may destroy the indoor environmental quality without any visual indication to occupants. These approaches have become more practical with the increasing access to building telemetry and sensor data, yet have not been practically implemented because of staffing, data integration issues, and the requirement to have actionable workflows that take diagnostics to maintenance [47].

The high-efficiency filtration and portable air cleaner interventions are of particular importance as their maintenance is vital because the performance drops in case of the wrong choice of filters or their delayed change [48]. Likewise, moisture containment measures rely on the ability to identify the leakage in time and control the risks of condensation, which can get higher under changing climate conditions. The engineering frontier is not just about inventing new devices, but is developing systems and processes that produce uniform performance under actual constraints, such as low budget, variable occupant behavior, and conflicting operational priorities.

3.8. Toward Integrated Portfolios of Indoor Environmental Interventions

The overall trend of developments in indoor environmental engineering is that of combined intervention portfolios as compared to one-solution solutions [49]. Ventilation, filtration, source control, and sensing-and-control technologies are becoming more and more self-reliant parts of the environmental management system of a building. The best plans are usually the ones whose implementation is oriented to the reduction of emissions upstream, the strong removal capacity of the unavoidable pollutants, and the operation based on measurements to ensure that the performance is maintained in different occupancy and outdoor environments. Simultaneously, the advances imply the necessity to make trade-offs and careful assessment of real-life performance, to consider user acceptability and equity. These ideas give grounds to the following part, which looks at the interaction between air-oriented progressions and the thermal, visual, and acoustic surroundings when IEQ is seen as an overall goal and not a collection of separated objectives.

4. Integration with Thermal, Visual, and Acoustic Environments

4.1. Rationale for a Multi-Domain IEQ Perspective

As a design solution, indoor environmental engineering has been based on the notion of decoupling of air quality, thermal comfort, lighting, and acoustics as issues dealt with through different standards, different professionals, and building subsystems [14]. In reality, such realms are interwoven via common physical channels and common facilities and meet at the interface of human perception and physiology. The occupants are not exposed to any of the independent variables, namely, the concentrations of particulates, operative temperature, glare, and reverberation time, but instead, an integrated interior environment that alters comfort, stress, sleep, attention, and health. Indoor environmental engineering is thus regarded in this section as a multi-domain optimization problem where actions in one domain may enhance or reduce performance in another domain. One of the core themes is the fact that integration is not only conceptual but also operational: the same HVAC equipment, envelope choice, and control schemes run temperature, humidity, airflow, noise, and sometimes lighting loads in the interaction with daylighting and the facade. Multi-domain interactions, as mentioned in this section, are schematically summarized in **Figure 2**.

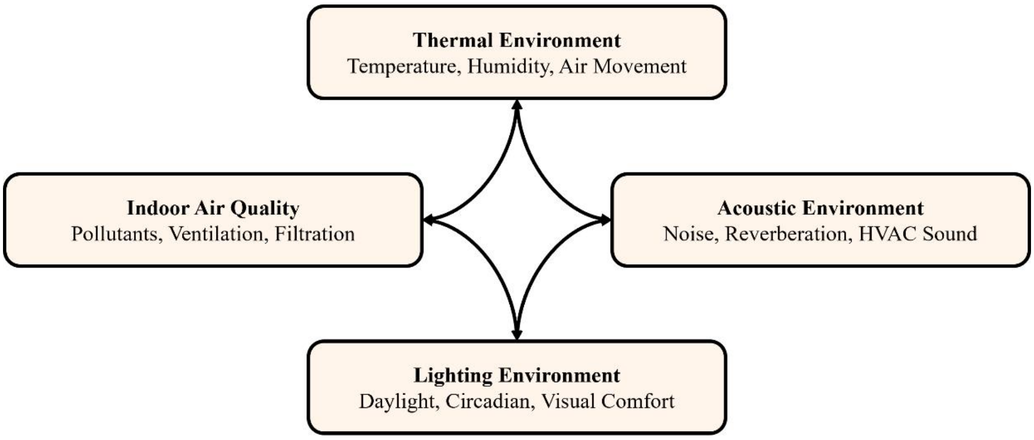

Figure 2. Interactions among indoor environmental quality domains, highlighting key synergies and trade-offs relevant to integrated engineering design and operation.

4.2. Coupling Air Quality Control with Thermal Comfort Engineering

There is the most significant interconnection between IEQ domains in the air quality and thermal control since both are mediated by the ventilation and HVAC functioning[50]. The air imported into the outside requires frequent heating or cooling, and variability of the ventilation rates can consequently alter thermal stability, drafts, and energy consumption. On the other hand, thermal strategies affect air quality by determining the pattern of airflow, transport by means of buoyancy, and humidity that control particle behavior, microbial activity, and chemical reactions. With the adoption of high-performance envelopes and low-energy conditioning by building designs, solutions that do not couple thermal conditioning and ventilation, including radiant heating and cooling systems and separate outdoor air systems, are becoming more popular in the design space. This architectural isolation can provide the ability to achieve more stable thermal comfort without compromising on the control of ventilation to achieve air quality, though it also creates new operational demands, such as humidity control to avoid condensation and close integration of control sequences among subsystems.

Another integration pathway with air quality implications is the personal comfort system and localized thermal control[51]. The fact that buildings can be controlled to provide local air flow or radiant exposure in occupancies has enabled buildings to operate with broader temperature setpoint ranges without apparent discomfort. Greater temperature intervals may minimize energy needs and provide some flexibility to improve ventilation or filtration in those instances when the risk of air quality is high. Local fans and air motion can also, however, affect aerosol transport and resuspension of settled particles, meaning that intervention into comfort can have exposure effects that should be taken into consideration in shared spaces. To achieve the desired goals is not to shun such technologies but to engineer them by considering air distribution and route of exposure, in particular in dense settings.

