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Indoor Air Quality: Rethinking rules of building design strategies in post-pandemic architecture

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ABSTRACT

To effectively reduce the spread of SARS-CoV-2, it is crucial to highlight the effectiveness of building design strategies in mitigating threats to occupants. The ongoing pandemic research and actions focus on how poor Indoor Air Quality (IAQ) amplifies the effects of airborne viruses. This review aims to draw architects' attention toward the high risk of airborne transmission of diseases by providing the latest updates and solutions to understand better the environmental and health issues associated with COVID-19. Based on the complexity of the problem and the need for interdisciplinary research, this study presents a conceptual model that addresses the integration of engineering controls, design strategies and, air disinfection techniques required to achieve a better IAQ.

1. Introduction

The emergence of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) has led to the global outbreak of coronavirus disease 2019 (COVID-19). The virus and related disease are called Coronavirus and COVID-19, respectively (Amoatey et al., 2020; Mehmood et al., 2020; Simon, 2020). The disease began to spread all over the world, and The World Health Organization (WHO) declared COVID-19 an epidemic at the time of its first outbreak and as a global pandemic in March 2020. More recently, infectious diseases can remain in society for an indefinite period. Human history has recorded several epidemics; however, this pandemic has a completely different dimension. During this war, humanity is fighting against this unforeseen incident, and everyone is involved in controlling the infection (Elavarasan and Pugazhendhi, 2020; Kumar and Morawska, 2019).

The results reported a high association of COVID-19 infection with air pollution, a mixture of high ambient air pollution levels, and the virus endangered the population. Recent studies provide evidence for indoor airborne transmission of viruses, particularly in crowded and poorly ventilated environments. Cities with poor air quality increase the probability of infections, especially regions with the lowest Air Quality Index. Air quality appears to be a critical environmental factor in the COVID-19 pandemic (Barcelo, 2020; Conticini et al., 2020; Hassan et al., 2020a; Lam, 2020; Liu et al., 2020; Setti et al., 2020; Van Doremalen

et al., 2020).

Most people live, work, and enjoy in densely populated environments, which increase their exposure to many pathogens. Infection control specialists often investigate the relative contribution of airborne transmission compared to the other modes of transmission. However, an infection can occur to varying degrees via all routes, depending on the specific exposure circumstances. Effective infection control requires protection against all potential exposure pathways. The risk of cross-infection is both a psychological stress factor and a health issue, reducing human well-being with an adverse economic impact. Thus, most countries have adopted improved ventilation, quarantine, social distancing, and disinfection as common measures to prevent infection with SARS-CoV-2 (Amoatey et al., 2020; Li et al., 2007; Morawska et al., 2020; Nishiura et al., 2020; Shakil et al., 2020).

This current pandemic needs continuous research to solve this interdisciplinary problem. Engineering and architectural solutions can play a role in reducing the load of pathogens released in the indoor built environment and preventing residents' infection. With a better understanding of this virus, experts are considering the role of efficient ventilation and air disinfection techniques in slowing the spread of COVID-19 in the indoor spaces (Bolashikov and Melikov, 2009; David, 2020). As various organizations attempt to adapt to the expected post-virus era, it is still important to protect people from potential viruses inside buildings.

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At present, the scientific literature on COVID-19 is large, especially for public health intervention and engineering techniques related to improving IAQ in the absence of an architectural perspective. In this paper, a holistic methodology incorporates the required building design strategies and air quality challenges into the post-pandemic architecture. This holistic approach aims to bridge the knowledge gap and draw the architects' attention toward the elevated risks of airborne transmission of diseases and the associated risks of COVID-19. In this context, the article begins by presenting the intertwined relationship between the health of the built environment and occupants. Then, engineering and construction controls to reduce the environmental risks for airborne transmissions are presented. Later in the article, we discuss ventilation-related interventions based on holistic engineering solutions to enhance IAQ. The rest of the article highlights the role of architecture and presents a conceptual model for reducing airborne transmission of infectious agents in buildings.

2. Indoor environment and occupant health

The impact of indoor environment quality on occupant health has long been one of the focus of architecture and public health research. Recent findings partially support the hypothesis that air pollution can increase susceptibility to SARS-CoV-2 infection (Filippini et al., 2020; Zhao et al., 2020). Previous studies have identified various indicators of indoor environment quality, including IAQ, thermal comfort, and visual and acoustic conditions. It is hypothesized that the quality of the indoor environment mediates the impact of the built environment on residents' health. Accumulation of indoor air pollutants appears to contribute significantly to sick building syndrome. Thus, occupants of buildings in a greener and a healthy environment are more likely to live in a better health condition (Chan and Liu, 2018; Van den Berg et al., 2010; Wang and Zhang, 2011; WHO, 2010). Fig. 1 shows the intertwined relationship between environmental health and the expected outcomes and impacts. As shown in the figure, many approaches work together for a common output regarding the occupant's health.

The current pandemic focuses on the adverse health effects of the built environment, primarily due to poor air quality caused by inefficient ventilation. Since people spend around 90% of their time indoors, the IAQ continues to be an important issue affecting occupants' health, comfort, satisfaction, and productivity. Accordingly, the IAQ has long been a critical factor in assessing the performance of different buildings and can be determined by the concentration of various air pollutants in

the indoor environment (Chan and Liu, 2018; Naethe et al., 2020; Rowan and Laffey, 2020; WHO, 2010; Yuan et al., 2019).

