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Perspective

Need for a Holistic Approach to Assessing Sustainable, Green, and Healthy Buildings

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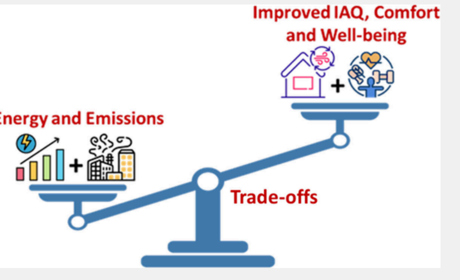
ABSTRACT: With the rising global population, economic development, and urbanization, building stock is bound to grow, warranting measures for optimizing their embodied and operational energy and resource consumption. Further, a building's indoor environment quality significantly affects occupants' health, productivity, and well-being since people spend almost 90% of their time indoors. Buildings safeguard occupant's well-being by shielding them from the outdoor air pollution and increasing climate extremes. However, buildings can also lead to acute and chronic exposure to pollutants trapped inside. The recent pandemic has demonstrated that indoor environments can prevent and promote airborne disease transmission depending on buildings' design and operation. The current segregated rating systems and regulations to gauge buildings' sustainability, health and safety, and energy efficiency have led to a fragmented approach hampering sustainable and healthy buildings' design, construction, and operations. This work discusses the environmental sustainability of buildings, their impacts on occupants' health and productivity, and if and how the existing global policies and frameworks regulate and promote the same. Developing a holistic and comprehensive framework is critical to ensure buildings' sustainability, occupants' health, and energy efficiency.



KEYWORDS: *sustainable and healthy buildings, building codes, energy-exposure trade-offs, health and well-being, green building rating systems*

1. INTRODUCTION

As more of the world transitions from being developing to developed, it is increasingly important for researchers and policymakers to focus on buildings, which can either protect or harm public health and the environment, depending on their design and operation. Built environments comprising buildings are critical for societal and economic development[1] and, therefore, often used as a proxy for a nation's growth. While comprehensive regulations and codes govern the planning and construction of buildings, minimal attention has been given to indoor air quality and the risk of infectious diseases and their interplay with building design and operation. This oversight has grave implications for public health, considering people now spend most of their time in indoor spaces,[2,3] potentially leading to indoor exposure to airborne pollutants and pathogens dominating that occurs outdoors. Apart from occupants' health, buildings severely impact the environment. Building construction is highly resource intensive, and embodied and operational energy accounts for a significant, if not the major, fraction of global energy consumption and, therefore, contributes to climate change.[4,5]

Building performance in terms of environmental impacts, energy efficiency, and occupants' thermal comfort has been guiding building design, construction, and operation. However, various stakeholders are yet to recognize or acknowledge that exposure to airborne pollutants and pathogens must be accounted for to ensure occupants' well-being. Although the sources and impacts of indoor air pollutants (IAPs) or household air pollutants (HAPs) have been researched intensively, the practical implications of such studies on building design and operation are limited.[6] The outbreak of the COVID-19 pandemic brought the focus to the risk of infectious disease transmission in indoor environments. Multiple superspreading events observed and studied during the pandemic demonstrated a much higher risk of spreading airborne pathogens indoors than outdoors. Indoor environments can lead to acute and chronic exposure to pathogens as airborne pathogens get trapped in a finite volume. Studies on transport and the fate of airborne pathogens in indoor environments suggested controlling occupancy,[7,8] ventilation modifications,[9−12] high-efficiency filters and air purifiers,[12−14] and UV air disinfection[15−17] to reduce infection risk. Adopting various control and mitigation measures for airborne pollutants

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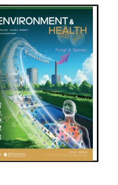

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and pathogens has financial implications. These measures require new or modified systems, potentially with higher energy consumption posing an energy-health trade-off.

