Article

Anticipating Emerging Research Frontiers Related to Indoor Air Quality: What Did We Learn from the COVID-19 Pandemic?

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ABSTRACT

Background: While the COVID-19 pandemic has officially ended, it remains a significant era that profoundly tests humanity's ability to solve challenges across various domains related to health hazards' crisis management, technological innovation, and requestioning the management of Indoor Air Quality (IAQ) in different building typologies.

Methods: This study examines early publications related to IAQ during the early phase of the pandemic, from March 2020 to August 2021, to identify thematic research areas anticipated to shape the scientific community's future interests for at least the following 10 years. This study proposes an analytical framework to further interpret the identified thematic areas of research related to IAQ based on intentionality and impact.

Results: Topics included the spatial design of indoor environments, occupants' health, thermal comfort, building performance and ventilation, technology use and energy efficiency, as well as health and social equity. The authors commented on key topics requiring immediate attention from architects, building operators, and researchers.

Conclusions: This review foresees the need for (1) building codes that balance spatial design and health aspects to reduce the rate of viral transmission, (2) carbon footprint reduction plans in response to IAQ ventilation requirements, and (3) ventilation systems that consider the thermal comfort of occupants, minimize energy losses, and safeguard air quality from external pollutants. Finally, (4) find a balance between the identified parameters to enhance the IAQ system control.

KEYWORDS: indoor air quality; COVID; built-environment; occupant health; consequences

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ABBREVIATIONS

AC, air conditioning; AI, artificial intelligence; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; BREEAM, Building Research Establishment Environmental Assessment Method; CDC, Centers for Disease Control and Prevention; EPA, United States Environmental Protection Agency; HEPA, High Energy Particulate Air; HVAC, heating, ventilation, and air-conditioning; IAQ, indoor air quality; IEQ, indoor environmental quality; LEED, Leadership in Energy and Environmental Design; REHVA, Federation of European Heating, Ventilation, and Air Conditioning Associations; SBS, Sick Building Syndrome; WHO, World Health Organization

INTRODUCTION

Since the onset of the COVID-19 pandemic, the field of indoor air quality (IAQ) has gained significant interest worldwide to combat the transmission of airborne viruses and ensure the safety and well-being of building occupants. While the COVID-19 pandemic has officially concluded, it is recognized as a remarkable era that undoubtedly tests humanity's problem-solving abilities on many fronts. The purpose of this study is to examine early publications related to IAQ during the onset of the pandemic to identify thematic research areas anticipated to shape the future interests of the scientific community for at least the following 10 years. This study proposes an analytical framework to further interpret the identified thematic areas of research related to IAQ based on intentionality and impact. Topics include the architectural design considerations of indoor environments, occupants' health, wellbeing and thermal comfort, building performance and ventilation, technology use, and energy efficiency of mechanical ventilation systems, as well as health and social equity pertaining to the use of innovative technology solutions to manage IAQ in buildings and health hazards in general.

Moving forward, this paper is organized into six sections. Section 2, the RESEARCH PROBLEMATIC, delves into the contextual backdrop of the early phase of the COVID-19 pandemic, establishing it as the foundation for the study. We acknowledge the prevailing indoor air quality guidelines and standards during that period and examine the instigated consequences resulting from adherence to such recommendations. Section 3, titled "MATERIALS AND METHODS", explains the methodology employed for identifying crucial research areas, namely the literature review process. In Section 4, "RESULTS", we provide a succinct overview of the academic journals reviewed. The main findings and recommendations are highlighted, along with a detailed examination of categorized literature topics, including heating, ventilation and air-conditioning (HVAC), ventilation and air quality guidelines; viral transmission; and building performance, comfort, and innovation. The analytical core of this paper is presented in Section 5—"ANALYSIS". This section discusses the implications of COVID-19 on indoor air quality, referencing the instigated consequences identified from the reviewed literature. The analytical framework differentiates between intended and non-intended consequences while also considering the temporal aspect of impact, distinguishing between long-term and short-term consequences. Section 6, the "DISCUSSION" section, elaborates on critical anticipated topics that revolve around better managing IAQ in built environments post-pandemic. Finally, Section 7—"CONCLUSION" encapsulates key findings derived from this comprehensive review article. This anticipates future avenues for research stemming from the insights gathered during the study.