Instead of integrating sound IAQ strategies into the design of a building, complex heating, ventilation, and air conditioning (HVAC) systems can increase the spread of infection throughout the building. The COVID-19 pandemic emphasizes the need to prioritize design strategies to improve IAQ. However, the success of these approaches must be supported by targeted policy changes across the public health, urban planning, and architectural design sectors. As poor IAQ is exacerbated by inadequate ventilation, lack of air filtration, and air recirculation in confined spaces, air quality can be improved in three ways, including source controlling, designing ventilation systems, and air cleaning (Brittain et al., 2020; Cui et al., 2003; Guo et al., 2003; Li et al., 2020; Kumar and Morawska, 2019).

3. Controlling potential airborne transmission of SARS-COV-2

The COVID-19 virus has changed our perspective on cleanliness and personal interaction toward our environment. Each day we learn more about the virus, how it behaves, and the best strategies for dealing with it. Several controls are necessary to maximize our protection against the airborne spread of SARS-CoV-2 or future virus-like attacks, as presented in the hierarchy of hazard control (Lam, 2020; Morawska et al., 2020).

3.1. Hierarchy of hazard controls

Hazard mitigation must always focus on implementing measures to eliminate or reduce the risk- COVID-19 in this case. These measures and controls are continuously updated based on infection control risk assessment in different fields. The hierarchy of hazard control consists of four layers of defense, and all layers must always be implemented in combination with other existing measures to reduce infection. The idea behind this hierarchy is that the control measures at the top of the hierarchy are potentially more effective than those at the bottom (CDC, 2015; Morawska et al., 2020; Nishiura et al., 2020; Powell, 2020; Tamers et al., 2019). The following points summarize each layer of the COVID-19 control hierarchy:

- Hazard elimination. Eliminating potential exposure to COVID-19;
- Engineering and construction controls. Re-design or modify building configuration and systems to incorporate healthier building strategies;

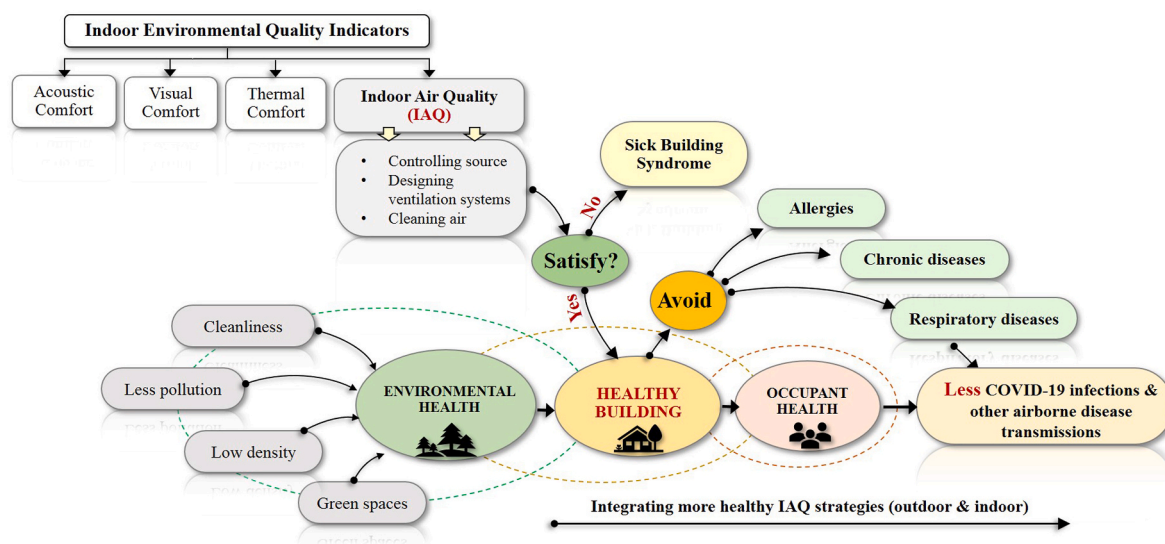


Fig. 1. The intertwined relationships between environmental health and the expected impacts on human health.

- Administrative controls. Instructing people on what to do based on rapid, continuous, and updated scientific evidence about the intensity and probability of airborne transmission pathways and an understanding of transmission exposures in indoor environments;
- Personal Protective Equipment (PPE). These controls are related to the protection of individuals via their own measures since people are the primary source of the virus and can be infected without symptoms. COVID-19 recommendations for PPE are subject to change in response to updated risk assessments and medical information. The public needs to regularly check the OSHA and CDC websites for the latest information on these recommendations.

3.2. Construction and engineering controls to limit indoor infection risks

The available construction and engineering controls include many useful strategies for controlling or minimizing the transmission of airborne disease in buildings. There are short-term and long-term strategies that can be implemented to increase IAQ, including ventilation, filtration, or a combination thereof. These strategies, coupled with architectural strategies, enhance their benefits (Coker et al., 2001; Gao et al., 2009; Kumar and Morawska, 2019; Lam, 2020).

4. Ventilation and air disinfection strategies: an overview

Congested spaces with asymptomatic carriers are potential sources of airborne SARS-CoV-2. Although the transmission of COVID-19 occurs mainly via droplets through close contacts or contaminated surfaces, recent studies have shown that SARS-CoV-2 can survive for several hours in aerosols. Therefore, improved ventilation and air disinfection strategies are essential to limit its spread in the buildings (Chen et al., 2006; Kumar and Morawska, 2019; Liu et al., 2020; Morawska et al., 2020; Van Doremalen et al., 2020).