The trade-off between a building's energy consumption and thermal comfort is well understood.[18−20] However, including human health adds another layer of complexity requiring optimization between energy, exposure to pollutants and pathogens, and thermal comfort of the occupants.[18,21] The trade-off between energy and well-being has been marginalized by stakeholders such as policymakers, regulators, and rating agencies. A recent study on green and clean buildings argued that technological advances and engineered solutions should be incorporated to modify building design and optimize indoor environment quality (IEQ) and energy use.[22] The buildings of the future need to be designed, constructed, and operated to maximize occupants' well-being while minimizing the associated financial and environmental impacts. Limited research has demonstrated that the gains achieved through improved productivity and reduced sicknesses due to improved indoor air quality might outweigh the costs incurred for energy penalties and system modifications.[3] This work discusses the impact of buildings on human health and the environment and how stakeholders can change the status quo.

2. BUILDINGS AND CLIMATE CHANGE

The building and construction sector, an economic growth and development indicator, accounted for 13% of global GDP in 2020. With rapid urbanization, the demand for buildings will increase, and the construction sector is anticipated to grow at an annual average higher than the manufacturing or services sector.[23] By 2030, the revenue generation from this sector is expected to double while remaining the leading sector of the global economy.[23] This rapid growth is accompanied by considerable resource consumption, depleting natural reserves and causing significant environmental impacts. Thus, optimal and judicious usage of resources and energy in building construction and operation is critical for environmental sustainability. Currently, the building and construction sector consumes ∼40% of forest timber, ∼16% of the world's freshwater, and 40% of all raw materials,[24,25] which is bound to increase as the demand for buildings rises. Regarding environmental impacts, the construction sector contributes to ∼23% of air pollution, ∼40% of drinking water pollution, and ∼50% of landfill waste[26] without accounting for the contributions from building operations.

Furthermore, building construction and operation consumes ∼34% of global energy, accounting for ∼37% of global energy and process-related carbon emissions.[27] Between 1990 and 2019, global CO_2 emissions from buildings increased by 50%.[28] In this period, population growth, increasing floor area per capita, and increasing carbon intensity of the global energy mix were the leading contributors, accounting for 28%, 52%, and 16% of the global CO_2 emission from buildings, respectively.[28] Additionally, the operational energy use in buildings has been increasing at an average of 1% annually over the past decade.[29] However, an increase of 4% in building energy demand in just two years (2020−22), the largest increase in the past decade, is attributed to the enhanced reliance on natural gas for building operations in emerging economies. This elevated energy demand caused the carbon emissions associated with building operations to reach an all-time high of 10 $GtCO_2$.[27] The energy intensity of buildings, i.e., the total final energy consumption per square meter, has remained constant for the past few years, indicating that the building performance has mostly stayed the same. By 2050, building energy consumption will rise considerably, and research demonstrates decreasing annual heating loads and increasing annual cooling loads owing to climate change,[30] resulting in more energy and carbon-intensive buildings, further exacerbating climate change. This demonstrates a causal loop where building construction and operation, while essential for economic and social development, add to climate change, which in turn governs building design and operation. Besides buildings' operation and resiliency, climate change-induced disturbances and extreme weather events affect occupants' health and well-being. Researchers have associated various climate change parameters with different health impacts, such as infectious disease transmission, mortality, respiratory and cardiovascular ailments, neurological and mental health, and many more. For example, meteorological parameters such as temperature, humidity, and precipitation have been linked with the transmission of vector-borne infectious diseases,[31,32] all-cause and specific-cause mortality,[33−35] and respiratory and cardiovascular ailments.[36] Rocque et al.[37] summarized the research on the health impacts of climate change and established that climate change deteriorates human health. Though the association between climate change and the resultant degree of health deterioration need more research, it can be ascertained that they have detrimental effects on human health, necessitating shielding occupants from ambient conditions and making buildings even more critical. Additionally, the exposure of buildings to climate change-induced disturbances, extreme events, damage, and disruptions will also increase.[38] Therefore, the interaction of buildings with the environment and resiliency factors, such as economic, social, and environmental, should also be analyzed and accounted for.

3. INDOOR ENVIRONMENT AND OCCUPANT HEALTH

People spend almost 90% of their time indoors. Therefore, indoor environment quality is critical for occupants' well-being and productivity. Researchers have proposed nine foundations of a healthy building: ventilation, indoor air quality (IAQ), thermal health, water quality, dust and pests, lighting and views, noise, moisture, and safety and security.[39] Although all these elements must be considered for a holistic approach to ensure human well-being and productivity, ventilation, IAQ, and thermal health are the three interdependent factors that have severe implications for occupants' health and buildings' carbon footprint. The interplay between IAQ, thermal health, and ventilation governs the energy-exposure trade-off.[18] Since it is reported that cumulative exposure to airborne pollutants that occurred indoors is comparable to or exceeds outdoors,[40−43] the discussion here primarily focuses on IAQ and its impact on humans.