4.3. Humidity as a Bridging Variable across IEQ Domains

A bridge variable of special concern is humidity control, as it cuts across thermal comfort, perceived air freshness, microbial growth, and indoor chemistry. Relative humidity influences thermal perception by causing heat loss by evaporation and may be used to make perceived dryness or stuffiness change at constant temperature. Regarding the environmental quality, the high humidity levels should be maintained over time to reduce the risk of dampness and molds, whereas excessive humidity should be prevented, as it may impact the mucosal comfort and increase the number of recurring electrostatics, which could affect the occupant satisfaction and behavior. Humidity is also a modulating factor of chemical reaction pathways in indoor air and may affect the persistence of certain biological aerosols; however, the direction and strength of these effects are dependent on organism type, particle size distributions, and the chemical environment surrounding them[52].

The development of engineering in the dehumidification, moisture buffering materials, and envelope design has enhanced the capability to control the humidity, although the integration is difficult since the humidity loading is caused by climate and people. In damp climates, ventilation can increase the moisture load of the building unless adequate latent capacity is achieved by the systems. Urgent humidification in cold climates to deal with apparent dryness may increase condensation hazard at thermal bridges and building assemblies. These tensions underscore the fact that humidity control is not a variable, but an inherent facet of integrated IEQ design, and it is necessary to consider envelope performance, ventilation strategy, and thermal system design together[53].

4.4. Interactions between Thermal Strategies and Contaminant Transport

Another layer of coupling is formed by the physics of the stratification through the airflow and buoyancy[54]. Vertical stratification can be caused by thermal differences caused by occupants, equipment, solar gain, supply air, and alter the distribution of pollutant mixtures in the occupied zone. These gradients are purposely used in displacement ventilation and underfloor air distribution, but even in nominally mixed systems, stratification may take place in large spaces or spaces with significant solar loads. The stratified environments can enhance the elimination of heat and some of the pollutants in the occupied area, though it can also lead to localized areas of greater concentration based on the location of the source and the extent of mixing. Equally, the application of radiant systems can lead to lower airflow rates required to condition the thermal system, which can alter the mixing conditions and then the meaning of area-averaged sensor measurements. Such dynamics are indicative of the need to integrate sensing strategies with airflow regimes and the realization that the average of the room measurements may not be a good indicator of breathing-zone exposure in non-uniform settings.

4.5. Lighting Engineering, Daylighting, and Implications for Environmental Quality

Lighting is commonly considered a distinct subsystem; however, it affects the work of the indoor environmental engineering in terms of energy, load of heat, design of the facade, and behavior of occupants[55]. The change to high-efficiency LED lighting has lowered the heat gains internally in numerous buildings, changing thermal loads and increasing heating requirements at colder times of the year in some instances. This modification can change the HVAC operating regimes and airflow patterns, which determine the transport of contaminants. Such visual comfort strategies as extensive glazing and dynamic shading may enhance electric lighting usage and energy, but may also enhance solar heat gain and surface temperatures, which affect stratification and may raise cooling-induced air movement or change humidity regulation needs.

The circadian-effective lighting and dynamic spectral tuning interest has introduced a human-oriented aspect of lighting design that is comparable to the advancement in air quality and thermal comfort. Nevertheless, this may be negated by the superior lighting controls to the extent that the glare, flicker, and improper daylight management will lower occupant satisfaction and instigate behavioral adjustments, including closing blinds, which may change solar gains and thermal loads. It has the possibility of integrated design using the facade, lighting, and HVAC design, which has the acknowledgement of the feedback loop between the visual comfort, energy consumption, and thermal conditions, as opposed to optimization in each subsystem separately[56].

4.6. Acoustics, HVAC Noise, and Acceptability Constraints on Air-Focused Interventions

Another constraint on air quality interventions that is underestimated is acoustic conditions[57]. Background noise may be increased by increasing the rate of ventilation, fan speed, and the use of portable air cleaners. Noise may reduce speech intelligibility and concentration in schools and offices, and it may reduce the quality of sleep in bedrooms. It has the practical implication that even effective interventions that are theoretically acceptable but acoustically unacceptable can be underutilized or rendered ineffective. Particularly here, with portable air cleaners where the higher flow settings can dramatically contribute to effective delivery of clean air but can contribute to noise that residents find unacceptable, it is better to run at a lower setting that is less effective than a higher one.

Acoustics regarding HVAC also relates to the design of building envelopes and natural ventilation. Operable windows are capable of bringing in fresh air and occupant agency but may add noise outside the building that may not appeal to window use, especially in urban areas near traffic lines. Consequently, natural or hybrid ventilation practices become feasible not only in the circumstances of climatic appropriateness and the quality of outdoor air, but also in terms of soundscape and facade acoustic performance. Design improvements in noisier fans, better duct design, sound attenuation, and low-noise diffusers thus enable technology to contribute to the air-based improvements and enhance the ventilation or filtration capabilities without unduly compromising the acoustic comfort [58].