4.1. Improving ventilation systems

Ventilation is an engineering control strategy for diluting and removing airborne contaminants and is closely related to IAQ. It also plays a crucial role in promoting the comfort and health of building occupants. Poor ventilation has been identified as a precursor to various respiratory disorders. Ventilation can be driven by mechanical systems, natural forces, or a combination of both. Mechanical ventilation can cause energy efficiency issues, while the outdoor environment constrains natural ventilation. The hybrid ventilation function takes advantage of both (Chan and Liu, 2018; Gao et al., 2009; Hoffman, 2019; Rackes and Waring, 2014; Yu and Kim, 2011; Zhao et al., 2020). The best strategies would be looking for effectiveness in contaminant removal but also at low energy cost.

Awareness of new emerging diseases serves to emphasize the need to design indoor environments that prevent cross-infection. The literature provides strong evidence for a link between ventilation and control of airflow direction within the buildings and transmission and spread of infectious diseases (Bolashikov and Melikov, 2009; Li et al., 2007). Most recently, researchers have highlighted the potential for much higher COVID-19 infection rates in closed environments with recirculated air. Therefore, for the current COVID-19 pandemic, the recirculation of air is not recommended. However, if applicable, recirculated air must be treated (Blocken et al., 2020; Brittain et al., 2020).

The concept of bringing outdoor air indoor to reduce contaminants is not new—it has been known as the answer to the IAQ problems. However, even with enhanced ventilation, congested indoor spaces can still be risky because the virus-containing particles can reach the residents before filtration. Thus, ventilation itself can also be considered a source of contamination and exposure. Now the question is whether engineers bring this air into the buildings when outdoor air polluted or is it outside the thermal comfort zone. In such circumstances, it is important to review other ventilation interferences and techniques to maximize the

indoor-outdoor exchange of clean air (Abouleish, 2020; David, 2020; Morawska et al., 2020).

4.2. Ventilation-related interventions

Airborne transmission of COVID-19 in indoor environments is significantly increased if restrictions are relaxed, and the most effective measures such as social distancing and self-isolation are absent. Based on this situation, the pandemic is raising awareness over air and surface cleaning (Bradley, 2020; Kumar and Morawska, 2019; ProLampSales, 2020; Yamano et al., 2020). There are many potential sites of infection in buildings, including sick persons or sick building syndrome, or air recirculated through the HVAC system. Much effort has been put into finding engineering techniques to keep airborne pathogens away from the population or to keep them at low levels so that they do not cause disease. Pressurization, dilution, filtration, purification, and nanotechnology (see Table 1) are the most technical interventions.

In practice, the ventilation-related interventions mentioned above have many standards and precautions that need to be updated to be more effective for preventing or controlling airborne infectious diseases in indoor environments. In this context, protection can be applied to existing ventilation systems to minimize the further spreading of SARS-CoV-2. In a mechanically ventilated building, ventilation systems are customized by HVAC engineers and updated to address the COVID-19 pandemic with ASHRAE, REHVA, and SHASE ventilation guidance. Viral and bacterial pathogens can be present in the air after being released by infected individuals. Filtration and other purification techniques are installed in the HVAC systems to protect the ventilation equipment and maintain healthy IAQ (Gao et al., 2009; Goyal et al., 2011; Morawska et al., 2020). Recent studies have recommended UV-based technologies, and others have highlighted the potential of biosystems with integrated microalgae systems. The following points discuss these two approaches in detail.

4.2.1. UV-based technologies

A direct approach to prevent airborne transmission is to inactivate airborne pathogens. Airborne antimicrobial potential of Ultraviolet Germicidal Irradiation (UVGI) has long been established. UVGI generally refers to a UV wavelength of 253.7 nm (UV-C). Although the UVGI system is microbiocidal, caution is required regarding irradiation. This limits its widespread use due to human health risks associated with eyes and skin (Bang et al., 2018; Brickner and Vincent, 2013; Memarzadeh et al., 2010). Recently, it has been determined that far-UVC light (207–222 nm wavelength) efficiently inactivates viruses and bacteria. This technology is believed to apply to large buildings to reduce the concentration of SARS-CoV-2 by using human-safe UV light intensities. Although its safety and economics have not yet been thoroughly studied, it can be applied as a promising technology in areas with heavy traffic and high-risk public spaces to prevent the spread of SARS-CoV-2, in addition to other viruses and bacteria (Horning and Davis, 2020; McNamara, 2020; Simon, 2020; Welch et al., 2018). Despite reduced safety concerns, it can still cause damage to eyes and skin. Far UV-C lamps can pose a risk to the cornea, and recent studies have been inconsistent as to whether far UV-C light poses a significant skin risk. Besides, until recently, very little research has been conducted to determine whether these technologies achieve their intended purpose for COVID-19. Therefore, research is still ongoing, and the behavior of SARS-CoV-2 under UV light is still controversial (Goel et al., 2020; The Illuminating Engineering Society, 2020). These technologies must be used in applications where nobody is present during disinfection to avoid adverse health effects.

