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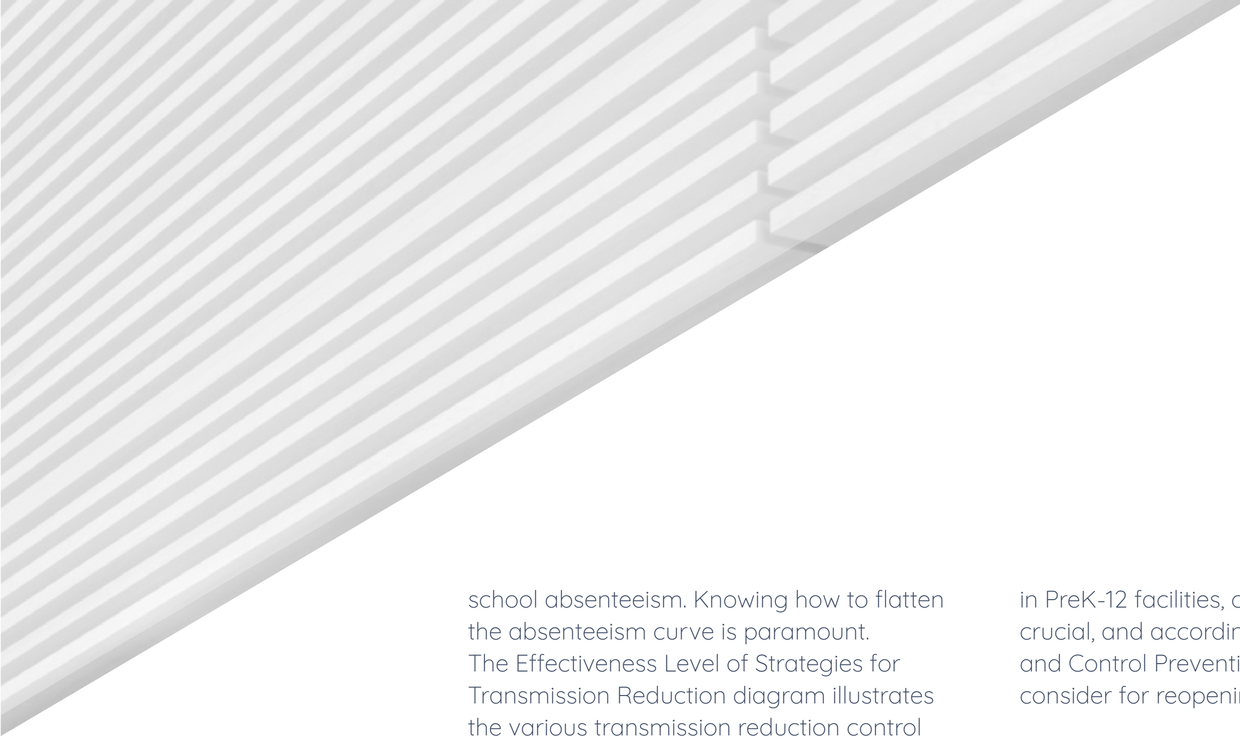
Rethinking Classroom Air Quality: COVID-19 Challenges and Opportunities

Scientists, researchers, and design professionals agree — buildings can be designed to reduce transmission of disease but also to bring back normalcy to everyday life. We reviewed the latest healthy school building research that places an unprecedented urgency on PreK-12 school planning and regulations during and beyond the COVID-19 pandemic. We assembled perspectives for overcoming the challenges associated with pandemics, building health and performance, and more important to reduce the common pathogens from spreading and reduce chronic absenteeism that affects as many as 6.5 million students nationwide.

This is not the first time in history that human health and well-being has dramatically redefined urban planning and building design. In the middle of the nineteenth century, the built environment was directly associated with the growing number of diseases and epidemics, leading to modifications of housing and urban regulations.[1] The Spanish flu pandemic in the early twentieth century resulted in the emergence of “garden cities” and introduced the needed fresh air into the cities.[2] Incorporating daylight, views and natural ventilation were recognized as improving health and well-being. Building construction technologies permitted buildings to span taller and wider with greater opportunity to build larger windows and bringing more daylight inside with the purpose of leveraging occupant health.