IAQ is governed by particulate and gaseous pollutants of both indoor origins (from indoor emissions sources) and outdoor origin (from infiltration). Major indoor sources of pollutants include fuel-burning appliances, smoking, cleaning, cooking, building materials, and furnishings.[44] Infiltration of outdoor pollutants depends on the outdoor-indoor air exchange rates. The physicochemical properties of the pollutants govern their transport, transformation, and fate in indoor environments, along with their health impacts. For example, particulate pollutants, termed particulate matter (PM), have varying impacts on human health depending on their size,[45,46] surface area,[47,48] and chemical composition.[49,50] PM exposure is associated with various health burdens, such as reduced lung function capacity, acute respiratory infections, COPD, asthma, and neurodegenerative diseases.[48,51−54] Recent studies on house observations of microbial and environmental chemistry (HOMEChem) study investigated the impact of everyday activities on the emissions, chemical transformations, and removal of trace gases and particles in indoor air.[55] The study reported cooking as a large source of VOCs, CO_2, NO_x, and particles. The cooking particles were predominantly in the ultrafine mode, and organic aerosol dominated the submicron mass. A subsequent HOMEChem study found significantly higher respiratory deposition masses for daily activities (∼5x and ∼2x more than outdoors during high-emission activities and regular activities, respectively).[56] The same study also found that the particles deposited in the head airways dominated (∼75%) total mass deposited except for the high emission activities when the fraction deposited in the alveolar region (∼50%) was higher than in the head airways (∼39%), owing to the prevalence of ultrafine particles in the total mass. Also, exposure to gaseous pollutants such as NO_x in residences has been associated with an increased risk of pediatric asthma, and early life NO_x exposure has also been associated with decreased cognitive function and inattention symptoms.[57,58] Cognitive impairment has also been attributed to high CO_2 concentrations in indoor spaces.[59−61] Additionally, indoor air pollutants and satisfaction with IAQ have been associated with the prevalence of sick building syndrome (SBS) and occupants' productivity.[62−68] Recent cross-sectional studies in multiple countries have linked the prevalence of SBS among residential building occupants with indoor PM concentration, building characteristics, cleaning frequency, and ventilation.[62−65]

Besides pollutant exposure, indoor spaces are major hotspots for airborne disease transmission. Researchers have been studying the indoor transmission of airborne diseases and various strategies to limit the infection risk.[69−71] However, the recently recorded superspreading events of COVID-19 in indoor spaces[72−74] gave renewed impetus to the research on sources, transport, and the fate of bioaerosols in the indoor environment. These studies are laying the ground for including such biohazards in building design and operation strategies. Recent studies have suggested high air filtration efficiency and intermeeting break times for offices,[75] improved ventilation rates, controlled air recirculation, and reduced number of people in an enclosed space to prevent airborne disease transmission.[76] However, increased ventilation rates increase energy consumption associated with HVAC operation.[77,78] A computational study conducted for 13 cities in the USA representing a range of ambient climate conditions demonstrated that the airborne infection risk is reduced by supplying 100% outdoor air, which also led to an average 45% increase in energy consumption.[78] The same study demonstrated that filtration could result in 31% lower energy consumption while also lowering the infection probability by 29% relative to the 100% outdoor air ventilation case. Although improving filtration has some associated energy penalties, it is significantly lower than supplying 100% outdoor air. Therefore, filtration and ventilation can be conjugated to reduce exposure to airborne pathogens and pollutants in indoor environments while minimizing associated energy penalties. Another study proposed a dynamic optimization strategy for indoor PM control while ensuring the thermal comfort of the occupants.[18] The study reported varying degrees of exposure reduction and energy penalty depending on the importance assigned during their optimization, thus highlighting the inherent trade-off. The same study also demonstrated diminishing marginal returns in terms of exposure reduction for every unit of additional energy consumption and defined normalized exposure reduction (percentage exposure reduction normalized by the percentage increase in energy consumption) to quantify and compare the trade-off in different scenarios.[18] However, as elaborated in the next section, such exposure-energy trade-offs are yet to be recognized and accounted for in the current building standards and rating protocols.