Most UVGI technology applications in buildings rely mostly on two areas: upper-room air irradiation and in-duct irradiation. Upper-room UVGI (UR-UVGI) is achieved by suspending lamps from a wall or ceiling so that irradiation is contained within the upper portion of the room. UR-UVGI is an appropriate technology to consider in congested, poorly

Table 1
Air disinfection and purification systems and techniques.

| Technique | Description | Pros and cons | Ref. | |
|----------------|--------------------------------|---|---|--|
| Pressurization | Positive and Negative | Differential pressurization refers to measurable differences in air pressure that creates a directional airflow between adjacent spaces. | It requires detailed calculation and simulation to get its benefit and acute monitoring. It may be used alone or in combination with other techniques. | Memarzadeh et al. (2010). |
| Dilution | Natural, Mechanical and Hybrid | It is one of the easiest methods to remove pathogens. Dilution by ventilation strategies can improve IAQ, reduce energy, and control particles by removal through ventilation. | It is related to air distribution patterns, location of the ventilation inlet and outlet, the physical configuration of space, residents' thermal comfort, etc. | (Memarzadeh et al., 2010; Rackes and Waring, 2014). |
| Filtration | Mechanical filtration | A method widely used in HVAC systems to improve air quality with High-Efficiency Particulate Air (HEPA) filters in specific areas or through filters treated with antimicrobial agents. | It requires proper installation, maintenance, and monitoring. Due to the small size of the coronavirus, the virus can pass through most filters. However, HEPA filters catch larger particulates containing it. | (Horning and Davis, 2020; Memarzadeh et al., 2010). |
| | Biofiltration technology | A plant-based technology that can absorb CO ₂ , NO ₂ , SO ₂ to filter the air. The green wall and microalgae structure are the most common applications. | More research is needed, especially the required infrastructure and maintenance. | (Cummings and Waring, 2020; Packer, 2009). |
| Purification | Bipolar ionization | Integrated into HVAC systems, high voltage electrodes create reactive ions in the air that react with airborne contaminants, including viruses. | Although it enhances the filtration system, it may emit ozone, and more scientific studies are required. | (Horning and Davis, 2020), ASHRAE, (2015). |
| | UVGI technology | This technology based on the ability of UVGI to damage the DNA/RNA of pathogens and makes them harmless. | Still under development to avoid adverse health effects on the skin and eyes of humans. | (Bradley, 2020; Goel et al., 2020). |
| Nanotechnology | Silver nanoparticles | This method utilizes silver nanoparticles to control the viability of pathogens. | Practical but still needs further investigations regarding its possible adverse effects on health. | (Bolashikov and Melikov, 2009). |
| | Photocatalytic oxidation (PCO) | Recent studies present nanomaterials-based coatings for antibacterial applications. The most common Photocatalyst is TiO ₂ . | It is still under exploration to avoid the potential impact of nanoparticles on human health and the environment. | (Chouirfa et al., 2019; Goel et al., 2020; Megahed, 2014). |

ventilated environments where the aerosol transmission can occur and has limited ability to enhance ventilation. Additionally, UVGI lights are mounted in deep louver enclosures at a high distance above the floor to avoid overexposure at eye level or excessive reflection from the ceiling. Installation of in-duct HVAC systems provides another means, which can be a practical approach for disinfecting contaminated extracts, or in cases where it is not possible to stop air recirculation (Bang et al., 2018; Bradley, 2020; Horning and Davis, 2020; Kujundzic et al., 2007; Memarzadeh et al., 2010; Yamano et al., 2020; Welch et al., 2018). For all those working in the field of UVGI, safety issues must be a concern as improper placement of UVGI fixtures or ignoring precautions puts residents at risk. Every effort should be made to devise and maintain a safe UVGI system (Brickner and Vincent, 2013).

The scientific evidence supporting the use of this technology depends mainly on collaboration during this COVID-19 crisis to bring their respective expertise to a potential solution for sustaining life in an increasingly complex world. Although most studies have shown effectiveness, many engineering specifications, practices, and questions arose to ensure a safe installation. Now the question is what precautions are needed, and what maintenance options and control strategies must be provided for proper use in architecture. Indeed, humans need to know the answers to these questions from the scientific community. These technologies are constantly modified and updated to be less dangerous to humans. This evolving technology can help limit the spread of future pandemics if safety results and solutions are confirmed and certified in other scenarios. Then, based on practical results, a building can be considered for possible integration methods in architectural design.

4.2.2. Biofiltration technology

Future experiments need to focus on passively purifying indoor air to create a more biophilic indoor environment. Biofiltration technology is gaining attention because of its economic, environmental, and social benefits. This includes the possibility of incorporating both traditional and emerging trends in sustainable zero-emission green buildings. Several systems have been developed, with green walls and microalgae structures being the most popular applications (Kisser et al., 2020; Malińska and Zabochnicka-Świątek, 2010; Pettit et al., 2018; Wang and Zhang, 2011).

It has long been known that plant-based technologies filter air and convert CO₂ into biomass and O₂. Such systems can use algae, which is

currently being extensively investigated. This offers new possibilities for integrating carbon capture technology into densely polluted environments, significantly improving the overall quality of life, human health, and residents' productivity (Biloria and Thakkar, 2020; Frangoul, 2019; Neill, 2019). However, implementing this technology in a built environment has received little attention and has limitations that can restrict its wide range of applications. Sophisticated technology is a barrier to bringing plant life to the indoor environment. Some species have been shown to produce certain VOCs under particular conditions.

Further research is required from the perspective of their efficiency in removing air pollutants and their effects on relative humidity and CO₂ control. Topics related to necessary maintenance and infrastructure, and lastly, residents' acceptance, need to be investigated further (Cummings and Waring, 2020; Llewellyn and Dixon, 2011; Soreanu et al., 2013). Finally, simulations of different climate zones are needed to provide more quantitative results on the applicability and energy saving potentials for a broader range of climate and air quality conditions.