4.7. Trade-Offs, Synergies, and Multi-Objective Optimization in Practice

The above interactions suggest that integrated IEQ is most appropriately regarded as a multi-objective optimization problem as opposed to successive single-domain optimization. The common trade-offs are between ventilation, energy, thermal comfort, and acoustics, and others occur when there is pollution of outdoor air or climate extremes that put pressure on thermal systems [59]. Meanwhile, there are significant synergies. Operational budget may be generated with better filtration, extra ventilation during risky times, or better humidity control through energy saving using better envelopes and efficient thermal systems. Personal comfort systems may provide broader setpoints that will consider less energy usage, yet maintain satisfaction, which may provide more resilient ventilation strategies. Lighting and daylighting have the potential to minimize cooling loads indirectly to facilitate thermal stability in the event of higher outdoor air exchange. Interdependencies between air quality, thermal comfort, lighting, and acoustics, and trade-offs between domains being optimized separately are summarized in **Table 2**.

Table 2. Representative interactions, synergies, and trade-offs among indoor environmental quality domains and their implications for integrated engineering design and operation.

IEQ Domain Interaction	Synergistic Effects	Potential Trade-Offs	Engineering Implication
Ventilation–thermal comfort	Improved perceived freshness	Drafts, thermal instability	Need for diffuser and control optimization
Ventilation–energy	Improved air quality	Increased heating/cooling loads	Decoupling ventilation from conditioning
Filtration–acoustics	Reduced particle exposure	Increased fan or device noise	Low-noise design and sizing
Daylighting–thermal	Reduced lighting energy	Solar heat gains	Integrated façade and HVAC design
Natural ventilation–acoustics	Occupant control, energy savings	Outdoor noise intrusion	Acoustic façade strategies
Humidity–thermal comfort	Improved comfort perception	Condensation risk	Coordinated envelope and HVAC control

Integrated sensing and control can take care of these trade-offs and synergies in the context of the emerging smart building [60]. Model predictive control and supervisory control layers can explicitly represent temperature, humidity, pollutant proxies, noise constraints, and energy signals, and choose operating points, which keep the competing goals at trade-offs across time. Nonetheless, effective optimization requires the quality of sensor feeds, the explainability of the control actions, as well as the capability of facility groups to support and troubleshoot systems. Besides that, the optimization goals should be more human-oriented and not just equipment-oriented, such as a tolerable level of noise and exclusion of drafts, which can be the requirement to make sure that the air-cleaning interventions continue to be active and effective in real occupancy.

4.8. Implications for Designing Integrated Indoor Environments

By describing an inherent sense of thermal environment, visual environment, and acoustic environment as a whole, this provides an integrated perception of the environment and creates a different approach to the integration of indoor environmental engineering, which is not an exercise of compliance, but rather it becomes a performance-based, human-oriented organization discipline. The main conclusion is that to enhance indoor environmental quality, envelope design, HVAC architecture, filtration strategy, and controls should be combined, based on the occupants' perception and response to the environment. The strongest solutions are those that maintain a reasonable level of comfort and sensorial level and provide effective control of contaminants with fluctuating occupancy and outdoor conditions. This integration preconditions the assessment of influences on the well-being of the people, since the efficiency of engineering interventions is finally measured not only by the manifested environmental changes but also by whether engineering interventions are sustainable, palatable, and fair in buildings in practice [61].

5. Impacts on Environmental Quality and Human Well-Being

5.1. From Engineered Conditions to Human Outcomes: an Exposure-Centered Interpretation

Exposure, duration, and susceptibility mediate the relationship between environmental engineering in the indoor environment and the well-being of a human being, contrary to the environmental conditions themselves [15]. Indoor concentrations, thermal states, and humidity, lighting effects, and soundscapes are all modifiable through engineering interventions, but their extent of human benefit will be determined by the extent to which these interventions can change into real inhalation exposures, physiological stress, and behavioral responses over time. Such translation is not necessarily linear. Minimal changes in average concentrations can be of significant value in reducing the magnitude of exposures to high levels when needed, like during cooking or cleaning, or in preventing the occurrence of situations that initiate the symptoms of susceptible individuals. On the other hand, interventions that enhance measures can have minimal value when not maintained operationally, when they transfer pollutants to other forms by inner chemistry, or when they enforce comfort or noise fines, which culminate in occupancy-based disabling. Owing to these reasons, the evidence of the relation of indoor environmental engineering to well-being is well explained in a chain that involves intervention performance to exposure modification, and finally, health and functional outcomes. To put the discussion on the health and well-being impacts into context, **Table 3** provides a brief summation of the existing evidence base of the connection between major interventions in indoor environmental engineering and a myriad of human effects.

Table 3. Summary of evidence linking indoor environmental engineering interventions to selected health, cognitive, and well-being outcomes, with indicative strength of evidence and key uncertainties.

Outcome Category	Primary IEQ Drivers	Typical Interventions	Strength of Evidence	Key Uncertainties
Respiratory health	PM, NO_2, dampness	Filtration, source control, and humidity control	Strong–moderate	Long-term exposure variability
Cardiovascular risk	Fine particles, combustion pollutants	Filtration, electrification	Moderate	Indoor dose estimation
Infection risk	Airborne aerosols	Ventilation, filtration, air cleaning	Moderate–strong	Real-world airflow patterns
Cognitive performance	Ventilation, thermal stability	Ventilation, comfort control	Moderate	Confounding, expectancy effects
Sleep quality	Temperature, noise, ventilation	Thermal control, low-noise air cleaning	Emerging	Limited field studies
Mental well-being	Noise, thermal discomfort	Acoustic control, comfort design	Emerging	Subjective outcome measures

5.2. Respiratory Health and Symptom Burden in Common Indoor Settings

One of the endpoints with consistently addressed literature in the indoor environment is the respiratory outcomes due to the fact that the airway is also a major route of exposure and a sensitive contact point with both the particulate and gaseous pollutants [26]. Indoor-based interventions to decrease fine particulate matter are generally linked to less burden of respiratory symptoms, decreased complaints of asthma, and perceived better air quality, though the effectiveness of the intervention depends on the nature of the study design and the underlying pollution regime. The filtration and portable air cleaners are expected to exhibit comparatively direct mechanistic correlations due to the fact that alterations in the concentrations of particles in the indoor setting can be quantified and, in certain research, also associated with the results of the symptoms or medication. Some indoor pollutants also may be lessened by ventilation interventions, but the overall effect of ventilation on respiratory outcomes is highly dependent upon the quality of outside air, the existence of indoor sources, and whether ventilation may augment moisture loads or bring reactive oxidants that may produce secondary irritants.