4. CURRENT ASSESSMENT SCHEMES FOR BUILDING SUSTAINABILITY AND OCCUPANTS' WELL-BEING

Mandatory building structure codes and regulations for construction practices have been developed and enforced worldwide as they directly affect safety. However, there are no such regulations to assess the sustainability of buildings. Multiple nonmandatory frameworks, commonly termed Green Building Rating Schemes (GBRS), have been developed globally, such as LEED (Leadership in Energy and Environmental Design) in the USA, BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, CASBEE (Comprehensive Assessment System for Built Environment Efficiency) in Japan, 3-Star system in China, and GRIHA (Green Rating for Integrated Habitat Assessment) and IGBC (Indian Green Building Council) rating system in India. These GBRSs are based on multicriteria assessment of environmentally, socially, and economically sustainable practices in building design, construction, and operation. Each GBRS has different assessment categories and weightage allocations.[25,79] The most common assessment criteria in GBRSs are comfort, energy, environmental awareness, materials, natural resources, climate change, waste, and water. Gonzalo et al. analyzed the eight most popular GBRSs from different countries and reported the average weightages for different criteria - comfort and well-being (28.5%), natural resources and climate change (27.9%), energy (12.3%), materials (10.9%), water (8.5%), waste (6.9%), and environmental awareness (5%).[80] Although comfort and well-being are allocated the maximum weightage, it is critical to understand their constituent factors. Most GBRSs measure comfort and well-being based on indoor environment quality (IEQ), proximity to transport facilities, privacy, efficient usage of space and accessibility, noise, and lighting.[80] Within the IEQ category, GBRSs usually assign minimal weightage to IAQ, and airborne pathogen transmission is not even considered apart from indirectly governed by ventilation. On average, the weightage of IAQ in these rating schemes is 7.5%, and volatile organic compounds (VOCs), CO_2, and formaldehyde are the commonly considered indoor pollutants.[81] VOCs and formaldehyde are allocated a certain weightage, requiring the use of low-VOC products such as paints and furnishing materials. However, continuous monitoring and measures to reduce indoor concentrations usually fall beyond the scope of GBRSs. Furthermore, most IAQ-based evaluations in the current GBRSs are performed during preoccupancy. Therefore, critical emission sources introduced postoccupancy during the operational phase of the buildings, and their impacts on IAQ are not considered. Moreover, the health implications and well-being in the indoor environment go well beyond these few pollutants. Globally, some organizations have recommended

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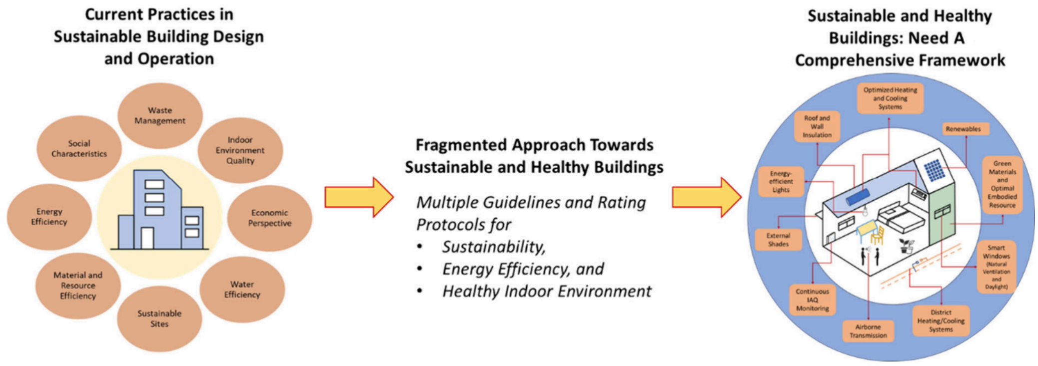

Figure 1. Currently fragmented building rating protocols, highlighting the need for comprehensive framework for building assessment to ensure health and sustainability.