Based on the above, ventilation-related interventions are undoubtedly crucial issues to avoid infections. However, machine-based technologies must be used as supplementary measures after adopting passive design strategies. Scientists have performed more studies into these technologies to prevent adverse health effects on humans, and to date, more research is required. Accordingly, caution and professional judgment are required to understand the choices, strengths, weaknesses, and impacts on other building systems. In summary, Fig. 2 shows a flowchart of the entire engineering solution to guide architectural decisions for enhancing IAQ. As shown in the figure, engineering solutions must consider collaboration between various disciplines while fighting COVID-19. Fresh air dilution needs to be regarded as part of the holistic engineering solution to pollution without ignoring proper air filtration and proactive air purification. However, the flowchart is based on a theoretical approach not tested practically. Thus, the authors encourage future developments and updates based on the latest scientific results.

5. Architectural engineering in post-pandemic controls

Health-related infections emphasize the need for a better understanding of how built environment aspects are related to infection transmission. In addition, we need to realize what design, structural, and operational changes can be made in a built environment for improved

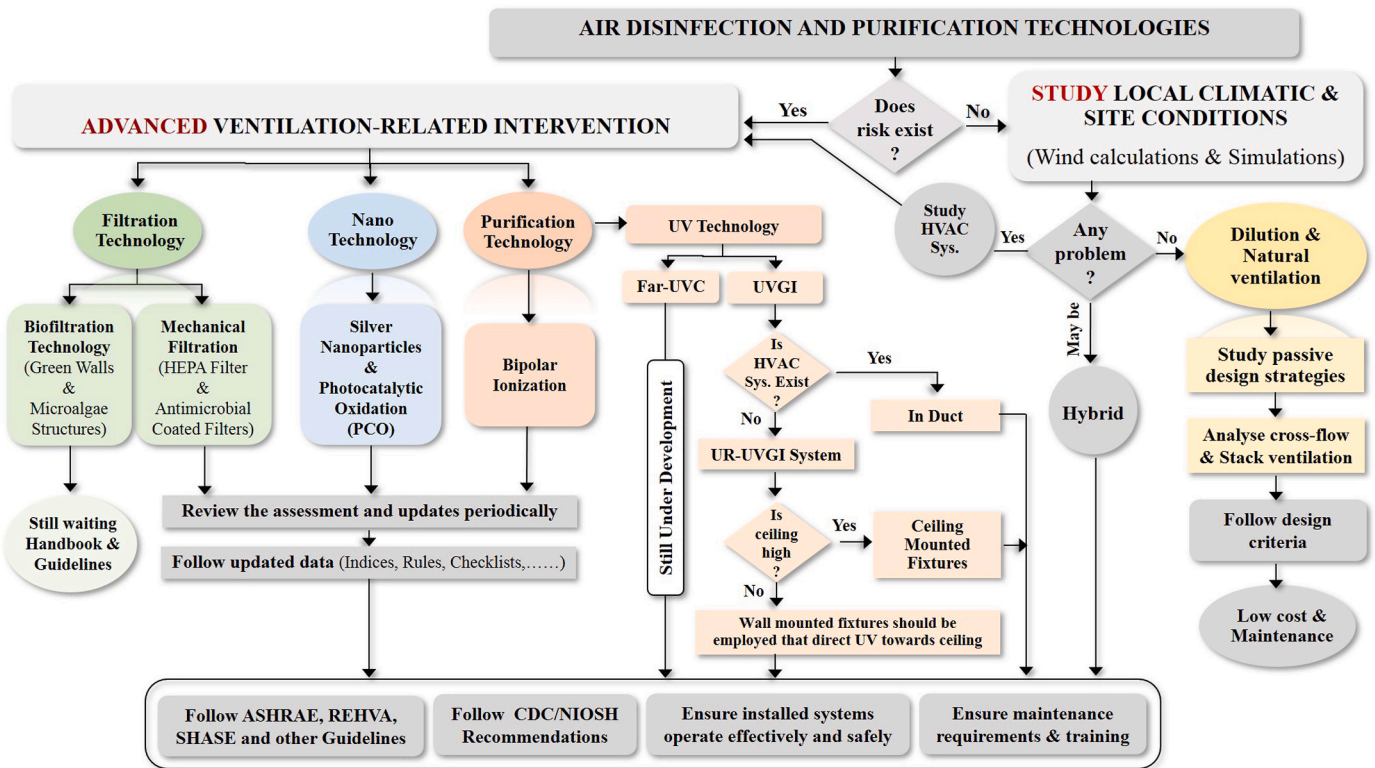


Fig. 2. Flowchart of the holistic engineering solutions for enhancing IAQ.

infection prevention and control.

5.1. More human-centered designs in the future

An architecture must avoid relying on mechanical ventilation and artificial environmental conditions to prevent chronic diseases, allergies, and sick building syndrome. The future built environment must focus on developing more human-centered designs in architecture and urban design. This protects residents as a permanent design strategy to avoid future health epidemics (Bolashikov and Melikov, 2009; Rassia, 2020). In this context, moving to a human-centered approach might be energy efficient. In addition, design for low-income areas and vulnerable populations need to consider affordable solutions in the future.

A passive strategy of urban and building morphology, based on a careful analysis of local climate and site conditions, can reshape the dispersion of air pollutants around the buildings. Then the use of passive design strategies inside the building facilitates natural ventilation and air distribution. However, for sites with high levels of pollution, it is recommended to use appropriate disinfection and purification techniques (Brittain et al., 2020; Zhao et al., 2020).