Control of moisture and dampness is a paramount consideration in respiratory health because dampness correlates with the growth of molds, proliferation of dust mites, and microbial byproducts that may cause asthma and allergic disease [62]. The implementation of engineering solutions to prevent chronic dampness by enveloping integrity, drainage, ventilation, and humidity control can have significant health benefits, they tend to have significant health benefits in the long term, but these benefits take time to manifest and demand regular maintenance. The fact that dampness-related issues persist in most stocks of housing can be used to explain the larger argument that any engineering solution needs to be operationally sound and cost-effective to generate health changes at the population level.

5.3. Cardiovascular and Systemic Impacts Linked to Indoor Exposures

An accruing literature on environmental health shows that fine PM is a contributor to cardiovascular and systemic effects, such as inflammatory and autonomic reactions [63]. Due to the large amounts of time that people spend indoors, it is plausible that any reductions in the exposure to indoor particles can make a cardiovascular risk reduction, especially in groups that are already vulnerable to cardiometabolic conditions. The exposures that can be affected by indoor environmental engineering include reducing the exposure to outdoor particles by reducing infiltration and controlling indoor sources. Efficient filtration and good enclosure strategies can be used to lower indoor levels of particles during outdoor pollution events, whereas better kitchen exhaust and source control can be used to lower exposure to cooking-related aerosols that can otherwise result in frequent spikes.

Indoor gaseous pollutants have a more complex cardiovascular relevance as they are usually not measured, and their exposures are a mixture of toxicological properties with various toxicities. Of special concern in gas appliance homes or other sources of combustion are nitrogen dioxide, carbon monoxide, and some of the combustion compounds. The cardiovascular co-benefits of engineering measures that minimize such exposures, such as good local exhaust, appliance care, electrification, etc., could thus be in addition to the respiratory benefits. Nevertheless, the evidence base is unequal because the long-term indoor exposure characterization is difficult, and socioeconomic and behavioral factors, which correlate with indoor conditions and health risk, confound the evidence base [64].

5.4. Airborne Infectious Disease Risk and Shared-Air Management

The renewed attention to airborne transmission has made ventilation, filtration, and air cleaning technologies more topical in the context of the risk of infection in common spaces [65]. In contrast to chronic pollutant exposures, the threat of infection is event-related and is dependent on the occupancy level, length of time, activity level, and infectious individuals. The main effects of engineering interventions are to minimize the risk either by decreasing the concentration of infectious aerosols in the air or by preventing the build-up of the aerosols during occupancy. This has promoted the application of removal-based ideas that portray ventilation and filtration as sources of an aggregate clean air capacity. The field and modeling research indicate that the risk of transmission can be decreased by the enhanced delivery of clean air, either outdoors or by recirculated filtration or in-room cleaning, especially in overcrowded, poorly ventilated areas.

Distribution and zoning are also of importance in the infection-control lens. The localized high exposure conditions may take place in stagnant zones, near-source areas, or in areas with short-circuit airflow. Consequently, the effective ventilation of a space, design of air distribution, and composition of occupants might affect risk in excess of that suggested by whole-room or whole-building ventilation rates [66]. The practical implementation should also consider the acceptability constraints, such as that noisy portable cleaners cannot be used frequently, and more ventilation can be unacceptable in extreme weather. Strategies that utilize both engineering controls and operational practice and communication are therefore the strongest and make sure that interventions are maintained at a time of high risk.

5.5. Cognitive Performance, Productivity, and Perceived Indoor Environmental Quality

In addition to clinical health outcomes, indoor environmental conditions affect cognition, work performance, and productivity, frequently the primary motivational factors in

IEQ enhancement efforts in schools and work [67]. Studies on this subject have investigated associations among ventilation sufficiency, pollutant proxies, and decision-making, attention, and perceived fatigue performance measures. Although the causal pathways may be challenging to separate because of the confounding and expectancy effects, the literature at large proposes that stuffiness, headaches, and inability to concentrate may largely be exacerbated by poorly ventilated or highly polluted environments, and that the perceived and occasionally objective performance can indeed be improved through ventilation and control of contaminants. The aspect of thermal comfort is also significant, as heat and cold stress may be detrimental to performance and heighten the error rates, and unstable or drafty conditions can be of specific concern in the case of prolonged tasks involving cognition.

Notably, the performance literature emphasizes the fact that the acceptable conditions are not entirely physiological. The perceived control, trust of the building system, and comprehensiveness of environmental cues determine the way the occupants perceive and react to the interior conditions [68,69]. By way of example, occupants can accept more background ventilation noise when they feel that it helps protect their health, but refuse similar noise when it is viewed as unneeded or annoying. It means that human aspects are directly related to technical performance as engineering effectiveness is partly based on communication, user interfaces, and organizational context.