RESEARCH PROBLEMATIC

If we look back on what was postulated by international health organizations, improving IAQ to safeguard the health of occupants was at the forefront of the published addenda of IAQ guidelines of renowned organizations, in alphabetical order, including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Centers for Disease Control and Prevention (CDC),the World Health Organization (WHO), the Federation of European Heating, Ventilation and air conditioning Associations (REHVA), as well as in many academic publications. Published works have tackled the issue of IAQ from various perspectives. These included studies that examined the means of viral transmission, validated the recommended IAQ ventilation rates and performance standards through simulation, investigated occupants' health and thermal comfort during the pandemic, and presented new products and approaches to monitor IAQ to make buildings safer. Other studies and reports resorted to recommendations based on state-of-the-art enhancements in the operation of heating ventilation and air conditioning systems. While there have been many studies on IAQ during the pandemic, it is important to first understand the background of air quality policy and contextualize it within the early phase of the COVID crisis.

Background

Policies, regulations, legislation, and guidelines issued by governments, policymakers, and international specialist organizations still play a significant role in managing the health crisis. The COVID-19 Pandemic put significant pressure on governments to come-up with timely and quick responses to 'contain' the situation[1]. Many such timely policy responses fall under "emergency legislation" and "emergency regulations" and regulations [2]. The most notable example is the lockdown procedure. Directives issued during the pandemic, including quarantine and lockdown measures, have highlighted the social, economic, and cultural dimensions of the global health crisis. This underscores the necessity of forecasting the implications and consequences of these guidelines and directives.

Scholars, including Scotford [3], explain why governments should change their perception regarding air quality and air pollution legislation. The main argument is that there is an invisible barrier separating the indoor air quality and ambient air quality. Scotford 's [3] exact words are: "There is often an artificial indoor versus outdoor barrier in regulating air quality and setting air quality standards. [...] The pandemic has starkly highlighted that air quality is a problem not only of public health but also of social inequality". In fact, IAQ guidelines that put facility managers accountable remain nonexistent. It is well known that IAQ is less regulated than ambient air quality.

The distinction between indoor and outdoor air quality is also a major division of research, and little has been published on the intersectionality of IAQ and ambient air quality.

Nevertheless, another obstacle that building operators and institutions faced during the pandemic relates to navigating the addenda of different guidelines and standards. Many of these studies have presented competing IAQ targets. During the early stages of the pandemic, the existing standards were not in agreement with the exact ventilation rates that should be applied to medical and non-medical facilities. In agreement with the same line of thought, Lewis [4] discussed the challenges of making medical and nonmedical facilities indoor spaces safe. They comment on the role of the World Health Organization (WHO) in issuing guidance documents and The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards. During the early stages of the pandemic, the existing standards were not in agreement with the exact ventilation rates that should be applied to medical and non-medical facilities [4].

Concerns regarding the health and well-being of occupants in indoor spaces were a hype research project long before the pandemic. Among the well-researched issues that resurfaced during the pandemic are Sick Building Syndrome (SBS), its antonym "healthy buildings", and the indoor environmental quality (IEQ) index. The Sick Building Syndrome "is a complication that can appear to occupants in buildings along with general, mucosal and skin symptoms such as headache, fatigue and irritation in the upper respiratory tract, throat, eyes, nose, hands and/or facial skin" [5]. Afshari [6] emphasized the correlation between improved indoor air quality and a given population's health and immune system conditions. Several practical measures have been proposed to limit SBS, including regular ventilation, ensuring sufficient air exchange, cleaning surfaces, and using exhausts, such as kitchen hoods, to remove pollutants [5].

However, the COVID pandemic has changed the course of the traditional IAQ and SBS research. Instead of asking why buildings make us feel so sick, researchers are now asking how buildings can make us feel healthy.

The notion of a healthy building entails that "a building continues to maintain optimal occupant physical, mental, and social wellbeing conditions during extreme events and over extended periods' [7]. Today, there are many combined parameters that assess a given space's indoor environmental quality (IEQ). Researchers and architectural practitioners are increasingly exploring how buildings impact our health, focusing on indoor environmental quality (IEQ) factors such as thermal comfort, ergonomics, and air quality devoid of pollutants. IEQ refers to "the quality of building" environments in relation to the health and well-being of those who occupy space within them [8]. Such parameters include the indoor air quality in addition to the thermal comfort, noise levels, water quality, interior design, furnishing within a space, and general social health and mental well-being of occupants [7]. IEQ-related studies have emphasized the importance of using materials with minimal emissions and providing occupants with control over their microclimate. Personalized interior design that reflects personal taste and a strong connection to the outdoors is also a key element.