The oil crisis of the 1970s shifted the focus from human health towards energy reduction strategies leading to smaller window sizes, sealed buildings, and lower air change rates. While the intentions were well placed, unintended consequences emerged, leading to sick buildings in the 1980s. Since then, health and comfort regained attention in architectural practice and research. Notably, Indoor Air Quality (IAQ) was recognized as an essential factor as it was closely associated with the Sick Building Syndrome.[3] Sustainability assessment certifications including Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and Collaborative for High Performance Schools (CHPS) focus on building performance and place significant value on IAQ measures. Yet, asthma is a leading cause of chronic disease-related school absenteeism affecting one in 12 U.S. children and associated with over 10 million missed school days annually.

History and common sense tell us that if we spend 90 percent of our time indoors then buildings have a role in spreading disease and directly related to primary and secondary

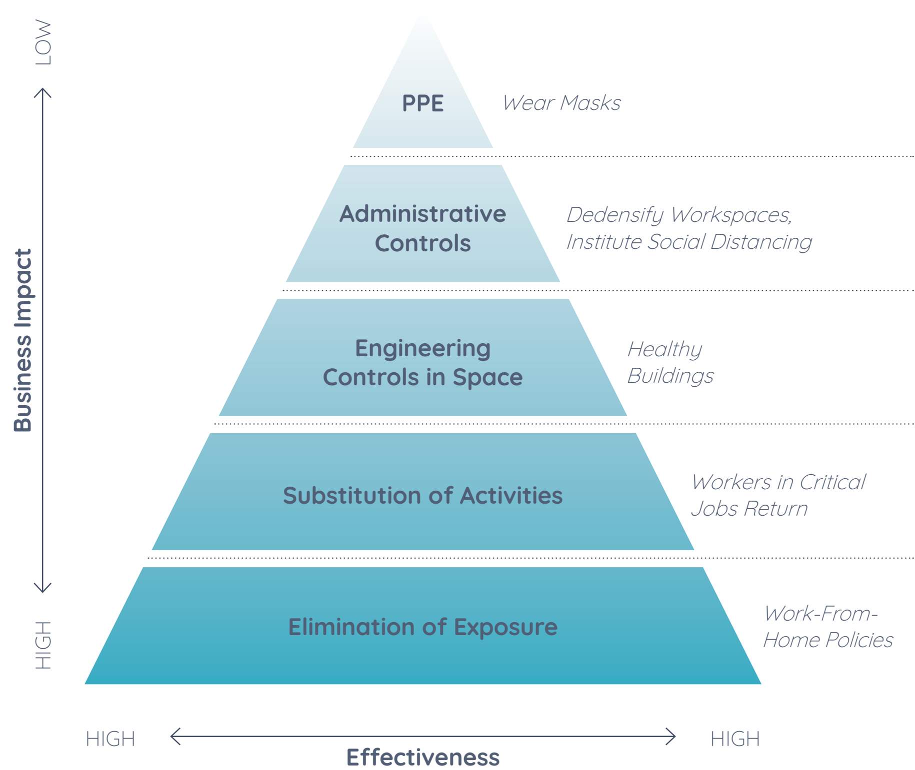


school absenteeism. Knowing how to flatten the absenteeism curve is paramount.
The Effectiveness Level of Strategies for Transmission Reduction diagram illustrates the various transmission reduction control strategies in buildings have different levels of effectiveness. One notable strategy is "engineering controls in spaces," which may lead to reducing the transmission of various pathogens the virus. Examples of these controls include managing air ventilation and filtration. Without such controls in place, the use of personal protective equipment (PPE) and social distancing measures may not be as effective as previously expected in the fight against COVID-19. Regarding the engineering controls in PreK-12 facilities, controlling air ventilation is crucial, and according to Centers for Disease and Control Prevention (CDC), a key factor to consider for reopening the schools.[4]

Poor Ventilation: An Unseen Obstacle On The Path Of Quality Education

The U.S. Environmental Protection Agency (EPA) encourages classrooms to offer greater access to outdoor air inside classrooms and has reported that sufficient outdoor air ventilation is linked with improved student and adult performance, higher test scores, transmission reduction,[6] as well as reduced health effects, and reduced absenteeism.[7] A 2017 study by the Lawrence Berkeley National Laboratory

Effectiveness Level of Strategies for Transmission Reduction
(Source: Joseph Allen and John Macomber)[5]



> Even though physical distancing and hand hygiene are crucial, they may not be enough for fighting against the airborne path of COVID-19.