For future human-centered designs, buildings require a holistic IAQ management plan that includes proper ventilation, air filtration, humidity regulation, and temperature control. These are considered vital strategies to improve IAQ and protect residents from airborne diseases. This plan must also find the specification of safe materials for long-term respiratory health, operation, and maintenance of the ventilation and HVAC system. When using an air purifier, filters should be disposed of as medical waste to prevent cross-contamination. Engineers should not rely on mechanical filtration as it requires continuous maintenance. Therefore, other biofiltration systems are currently under development. In terms of temperature regulation, the automated temperature in most climates can be minimized or eliminated by integrating a passive temperature control strategy into the building design process (Brittain et al., 2020; Cummings and Waring, 2020; Yu and Kim, 2011; Zhao et al., 2020).

5.2. Assistant decision-making tools in post-COVID-19 architecture

The current pandemic has reinforced modeling capabilities and seeks architects to use digital simulation tools to help study the dynamics of COVID-19 particles. At the scale of a building, architects need to understand the potential risks in and around a building. Computer-Aided Design (CAD) tools have continuously improved to simulate natural ventilation and air distribution. Besides, the development of Building Information Modeling (BIM) and Computational Fluid Dynamics (CFD) has made it easier for architects to access airflow simulation tools. Mechanical engineers regularly use CFD models that show how air moves through space and the effectiveness of ventilation systems. Recently, they have reapplied these techniques to understand how airborne pathogens can move through buildings (Brittain et al., 2020; Cousins, 2020). Collaboration between mechanical engineers and architects via CFD models significantly develops the architectural design process. These tools can generate predictive models and help bridge the knowledge gap on airborne virus transmissions in built environments and the effectiveness of ventilation systems to create more robust architecture (Hassan et al., 2020a, 2020b). Also, future architects need to learn more about performance-based modeling. This type of modeling has a variety of digital tools for simulation, analysis, and assessment of high-performance aspects that can optimize natural ventilation and air distribution to mitigate the airborne spread of viruses (Brittain et al., 2020; Cousins, 2020).

The COVID-19 pandemic is a big shock, but the positive news is that it has increased the importance of the scientific role in society. Engineers and designers play a major role in jointly developing new ideas for the facilities the community needs. Architectures deal with the design of interdisciplinary engineering researches and integrated technologies. Fig. 3 shows the architectural and engineering controls based on the hierarchy of hazard controls in built environments. As shown in the figure, effective disinfection and purification techniques must be integrated to counter COVID-19. This adds weight to architecture and requires advanced tools and preparations.

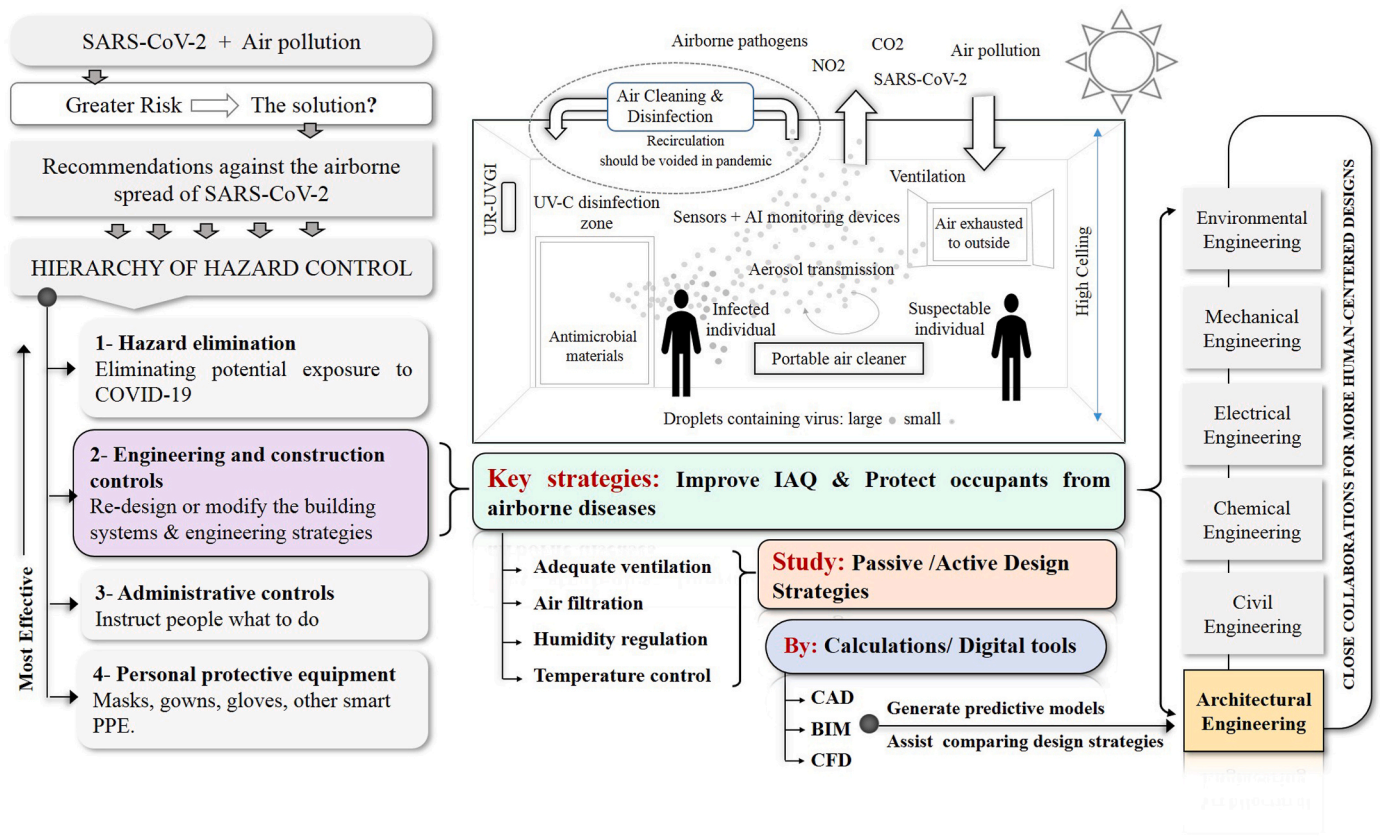


Fig. 3. Architectural and engineering roles based on the hierarchy of hazard controls (Adopted from Brittain et al., 2020; Morawska et al., 2020).