5.6. Sleep Quality, Mental Well-Being, and the Indoor Sensory Environment

The outcomes of sleep and mental well-being are at the crossroads of various IEQ domains, one of which is thermal stability, which is the other, along with humidity, lighting, and acoustics. Excessively hot, poorly ventilated, or noisy bedrooms may also increase sleep fragmentation and poor sleep quality, as well as mood, cognitive, and cardiometabolic health. Perceived freshness and the prevention of accumulation of pollutants during the night can be enhanced by ventilation and filtration, although the advantageous effects may be negated due to noise and drafts that come along with the interventions that disrupt sleep. Lighting is also involved in the process of sleep, and it is circadian entrainment; wrong time and intensity of light exposure can adjust circadian rhythms and disrupt sleep initiation. Although lighting measures have been considered besides air and thermal measures, integrated design remains a significant consideration in residential and healthcare settings, where sleep is one of the primary elements of well-being and recovery [70].

There are direct physiological mechanisms that affect mental well-being; this is coupled with indirect mechanisms that both comfort and perceived safety are mediated by environmental stressors such as noise and poor thermal conditions [20]. Noise and poor acoustic conditions could increase stress and irritation, whereas thermal discomfort could make people more irritable and change their feelings towards the environment. These are difficult to measure, and can be situation-specific, but add to the built-up IEQ view: interventions that are optimized only based on a single measure can be ineffective at providing holistic well-being benefits when they produce negative sensory stimuli.

5.7. Differential Susceptibility and the Distribution of Benefits

Interventions in indoor environmental engineering cannot have an equal impact on all populations since baseline exposures, vulnerability, and access to mitigation vary. The emerging respiratory system and increased ratio of inhalation per body mass make children more prone to some of the pollutants, and the time spent at school is significant and fluctuates in terms of ventilation quality and maintenance. It is also possible that older adults and those with chronic respiratory or cardiovascular disease will see larger benefits of exposure reductions, but be more susceptible to thermal stress in heat waves or power outages. Pollutant transport across units, corridors, and shared combustion sources also may make interventions in multi-family housing more complicated, because they are interested in the individual units. These facts are a pointer that engineering solutions should be developed keeping in mind building typology and occupant demographics, and not based on a homogenous starting point [71].

Feasibility is also determined by equity. High efficiency filtration, portable air cleaners, and sensor-based control can be of meaningful benefit, but initial cost, replacement materials, and power costs may restrict their use in low-income households and schools with limited resources. The maintenance loads are also not equal because constrained staff buildings might fail to maintain filter replacement and commissioning activities needed to achieve long-term performance. Consequently, the spread of benefits could be similar to the spread of resources unless the policy, procurement models, and support programs are aimed at promoting equal access to healthy indoor environments [9,72].

5.8. Interpreting the Evidence Base: Strengths, Limitations, and Practical Meaning

In diverse outcomes, there is a stronger evidence base in the situations where the link between intervention and exposure is unambiguous and quantifiable, as in the case of particle removals due to filtration and air cleanup, or the humidity effect on the dampness risk. It becomes more challenging in situations where exposures are not well described, where mixtures are complicated, or where consequences are remote and sensitive to a myriad of other situations. This does not devalue the role of these endpoints; however, it suggests that the strength of the evidence and precaution of indoor environmental engineering must be directed towards those interventions that can respond to well-known hazardous conditions, and an effort should be made to improve the measurement and causal study designs of the emerging questions [73].

A functional interpretation is that well-being advantages are best accurately obtained as a result of stratified engineering techniques. The source control in place ensures that the downstream systems do not endure heavy loads; filtration and air cleaning ensure that the particles and certain bioaerosols are removed strongly; ventilation makes the occupant-related contaminant under control and dilution in cases when the outdoors conditions are favorable; and sensing and control allow maintaining the performance and targeting interventions to the high-risk periods [74,75]. The acceptability, maintenance, and integration across IEQ domains is what makes this layered approach effective and predetermine the discussion in the following section on standards, barriers to implementation, and future research directions.

6. Challenges, Standards, and Future Research Directions

6.1. The Persistent Performance Gap between Design Intent and Operational Reality

The frequent problem with indoor environmental engineering is that actual conditions in occupied buildings tend to be different than design and code or standard assumptions [76]. The causes of this performance gap are complex, and there are numerous factors that form over time. HVAC systems can be properly sized and specified, but are unable to provide the amount of outdoor air they are supposed to because of the miscalibration of dampers, fan wear and tear, filter loading, or changes in control sequences that had been made to solve the complaint or cut down on the energy bill. Designing envelopes that are successful in design simulations may contain unexpected leakage pathways, water movement, or thermal conduction that may impact infiltration and humidity control. Occupant behavior adds more variability by opening windows, thermostat overrides, use of portable heaters, cleaning habits, and alterations in space use, not included in design occupancy schedules. These facts imply that the attainment of the indoor environmental quality is not a design success but an operational success that should be checked, upheld, and changed in accordance with the prevailing circumstances.

The performance breakage is particularly significant in the context where the interventions are assessed according to nominal specification, as opposed to delivered performance. An example is a high-efficiency filter that is specified, but does not ensure that there is equal delivery of clean air when airflow is reduced by the construction of a fan or when filters are circumvented by bad installation. Likewise, demand-controlled ventilation can, in theory, do well, though it can fail to ventilate sufficiently in a systematic way when sensors drift, or control setpoints are chosen without considering non-correlating with occupancy proxy sources of contaminant sources. These concerns indicate the need to have operational verification structures to consider the performance of the indoor environment measurable and responsible, similar to the developing strategies in building energy benchmarking [77].