(LNBL) reviewed studies on the associations of ventilation rate with health symptoms in schools. This review revealed that 8 of 11 studies report health and performance improvement with increased ventilation rates.[7]

However, many schools suffer from lower than standard outdoor ventilation rates.[7,8] Significant air quality issues in California schools were presented in a 2003 report.[9] These problems include "ventilation, temperature and humidity, air pollutants, floor dust contaminants, moisture, mold, noise, and lighting." According to this study, insufficient ventilation was reported for 40 percent of classroom hours, and "seriously deficient" for 10 percent of classroom hours. "Cost-saving measures" and "lack of systematic data" required for districts and managers to address the issues[10] are reported as the main reasons for this persistent problem.

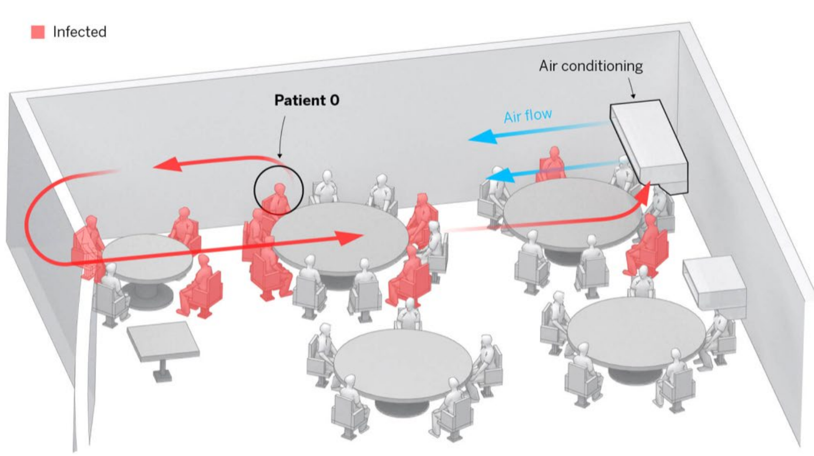
A recent study by LNBL and the University of California-Davis inspected new HVAC systems of 104 classrooms in 11 California schools,[10] and found that 65 percent of the classrooms had high CO_2 levels indicating that ventilation was not adequate. The researchers concluded that more care is needed regarding the installation, commissioning, and maintenance of the systems to ensure sufficient ventilation is provided.

Airborne Transmission Of COVID-19: Are Our Schools Prepared?

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) issued a statement indicating that "transmission of SARS-CoV-2 through the air is sufficiently likely and that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating, ventilating, and air-conditioning systems, can reduce airborne exposures".[11] Several studies highlight pieces of evidence that recognize airborne transmission as a potential route.[12, 13, 14, 15] Reasons could be that small droplets exhaled by an infected person may travel tens of meters bearing their viral load in the air[13] and that SARS-CoV-2 can remain infectious in the air (aerosolized) for hours[16]. In a recent update, the World Health Organization (WHO) also identified this mode as one of the possible paths but noted that further research is still needed.[17]

These findings have significant implications for identifying strategies against transmission reduction at schools. Even though physical distancing and hand hygiene are crucial, they may not be enough for fighting against the airborne path of COVID-19. Bringing high rates of fresh air in populated areas such as classroom environments is a crucial strategy to suppress the spread of viral aerosols. It helps eliminate exhaled virus-contaminated air and could lead to a decrease in the concentration of the virus in the indoor air.[18] An example of evidence is a recent study where three rooms with different levels of ventilation were analyzed. The number of droplets in the best-ventilated room was halved after 30 seconds, comparing to the no ventilation room where the time increased to five minutes.[19] Researchers concluded better indoor air ventilation reduces "the airborne time of respiratory droplets." Several studies on COVID-19 outbreaks also emphasize the importance of ventilation.[20] One case that

Effect of indoor air recirculation, lack of outdoor air ventilation, and airflow direction on a COVID-19 outbreak in a Restaurant in China (Source: Javier Salas and Mariano Zafra)[20]



received a lot of media attention is the case of a restaurant in Guangzhou, China.[21] Several factors have shown to be the reasons for this outbreak, including the direction of airflow and constant recirculation of the indoor air with no outside air ventilation.