6. Discussion

The present review explains why we need to rethink building design strategies and how the pandemic offers a unique opportunity to improve IAQ. This review attempts to summarize and integrate the environmental and human health aspects associated with the IAQ in the COVID-19 challenge in architectural awareness. The virus has many lessons for architects to learn. The most obvious lesson is that IAQ can lead to a healthier experience for everyone, and poor ventilation can increase the spread of the virus. Accordingly, IAQ is attracting more attention as people spend more time indoors (Lam, 2020; Megahed and Ghoneim, 2020; Pettit et al., 2018).

A holistic approach is required to address challenges on IAQ. There must be an element of prevention and mitigation with supporting technology and social behavior. The hierarchy of hazard controls in the built environment consists of four layers of defense for post-pandemic controls, including engineering controls that help reduce the spread of infection. Choosing the most appropriate type of control depends on accurate data from many disciplines (Abouleish, 2020; David, 2020; Morawska et al., 2020; Tham, 2016). Based on the lessons learned from this pandemic, the role of engineering controls is recommended to reevaluate how both new and existing buildings are designed to prevent infection and improve IAQ. Architects need to choose and implement passive design strategies tailored to the local climate, with minimal energy input and maintenance based on the analysis of the optimum airflow, best building orientation, careful openings design, spatial sequencing and configuration. With a passive design strategy, natural ventilation does not require advanced technology. However, in some cases, it may be necessary to remove pollution from the outdoor air. These passive strategies lead to a more sustainable architecture that can address the challenges of future health outbreaks (Amoatey et al., 2020; Brittain et al., 2020; David, 2020; Morawska et al., 2020). The cleanliness and disinfection of the indoor environment are essential for

infection prevention and human well-being. However, some advanced air disinfection techniques can be harmful to residents if not properly installed and maintained. Therefore, more targeted multiparameter studies are required to evaluate the efficacy, safety, and potential for incremental protection against SARS-CoV-2 virus transmissions.

COVID-19 is not the first and probably not the last pandemic. Hence, the complexity of SARS-CoV-2 and its behavior requires enhanced collaboration and highly sophisticated research. Future research opportunities for architects must focus on simulation tools and CFD techniques for investigating building ventilation (Blocken et al., 2020; Bolashikov and Melikov, 2009; Li et al., 2007). However, calibrating the models requires additional quantitative experimental data and close collaboration between microbiologists, IAQ scientists, and specialists in building flow dynamics.

Human health is the consequence of a healthy indoor environment that resists COVID-19 in indoor air. Like our bodies, our buildings require regular physical examination and monitoring to identify issues that need to be addressed. Battle against COVID-19 may require novel approaches to improve air quality monitoring. Robots and Artificial Intelligence (AI) can play a role in detecting filtration performance, resident density, and air quality. Sensors can be installed in high-risk areas to monitor IAQ and other indicators of indoor environment quality continuously. Besides, on-site assessments, digital modeling, and simulations can quickly identify high-risk areas. This allows operators to identify sources of pollution and optimize building operation and management. This digital platform can sense body temperature, measure fine particulate matter, and improve IAQ with more ventilation or air purification techniques. This AI capability means that it can offer the most valuable mitigation measures and draw insights from historical data, predicting pollution levels before they occur. The system also verifies that relevant actions can be taken based on resident behavior, building type, and other potential risks (deSouza et al., 2020; Forman et al., 2020; Lam, 2020; Waters, 2020; Yang et al., 2020).

The conceptual model of this study is proposed in Fig. 4, based on the required engineering and construction controls. As shown in the figure, improving IAQ requires interdisciplinary intervention and targeted collaboration. Advanced engineering techniques must be combined with public health interventions to help combat diseases. However, experts are actively working on publishing guidelines for indoor environments. Information on SARS-CoV-2 is insufficient, and many questions remain unanswered about viral transmissibility, making it difficult to quantify the efficiency of engineering and construction controls. These controls are complex systems whose interconnected subsystems belong to the indoor environment. The conceptual model is based on information from an extensive literature survey to date. This is expected to help architects integrate human health into the design process and consider appropriate air disinfection techniques to improve their IAQ. We need to apply the lessons learned to coordinate our efforts to address this pandemic and other future health and environmental crises. Therefore, the authors suggest that future work is needed to improve the model.

7. Conclusion and outlook

Protecting humans from hazards has been one of the fundamental goals of architecture since its existence. Concerns over the airborne transmission of SARS-CoV-2 and other pandemic related risks help architects rethink the rules of building design strategies. In post-pandemic architecture, in addition to increasing physical distances, experts suspect that the coronavirus airborne pathways may be more widespread. Therefore, certain precautions will help reduce indoor spread. Successful solutions consider environmental health and prioritize IAQ in future designs. A healthy indoor environment requires multidisciplinary investigations, the results of which will reshape future interior spaces and architecture. Interdisciplinary teams need to address standards, guidelines, and recommendations to follow. In this context, architects designing the last item need to keep these scientific results in mind and update their knowledge toward healthy building strategies that can limit

the spread of the SARS-CoV-2 virus. Ventilation systems are effective, but not a reliable method to address these issues. Therefore, a combined approach with other related interventions is required to maintain a healthy indoor environment for the well-being of the occupants.