IAQ and ventilation requirements in buildings, such as ASHRAE 62.1 (Ventilation and Acceptable Indoor Air Quality), ASHRAE 62.2 (Ventilation and Acceptable Indoor Air Quality in Residential Buildings), and WHO indoor air quality guidelines. However, these are guidelines, not regulations; thus, they are not mandatory. A recent study by more than 40 scientists advocated for mandatory indoor air quality guidelines for public buildings and recommended concentrations of $PM_{2.5}$, CO_2, CO, and ventilation rates while arguing that if some countries lead by example, IAQ standards will become normalized.[82]

The energy-IAQ trade-offs, lack of standardization of IAQ-related metrics, and missing focus on airborne disease transmission in GBRSs reflect their lack of comprehensiveness, especially regarding health and well-being. Currently, GBRSs focus primarily on environmental aspects, with an average of more than 68% weightage assigned to indicators related to environmental sustainability.[80] Additionally, of all the stages in a building's life, more than 58% weightage is allocated to the building design stage. The use stage of a building only accounts for about 30% of weightage, while the environmental, social, and health impacts outweigh that during the design stage.[80] Besides GBRSs and IAQ guidelines, some countries have formulated building energy codes to improve energy efficiency and reduce carbon emissions.[83] Compliance with these codes varies among countries; some countries, such as Australia, Germany, France, and Spain, have made them mandatory for residential as well as commercial buildings. These codes are not enforced nationally in other countries, including India, China, and the USA. Existing IAQ guidelines, GBRSs, and energy codes target well-being, sustainability, and energy, usually focusing on only one with little consideration for other aspects. This fragmentation must be addressed as well-being, sustainability, and energy usually pose trade-offs.

Considering that the building and construction sector is among the largest contributors to global emissions, holistic frameworks for benchmarking and assessing building performance, resource utilization, and energy efficiency while safeguarding occupants' health are imperative. Considerable research is being done on nearly zero and net-zero energy buildings.[84−88] However, such studies fail to incorporate how interventions that make building low or net-zero energy affect the health and well-being of its occupants. An interim step toward making buildings net-zero or nearly zero energy is creating benchmarks and performance standards for existing buildings. Recent studies have demonstrated that ensuring thermal comfort while reducing exposure comes at an energy penalty.[18,89,90] Thus, the trade-off must be accounted for in energy benchmarking scenarios. Developing building codes and standards that account for embodied and operational consumption along with energy-exposure-comfort trade-off will ensure the integration of the life cycle approach. Apart from codes and standards, technical and scientific interventions such as onsite renewable energy generation, intelligent control algorithms (predictive control, artificial intelligence, and others) to optimize ventilation and energy-exposure trade-offs, energy-efficient and acoustic lights, and appliance scheduling could be crucial to promoting net-zero buildings. The control algorithms, such as model predictive control and reinforcement learning, could be designed to control multiple comfort and health parameters for adaptive and occupancy-based air conditioning operations, dynamic set temperature of the HVAC system, and variable indoor-outdoor air exchange. Ultimately, there is a need to take a step further in the design and operation of the buildings of the future that are low or net-zero energy while also promoting health and well-being by shielding occupants from airborne pollutants and pathogens. Figure 1 summarizes the current practices for assessment of building sustainability, existing fragmentation, and the need for a comprehensive framework for sustainable and healthy buildings.

5. CONCLUSION

This work discusses and identifies the gaps in the current approach for environmentally sustainable buildings that also ensure the health and well-being of its occupants. The building and construction sector abides by different mandatory regulations and codes, such as structural integrity and fire safety. However, compliance with the regulations and guidelines on aspects such as energy, comfort, and well-being vary by country, with limited focus on factors such as indoor air quality and transmission of airborne diseases. GBRSs, the most popular for building certifications, primarily measure the environmental sustainability of buildings. A diverse set of codes, guidelines, and certification schemes has led to a fragmented approach toward designing, constructing, and operating sustainable and healthy buildings.