Proper ventilation distribution is in place in many hospitals; however, that is not the case in many public buildings such as schools and offices due to energy and cost savings.[18]

METHOD

A comprehensive review of the recently published studies regarding COVID-19 transmission reduction strategies with a focus on air quality in buildings and schools is presented. Some of the research reviewed include the studies of the CDC, ASHRAE, Queensland University of Technology, Harvard University T.H. Chan School of Public Health, University of Oregon Biology and the Built Environments Center, and UC Davis Western Cooling Efficiency Center. The experts tend to agree that schools consider **dilution through increasing ventilation rates, reducing pathogen transport through air filtration, mitigating virus survival by humidification, deactivating the virus via disinfection, controlling infection transport through pressurization and airflow patterns, and constant monitoring of indoor air quality** using the Internet of things (IOT). The following sections describe the findings and the mentioned strategies in further detail.

RESULTS

Increasing ventilation rates: Dilution

According to ASHRAE, sufficient ventilation is a key "infectious disease control strategy" as it can dilute the indoor air close to the source and eliminate infectious particles.[11] Ventilation is a mechanism by which outdoor air is provided into the indoors through mechanical or natural equipment. The objective is to ensure occupant health and comfort through removing humidity, heat, and contamination from the indoors. Higher ventilation rates may dilute the contaminated air more quickly and mitigate the risk of "cross-infection" in long-range airborne transmissions.[22]

Increasing outside air (OA) rates through Mechanical Ventilation: ASHRAE's Position Document on Infectious Aerosols recommends outdoor air dampers in HVAC systems to be opened to 100 percent in non-healthcare buildings as conditions permit. This permits indoor air to exhaust at a higher rate and carry away more airborne contaminants. However, increasing outside air may result in increased energy consumption and cost, and require air filters to be replaced more often to address larger volumes of air pollutants passing through the system. Yet, when you break down the unintended consequence, increasing outside air is a measure that may protect lives.

To optimize energy savings, UC Davis Western Cooling Efficiency Center suggests commissioning systems to full capacity per ASHRAE 62.1 or California Title 24 requirements when classrooms are filled at lower capacities.[23] Another technique is using economizers that balance outside air temperature and humidity levels. Economizers use outside air to cool your building and lower air conditioning compressor demand.

If there is a Dedicated Outdoor Air System (DOAS), it is recommended to introduce the maximum possible outside air flow 24/7.[24] In the long term, schools may consider using DOAS units to facilitate flexibility and respond to pandemic conditions, while maintain energy efficiency goals. Many high-performance schools are moving to separate ventilation from heating and cooling, through DOAS systems, particularly when the target is net zero energy.

One beneficial strategy is natural ventilation, which can provide higher rates of outside air compared to mechanical ventilation.[22] Further consideration would be to extend the use of renewable energies in schools to compensate for the increased consumption.

Building Flushing: ASHRAE recommends extending ventilation time prior to reopening, and before and after school.[24] This includes operating ventilation systems in all spaces

Natural ventilation strategies used operable awing windows and trickle vents for nighttime flushing, Oxnard UHSD Rancho Campana HS, HMC Architects

in the occupied mode for at least one week before reopening, with outside air dampers open. Ventilate spaces daily two hours prior to opening, between classes, and two hours after school.

Avoiding Indoor Air recirculation: Recirculating indoor air is an energy reduction strategy. However, during the pandemic, indoor air recirculation should be avoided or minimized as much as possible.[18] Increasing indoor airflow rates, without increased outside air delivery can potentially increase transmission, as it could escalate exposure to viral aerosols exhaled from other infected occupants, as well as "resuspension from fomites and the potential for contamination."[10] If avoiding recirculation is not possible, maximizing outside air levels, and air disinfection techniques are recommended to eliminate viral particles from the air that is recirculated.[25] ASHRAE recommends six air changes per hour (ACH) of clean air for schools.[26]