In the past, improving IAQ was considered a luxury parameter. Now it needs to be considered essential, and the current pandemic emphasizes the need for efficient techniques for indoor air disinfection and purification. The incomplete knowledge and uncertainties about the safety of these technologies limit their practical applications in architecture, which need further studies. Any strategy for resilience against a pandemic also needs to consider other intensified threats. Advanced ventilation-related interventions are necessary for protecting people from cross-infection. Therefore, the future will be more focused on touchless technology. Together with other engineering measures and guidelines, if these technologies are implemented and integrated with architecture correctly, building immunity is enhanced. Such actions can reduce airborne transmission of SARS-CoV-2 in the current pandemic as well as other airborne pathogens.

The research proposes holistic engineering solutions and conceptual models to improve IAQ based on the hierarchy of hazard control and recommendations. The conceptual framework aims to help architecture to ensure sufficient ventilation in the design process while managing the risk related to the COVID-19 pandemic. In short, a lot of work needs to be done, and this review is expected to help architects prepare for their new role in post-pandemic architecture. Just as the pandemic forces us to rethink the rules that define the design strategy for controlling the IAQ, our perspective on cleanliness and environmental responsibility is as much a spotlight.

CRedit author statement

Naglaa A. Megahed: Conceptualization; Investigation; Methodology; Resources; Visualization; Writing - original draft; Writing - review & editing. **Ehab M. Ghoneim:** Conceptualization; Writing - review &

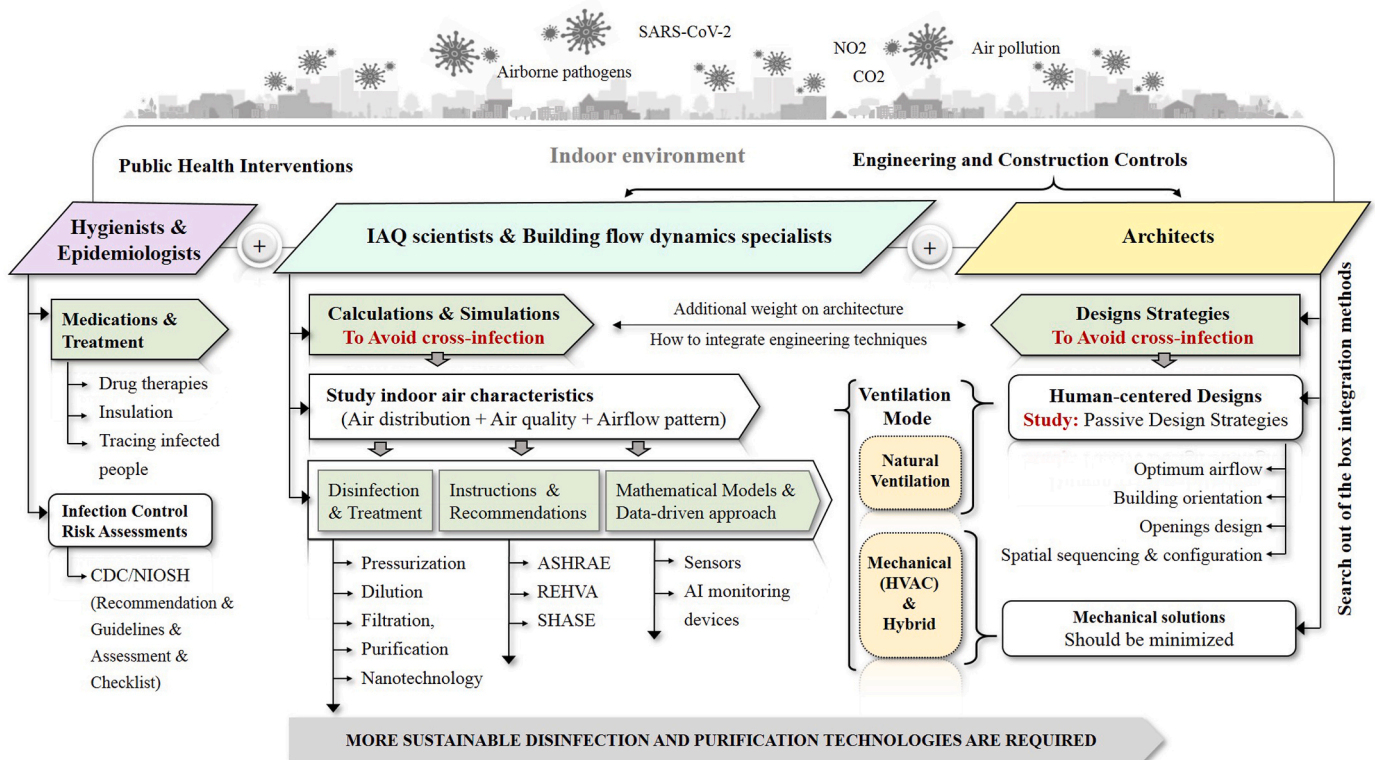


Fig. 4. A conceptual model for reducing airborne transmission of infection inside buildings.

editing; Supervision.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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