6.2. Energy, Carbon, and Resilience Trade-Offs under a Changing Climate

The emerging trend in indoor environmental engineering is to work within the context of decarbonization needs, being compatible with the improvement. Ventilation, dehumidification, and filtration will introduce energy costs that depend on climate, system design, and operational plan. An increase in outdoor air rates may flip heating and cooling loads, and an increase in the efficiency of filters may cause an increase in fan energy due to the additional pressure drop unless systems are designed and tuned to accommodate it. The carbon effects of these energy expenses are determined by the mix in the electricity grid, when energy is used, and the availability of onsite generation or storage. This has inspired concern over approaches that can separate clean air delivery and outdoor air volume, which could comprise optimization of recirculation with a highly effective filtration system, in-room air cleaning, and source control methods to reduce the initial generation of contaminants [78].

Climate change also resets the objectives of indoor environmental concerns to resilience and episodic extremes as opposed to the average [79]. Heat waves, smoke clouds of wildfires, and serious storms can lead to conditions when the traditional operating assumptions do not hold. The introduction of outdoor air to the indoor environment without sufficient filtration may exacerbate the indoor exposures during the smoke events, and sealing buildings may result in thermal stress when the cooling capacity is insufficient. Both mechanical ventilation and filtration can be turned off by power outages, increasing thermal hazard as well as pollutant and concentration. These facts imply that the resilience metrics and emergency operating modes should also be considered in indoor environmental engineering in the future, alongside the plans of sustaining safe temperatures and acceptable air conditions during disruptions. The need to design resilience must also consider the vulnerability of the population because individuals who have less access to cooling or filtration, or who maintain well-maintained buildings, face a disproportionate amount of risk during extreme events.

6.3. Standards and Guidelines: Strengths, Limitations, and Evolving Priorities

The current standards and guidelines offer necessary baselines on ventilation, thermal comfort, lighting, and acoustics, but they were mostly developed within the normal operating conditions and usually taught on prescriptive requirements [80,81]. Although prescriptive methods are useful in terms of enforceability and minimum safety, they might not be effective in the context of changing evidence fast and varying contexts. In the case of air quality, standards in ventilation were based on standards traditionally concerned with odor containment and a general notion of acceptability, and several systems were developed on the belief that outside air is a homogenous, freely available resource. Extremes of outdoor pollution and occasional smoke issues challenge that assumption, establishing a requirement for more of an outdoor air quality fitness, filtration effectiveness, and adaptive performance.

An increasing awareness has also led to the improvement of indoor environmental standards to reflect more on health-based outcomes instead of being driven by comfort or acceptability proxies. The translation of health evidence into practicable building needs is not an easy task, since health hazards depend on mixtures of pollutants, time of exposure, vulnerable populations, and since building standards are enforced in a variety of buildings and with a range of economic limitations. The trend is, however, in the direction of hybrid schemes where prescriptive minimums are maintained, but performance-based routes are allowed, where compliance can be shown in terms of measured results, such as contaminant levels, ventilation delivery testing, or some other clean air measure. Another related priority is the harmonization between domains, since progress on one IEQ dimension can derail another dimension when standards are implemented individually. The development of standards is thus becoming more cross-disciplinary, including building science, exposure assessment, epidemiology, and control engineering [82].

6.4. Measurement, Verification, and the Challenge of Actionable Metrics

The capacity to control the indoor environmental quality is based on quality measurement and interpretation [22]. But the heterogeneity of space, intermittent sources, and the limitations of sensors render the monitoring of indoor areas difficult. Often, the monitoring in many buildings is sparse, and where sensors are available, it is common to have problems with data quality, like drift, cross-sensitivity, and uneven placement that may invalidate inference. The proliferation of sensors at relatively low prices has widened the monitoring capacity, though it has also created the danger of misinterpretation in cases where proxy signals are used as definitive measurements of the pollutant or in cases where short-run measurements are over-weighted without the information that the answer should be provided with.

The main area of research and practice is the design of practical metrics that can be used to relate engineering activities to useful outcomes [83]. On ventilation, to translate the CO_2 measurements into the ventilation rate, assumptions regarding occupancy, rates of emissions, and mixing need not necessarily apply in the actual space. Operationally based performance metrics are most appropriate as they are used to measure performance with respect to filtration and air cleaning because they feature clean air delivered and not nominal device ratings. In integrated IEQ, composite indices may be desirable but dangerous unless they are built in a transparent way. The domain thus requires methods of verification that are both interpretively and practically sound, such as standardized protocols of measurement, minimum data quality standards, and conventions of reporting that allow studies to be comparable and interventions to have audits.

6.5. Implementation Barriers and Enabling Conditions in Real Buildings

Interventions that are well supported may not scale at all unless the realities of implementation are considered. Cost is one of the biggest obstacles, especially where the upgrade involves replacement of equipment, ductal adjustments, or continuous consumables like filters [9]. Split incentives between building owners and occupants may decrease the incentive to invest in the improvement of the IEQ, whose benefits go to the tenants. Commissioning, continuous monitoring, and proactive maintenance are often hampered by staffing and expertise issues, particularly in public buildings and smaller organizations. Also, procurement procedures can focus on the initial cost, instead of the lifecycle performance, resulting in underpowered fans, unsuitable filtration, and control systems, which are hard to use and maintain.

Enabling conditions are having clearer performance targets, a simple playbook of operations, and inclusion of IEQ into the daily running of the facilities [10]. Sustained use may also be enhanced with the help of transparent communication; occupants tend to accept minor inconveniences like more noise generated by the fans, in case they are aware of the health reason behind the intervention, and as long as the intervention is supported by visible performance feedback. Systematically, implementation is also better in providing interventions as integrated solutions as opposed to individual components, such as the use of a filtration upgrade with assessment of fans or commissioning of a system and a maintenance plan, or portable air cleaners with advice as to sizing, location, and acceptable operating conditions. **Table 4** summarizes the major barriers to successful implementation along with the related research and practice needs. Based on the difficulties mentioned above, **Figure 3** outlines an implementation and research roadmap.