Natural Ventilation: Natural ventilation is an energy-efficient technique for bringing outside fresh air into the indoor environment. Opening doors, windows, or skylights can be a beneficial strategy when mechanical ventilation is insufficient. A 2007 study compared natural ventilation with mechanical ventilation and concluded that natural ventilation can provide higher outside air rates than mechanical systems and can be used for infection control in hospitals.[27] In 2009, WHO identified natural ventilation as a means to control infection in healthcare facilities.[28] Similarly, schools can benefit from this technique during the Pandemic. A recent study compared classrooms using mechanical ventilation and natural ventilation. Both classrooms used mechanical ventilation, but it was not adequate. In one classroom, windows and doors remained open all day. The openings in the other room remained closed. The results demonstrated that CO_2 levels (a proxy of ventilation sufficiency) were below the maximum level for the classroom in which natural ventilation was used.[23]

For classroom natural ventilation to be effective, it is recommended to locate openings on two opposite sides, with a total area of four percent of their adjacent floor.[23] However, the use of natural ventilation comes with its challenges. Noise, security, and air pollution are concerns that must be weighed appropriately, but behavioral conditioning is central to the success of any passive strategy. It requires teachers and staff dedication to ensure windows are open throughout the day as well as two hours before and after occupancy for flushing.

Reducing Pathogen Transport: Filtration

In general, all commercial buildings, including schools, are required to use filters with Minimum Efficiency Rating Value (MERV) of 6 or higher per California Title 24. In the aforementioned study by LNBL and UC Davis, 85 out of 104 California classrooms with new HVAC systems had filters with MERV 7 or MERV

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8 rating.[10] However, nearly one-third of the classrooms with wall mount systems had no MERV rating. For a safer reopening during the Pandemic, ASHRAE recommends improving HVAC filtration in schools to MERV 13 or higher or using High Efficiency Particulate Air (HEPA) filters to reduce the transfer of the infectious particles.[24] Using portable HEPA/UVC machines in each classroom is also suggested. Change of filters every three to four months is recommended. Note that filtration does not remove all transmission risks, as many other factors may cause infection transmission.[11]

Mitigating Virus Survival: Humidification
Dry air is linked to higher rates of infectious diseases in buildings.[29] Coronaviruses, in general, last longer in the air when relative humidity (RH) is between 20 and 30 percent[30]. ASHRAE recommends RH in the classroom between 40 and 50 percent at 72 degrees temperature in the winter and 50 to 60 percent at 75 degrees temperature in the summer to reduce virus transmission.[24]

A study by the University of Oregon and UC Davis explains that higher relative humidity retains larger droplets that hold viral aerosols and consequently making them fall on surfaces more rapidly.[25] This, in turn, leads to a reduction in their "airborne dispersal." Besides, high RH levels impact the structure of coronaviruses resulting in their inactivation.

Keep in mind that humidity affects the vulnerability of an induvial to be infected by viruses.[25] Relative humidity in the air ranging between 40 and 60 percent improves the capability of the human immune system to fight infections[29] and should be closely monitored such that relative humidity levels don't exceed 80 percent and stimulate mold development that may cause adverse health effects.[25]

Deactivating the Virus: Disinfection
Another strategy for reducing the viability of infectious agents is using Ultraviolet Germicidal Irradiation Light (UGVI) and Air Ionization systems. It is important to recognize differences among UV spectrum bands, as not all wavelengths are effective in destroying the virus. UVGI is usually based on UV-C radiation.[31] ASHRAE recommends the use of UV-C in ductwork and in upper-air units at schools.[26] However, the use of UV-C in ductwork is only effective when there is enough contact time between the light and the airborne virus. In upper-unit applications, it is useful when the inside air is mixed well enough so that exhaled viral aerosols in the lower parts of the room are floated into the upper portions to be treated.[32]

UV-C light is harmful to viruses and bacteria, but it is damaging to human eyes and skin.[31] As such, care must be taken to avoid UV-light exposure to address potential health concerns.

Controlling Transport
Pressurization: Managing airflow between zones through pressure differentials is a common practice in healthcare settings. This technique controls airflow from clean zones to dirty zones and prevents the transport of infectious particles among hospital wards and reduces long-range airborne transmission.[22]

During the Pandemic, ASHRAE recommends using pressurization as one of the reopening strategies in particular zones of the schools that are in isolation mode.[24] These areas include nurse's office and isolation rooms (negative pressure), as well as protective rooms (positive pressure) and anterooms. Care should be taken in areas where social distancing cannot happen, including bathrooms and adjacent zones.[26] Future strategies may include using room pressure differentials in classrooms and corridors.[26] The design criteria must follow ASHRAE 170 requirements.