The quantifiable metrics, such as energy and carbon footprints of building construction and operation, are critical and adequately considered, as evident by the dominance of these metrics in GBRSs and other building codes. However, critical but challenging to quantify metrics, such as buildings' impact on occupants' health, well-being, and productivity, must be integrated into GBRSs and building codes for sustainable and healthy buildings. GBRSs and building codes accounting for the currently overlooked trade-off between IAQ, energy, comfort, and well-being are imperative to incentivize the transition from green buildings to green and healthy buildings. Filling these gaps will require rethinking how we design, operate, and assess buildings using existing and yet-to-be-developed technology, policies, and regulations. Buildings of the future ensuring occupant health, comfort, and well-being, along with lower energy and carbon footprint, will require affordable real-time monitoring systems, intelligent control algorithms, advanced air purification techniques, and sustainable building materials.

The advances in low-cost sensors (LCSs) for measuring pollutants and comfort parameters such as temperature, relative humidity, illuminance, and acoustic comfort are critical for real-time monitoring of indoor environment quality as the first step toward safeguarding the health and well-being of building occupants. The real-time measurements from sensors can be fed to different control algorithms for real-time control of HVAC systems to optimize energy, exposure, and comfort. Furthermore, continuous monitoring can also be utilized for early warning systems in case of hazards. Integrating LCSs in buildings could provide crucial information on various emission activities, exposure scenarios, occupancy levels, and comfort conditions that could help take corrective measures to improve indoor environment quality while also minimizing the associated carbon footprint. However, the reliability and accuracy of LCSs for pollutant monitoring remain challenging. LCSs need more robust calibration and testing under different climatic and operating conditions to ensure reliability. For example, low-cost PM sensors, operating on the principle of light scattering, have demonstrated higher accuracy in sensing ultrafine particles in a size range of less than 1 μm. In contrast, these sensors perform poorly for coarse and fine particles (PM_{10} and $PM_{2.5}$).[91,92] In summary, LCSs will undoubtedly play a significant role in ensuring occupants' health, but the field still needs more research. Apart from sensing, mitigation and control of indoor pollutants and pathogens are critical to improving IAQ, lowering contamination probability, and improving occupants' health. The advent of artificial intelligence and its capability could be a key to learning the dynamics of varying indoor environments for building operations and intelligent control. Researchers have proposed various control algorithms, such as model predictive control,[93] dynamic optimization,[18] and reinforcement learning,[94,95] that have shown great potential to learn the dynamics of the indoor environment and for varied applications ranging from controlling HVAC systems to creating decision support systems.

Furthermore, a benchmarking framework must be developed for building energy consumption and performance encompassing occupants' health and well-being metrics. Such benchmarks should account for geographical variations in resource availability, their carbon intensity, and perceived comfort conditions. Ultimately, policymakers and governments must recognize the existing gaps, and multidisciplinary stakeholders must collaborate to develop comprehensive frameworks for the building of the future. Finally, the goal should be securing equity in a healthy and comfortable environment for occupants while minimizing its impact on the environment.

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Notes

The authors declare no competing financial interest.

Biography

Sameer Patel is an Assistant Professor jointly appointed in the Department of Chemical Engineering and Civil Engineering at the Indian Institute of Technology (IIT) Gandhinagar, India. His research focuses on the nexus of energy, environment, and exposure in built environments, encompassing multidisciplinary work on low-cost instrumentation, aerosols, air quality, renewable energy integration, solutions for optimizing indoor air quality and energy consumption, and development of comprehensive frameworks for building assessment and certification. He received his Ph.D. from Washington University in Saint Louis and then conducted postdoctoral research at the University of Colorado Boulder before joining IIT Gandhinagar.

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ABBREVIATIONS

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

BREEAM Building Research Establishment Environmental Assessment Method

CASBEE	Comprehensive Assessment System for Built Environment Efficiency
COPD	Chronic Obstructive Pulmonary Disease
COVID	Coronavirus Disease
GBRS	Green Building Rating Scheme
GDP	Gross Domestic Product
GRIHA	Green Rating for Integrated Habitat Assessment
$GtCO_2$	Gigatonnes Carbon Dioxide
HAP	Household Air Pollutant
HVAC	Heating, Ventilation, and Air Conditioning
IAP	Indoor Air Pollutant
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
IGBC	Indian Green Building Council
LEED	Leadership in Energy and Environmental Design
PM	Particulate Matter
UV	Ultraviolet
VOC	Volatile Organic Compounds

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