Table 4. Important implementation challenges in indoor environmental engineering, their consequences for performance and equity, and corresponding research or practice priorities.

Challenge Category	Description	Consequence	Priority Research or Practice Needed
Performance gap	Design intent not realized in operation	Reduced IEQ benefits	Commissioning and verification protocols
Measurement uncertainty	Sensor drift and proxy limitations	Misleading control decisions	Standardized calibration and QA/QC
Energy–IEQ trade-offs	Increased energy use for air quality	Carbon penalties	Carbon-aware IEQ optimization
Technology acceptance	Noise, drafts, complexity	User disengagement	Human-centered design
Equity constraints	Cost and maintenance barriers	Unequal benefits	Low-cost, low-burden interventions
Climate extremes	Smoke events, heat waves	System failure risk	Resilient IEQ design strategies

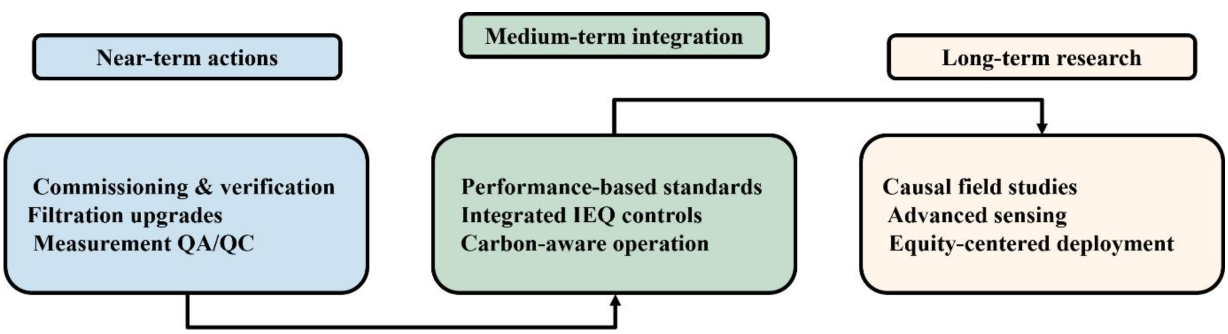

Figure 3. Roadmap for implementing and advancing indoor environmental engineering, illustrating near-term actions, medium-term system integration, and long-term research priorities.

6.6. Digitalization Risks: Privacy, Cybersecurity, and Governance of "Healthy Smart Buildings"

The shift to sensor-intensive, data-driven building operation presents a governance risk that needs to be dealt with as a subset of indoor environmental engineering [84]. The use of occupancy inference based on CO_2 sensors, motion sensors, Wi-Fi signals, or access control data can result in better control performance but introduces privacy issues and could necessitate open policy statements, data minimization, and well-defined limits on usage. The creation of automation systems linked to networks also increases the attack surface of cybersecurity, and potential consequences may not just be in the data integrity but also in physical security in case ventilation or thermal control is impacted. Such issues may delay the implementation of smart IEQ solutions where stakeholders distrust the solutions or regulatory frameworks are not clear.

Governance is also important for scientific credibility and operational accountability. The controlling algorithms of the ventilators or air purifiers should be understandable to the facility staff to be able to detect a failure, so that occupants can be certain that the choices are made based on the health and comfort values and not on the energy-saving principles. The data management practices must facilitate reproducibility of research and sustainability of operation, including recording sensor specifications, calibration records, control logic modifications, and maintenance procedures. These risks are not independent of IEQ improvement: they belong to the group of making sure that digital tools are the source of long-term benefit and not the source of complexity and failure modes [8].

6.7. Priority Research Needs: Toward Causal, Scalable, and Equitable IEQ Improvement

Future studies should enhance the causal inferences between indoor environmental interventions and well-being, as well as enhance extrapolation as a scaled practice [85]. One thing that is highly required is stronger field studies, which integrate quality exposure characterization with clear interventions and valuable outcomes. Some of the designs that can help isolate effects and represent real operation constraints include quasi-experimental designs, natural experiments, and intervention trials in schools, multi-family housing, and workplaces. Longer period studies are especially needed in moisture control, material emissions, and long-term outcomes, where short campaigns can overlook seasonal variations and system drift over time.

The subject would be methodologically improved with consistent reporting standards that would detail building context, system configuration, sensor placement, maintenance conditions, and uncertainty bounds in a manner that allows the synthesis of cross-studies. More open datasets, in the case of privacy, may boost model creation and control strategy benchmarking. On the technology edge, advancement in technology on the side requires research to enhance dependable measurements of gaseous pollutants, and to design methods of verification of enhanced air cleaning technologies, taking into account not only their effectiveness, but also their byproduct hazards. Carbon-aware control and resilience goals should be integrated into the research of optimization, and the ways to ensure safe indoor conditions in case of smoke, heat waves, and outages should be stated [86].

Equity must be considered as a core research and policy goal and not a kind of fringe consideration [9]. Research involving under-resourced structures and a wide range of populations can highlight obstacles that remain unknown in demonstration projects with sufficient funding. Studies on the low-cost, low-maintenance interventions and financing and procurement models that would help maintain performance are necessary to ensure that IEQ interventions do not support but reduce the already existing health disparities. It will be technically innovative or not, but also a matter of whether it can provide long-lasting, provable, and fair benefits to human welfare in the entire range of buildings where people live, educate, work, and rest.