Airflow Patterns: According to researchers Qian and Zheng, there is strong evidence demonstrating the association between airflow and infection spread in healthcare settings.[22] This can be the case for other public environments, including schools during the Pandemic. One consideration for addressing this issue is to consider airflow patterns and students' distribution in the room when locating local air cleaner devices.[32] ASHRAE

CO2 tracking device for monitoring indoor air quality.

recommends to "ensure airflow patterns in classrooms are adjusted to minimize occupant exposure to particles."[24] Classrooms of the future may consider computation fluid dynamic studies to study the location of HVAC diffusers and returns to minimize the risk of inadvertent cross-infection through airflow.

Monitoring Indoor Air Quality

Constant monitoring of the indoor air quality can help schools identify areas of deficiency and take relevant measures accordingly. During the pandemic, one crucial IAQ indicator is the level of Carbon Dioxide (CO_2) within the classrooms, as it is a proxy for measuring the adequacy of ventilation.[10] In an empty class, the level of CO_2 relatively equals the concentration in the atmosphere, which is about 410 parts per million (ppm).[32] As the students and teachers occupy the classroom, they exhale CO_2, and the level rises depending on the amount of ventilation. In classrooms with adequate ventilation, CO_2 levels are below 1000 parts per million (ppm).[33] CO_2 levels can be measured by various methods, including "CO_2 sensing thermostats, building automation system sensors, standalone monitors, indoor environment monitoring systems."[23]

SUMMARY AND DISCUSSION

Indoor air quality strategies include increasing outdoor ventilation rates, filtration, disinfection, and humidification, along with testing and commissioning ventilation systems for a safe reopening. Depending on the existing conditions, schools may require repairing, replacing, or adding ventilation equipment, upgraded filters, and monitoring heating, ventilation, and air conditioning (HVAC). These strategies come with a cost and school officials will need to weigh in on the importance of indoor air quality among other priorities.

According to a recent report by The School Superintendents Association (AASA) and Association of School Business Officials International (ASBO) (2020), the cost of safely reopening for the 2020-2021 school year for an average school district may amount to about $1.8 million.[34] This estimated number only includes costs for cleaning and disinfecting equipment, hiring staff to perform safety protocols, personal protective equipment (PPE), transportation and childcare and does not comprise HVAC systems repair/replacement costs.

Indoor air quality should be considered as a long-term investment in providing quality air to students, teachers, and administrative staff. It should not be a plan exclusive to the COVID-19 strategies because we are still subject to other airborne diseases such as the seasonal flu and the common cold. Poor indoor air quality in schools may instigate health issues and lead to lower performance and higher rates of absenteeism.

According to a recent report by the U.S. Government Accountability Office, we have serious HVAC-related problems in our schools nationwide. Problems with HVAC were reported

> Some of these challenges, however, if managed properly, may be turned into opportunities for constructive long-term improvement that will elevate school performance.

in about half of the 55 schools visited by GAO in six states. Examples of these issues are leaking old systems as well as damaged tiles on the floor or ceiling. GAO estimates that 41 percent of the districts require to "update" or "replace" their HVAC systems in around half of their schools, which would be about 36,000 schools nationwide.[35] Considering the health and performance advantages of improving ventilation in schools, the cost may be a minor price to pay. As reported in the study by the LNBL, the annual cost of increasing ventilation rates in schools ranges "from a few dollars to about ten dollars per person" which is "less than 0.1 percent of typical public spending on elementary and secondary education in the U.S."[7]

The COVID-19 pandemic has brought about uncertainties and challenges for our schools and learning environments. Some of these challenges, however, if managed properly, may be turned into opportunities for constructive long-term improvement that will elevate school performance.

Throughout the history, pandemics and epidemics have had considerable impacts and everlasting transformations on our societies. Now, more than ever, schools can take measures that will have mutually beneficial outcomes to address the past, today, and the future of indoor air quality.

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