To address the concerns regarding the dispersed nature of future research priorities across Section 6, we present a consolidated summary table that organizes each key research gap by its associated challenge area and offers concrete methodological or policy pathways. **Table 5** is intended to serve as a practical reference for researchers, funding bodies, and practitioners seeking to prioritize efforts that close critical evidence gaps and advance equitable, resilient indoor environmental engineering.

Table 5. Summary of Future Research Priorities, Challenges, and Methodological Approaches for Indoor Environmental Quality.

Research Priority	Key Challenge Area	Suggested Methodological/Policy Approaches
Causal inference linking interventions to well-being outcomes	Evidence strength, confounding	Quasi-experimental designs, natural experiments, intervention trials in real-world settings (schools, multi-family housing, workplaces)
Long-term field studies capturing seasonal variability and system drift	Performance gap, temporal dynamics	Multi-season monitoring campaigns, longitudinal exposure characterization, and maintenance tracking
Standardized measurement and reporting protocols	Heterogeneous methods, comparability	Consensus reporting standards (building context, sensor placement, uncertainty bounds), open data repositories (privacy-preserving)
Low-cost sensor calibration and quality assurance	Measurement uncertainty, data quality	Field co-location protocols, algorithmic drift correction, sensor fusion techniques, and minimum data quality standards
Reliable gaseous pollutant monitoring and air cleaning byproduct assessment	VOC control, secondary pollutants	Third-party testing frameworks, byproduct hazard evaluation, and standardized clean air delivery metrics for gas-phase removal
Carbon-aware IEQ optimization under decarbonization constraints	Energy–IEQ trade-offs	Model predictive control with carbon signals, decoupled clean air delivery strategies, and renewable integration
Resilient design for extreme events (heat waves, wildfire smoke, power outages)	Climate adaptation, system failure	Emergency operating modes, passive survivability metrics, low-energy filtration, backup power strategies
Equity-focused interventions in under-resourced buildings	Disparities in access, maintenance burden	Low-cost, low-maintenance solutions; alternative financing models; community-engaged research; policy support programs
Human-centered design addressing noise, drafts, and acceptability	Technology acceptance, behavioral response	User interface research, participatory design, communication strategies linking interventions to health benefits

7. Conclusions

There is a high shift rate in the field of indoor environmental engineering, where the field has ceased to be about meeting minimum compliance requirements and comfortable acceptability to become one that is more and more measured by performance, resiliency, and human well-being. Recent progress in ventilation and air distribution, efficient filtration and air cleaning, source control with materials and appliance selections, and sensor-controlled controls has increased the toolset of managing indoor exposures and enhancing the overall indoor environmental quality. Together, these trends support a significant change in practice: healthy indoor environments are hardly a one-technology issue, but instead, a systems issue where reduction in exposures relies on design, checking, and maintenance.

One of the key findings of the literature is that the improvements are most reliable when various links in the chain of sources to outcomes are targeted by interventions. Upstream controls that decrease emissions at the source can mitigate the stress on ventilation and cleaning systems, whereas strong removal measures, when possible, due to conditions, outdoor air exchange, recirculated filtration, and well-located in-room cleaning can decrease the chronic levels of pollutants as well as event peaks. Increased use of sensing and data-driven control provides an opportunity to sustain performance in actual variability of occupancy and outdoor conditions, and to implement interventions where there is a high level of risk. These advantages, however, are conditional on the quality of measurements, the transparency of the logic of the control, on encouraging commissioning, and the operation of maintenance to avoid drift.

Another point of the review is that the aspect of indoor environmental quality should be considered an interdisciplinary goal in terms of air quality, thermal comfort, humidity, lighting, and acoustics. One domain of intervention can disadvantageously affect another, and the acceptability constraints, especially noise, drafts, and glare, can be the defining factor of an intervention being active and effective. Multi-domain integration is thus no longer a choice; it is a part or aspect of an eventual well-being outcome. The evidence base indicates a rational advantage to respiratory well-being, reduction of symptoms, and control of risks in shared-air circumstances when the control of particles and clean-air delivery is enhanced, whereas new literature indicates an improvement in cognitive performance, sleep quality, and overall well-being due to enhanced indoor conditions. Meanwhile, just in case it is not known, exposures are ill-posed, there are combinations of pollutants and indoor chemistry relying on context, and results are remote or confounded.

In the future, the field will be based on the ability to bridge the divide between laboratory or design efficacy and building-scale efficacy. Measures of performance that represent the supplied clean air and confirmed ventilation, standardized measures of measurement, and operationally realistic field studies are critical to creating evidence that is able to inform codes, standards, and purchasing. Simultaneously, decarbonization and climate adaptation need to be met with a complex of strategies that co-optimize the indoor environmental quality in relation to energy and carbon limits and enhance resilience during extreme heating, smoke excursions, and disruptions. Lastly, equity has to be considered as one of the markers of achievement: unless there are proper policies, funding structures, and low-stress interventions, the fruits of high-level indoor environmental engineering will continue to be unevenly distributed.

To conclude, innovations in indoor environmental engineering have provided a plausible route to the healthier, more resilient, low-carbon compatible indoor environment. To capitalize on this possibility, integrated intervention portfolios, a practice that is focused on verification, and governance that facilitates the reliable operation, transparency, and equitable access are needed. With engineering innovation coupled with exposure science and human-centered outcomes, the next level of indoor environmental engineering may no longer acceptable indoor environment, but a proactive, protective, and promoting indoor environment.

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The author declares no conflict of interest.

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