The idea of healthy buildings is a buildup of several concerns that existed pre-COVID, including concerns about the impact of climate change on micro-climates, aging demographics in the northern part of the globe, and rapidly growing populations in the south [7]. Additionally, addressing energy inefficiencies in existing buildings and adapting to changing lifestyle patterns characterized by long working hours and high anxiety levels are critical.

Researchers aim to create buildings that promote well-being, acknowledging that a holistic design approach can significantly enhance the quality of life of occupants. Air quality is a crucial aspect of healthy buildings. Ensuring that indoor air is free from pollutants requires efficient ventilation systems, high-quality air filtration, and regular maintenance to prevent the buildup of harmful substances, such as volatile organic compounds (VOCs), mold, and allergens. The COVID-19 pandemic has highlighted the need to efficiently use indoor spaces, upscale living environments, and engage all family members in creating healthier living conditions. Constraints, such as occupant density and building typology, significantly influence how these factors can be implemented.

Researchers often employ either one of the two methods to assess occupant comfort and well-being in buildings. The first was the use of field measurements [7]. For example, monitoring temperature and humidity levels or visual examination of molds and bio-pathogens. The second method involves conducting occupancy surveys to obtain direct feedback. Building performance standards, such as WELL standards [9], Building

Research Establishment Environmental Assessment Method (BREEAM) [10], Leadership in Energy and Environmental Design (LEED) [11], and Fitwell [12], as well as other local standards such as the Greenship Interior Space rating system adopted in Indonesia [13], all use a combination of the two schemes to obtain an accurate assessment of occupants' comfort and well-being.

Research Objectives

Given this background, the purpose of this study is to review the implications of the pandemic on IAQ by identifying consequences related to IAQ recommendations published in early publications during the pandemic. This research points to several lessons learned on adapting best practices to improve IAQ after the pandemic. Through the literature review, this paper studies IAQ recommendations to make their impacts on the built environment explicit. Some of the recommendations within the published literature utilize different building typologies as case studies; these include educational spaces, classrooms, healthcare facilities, and residential spaces, and each has been tackled with a unique set of methodologies for IAQ testing and validation. Thus, the available studies present a set of rule-of-thumb practices for building operators to improve the IAQ of their respective facilities. Most importantly, they present methodologies to realize improved IAQ in different facilities. While many researchers have extracted, summarized, analyzed, and compared these recommendations, to the best of our knowledge, no previous work has attempted to examine the consequences of these recommendations on the built environment.

Research Scope, Limitations and Main Contribution

The main scope of this research is to examine early publications related to indoor air quality (IAQ) during the early phase of the pandemic—from March 2020 to August 2021—to identify thematic research areas anticipated to shape the future interests of the scientific community for at least the following 10 years. The selected timeline is understandably a research limitation but is justifiable on a number of fronts. First, the onset of the COVID-19 pandemic in March 2020 marked a significant shift in global health priorities, bringing unprecedented attention to IAQ due to the airborne transmission of the virus. This period witnessed a surge in scientific publications focusing on IAQ, where a growing number of countries around the globe were implementing stringent lockdown measures.

Second, the 18-month window captures the breadth of the initial responses, adjustments, and innovations in IAQ practices and policies, providing a comprehensive snapshot of the early pandemic phase. By analyzing publications from this specific timeframe, the authors were able to pinpoint the foundational ideas and urgent questions that arose in response to the pandemic. These insights are crucial for developing an analytical framework to interpret IAQ research areas based on intentionality and impact. The limitation of this period also ensures that the study remains focused and manageable, allowing for an in-depth examination of the selected publications without being overwhelmed by the subsequent flood of research that followed. What we understand from the narrative of air quality policy is that the quick emergency response taken by governments around the globe has, to some extent, affected the quality of the initially published recommendations by policymakers, including leading organizations such as the WHO, CDC, REHVA, and ASHRAE [1–3]. While this can be considered a strong claim, the deduction is best understood considering the urgent need to issue IAQ guidelines and practical recommendations to combat the pandemic promptly. These were mostly written under the assumption that they are temporary based on the belief that the pandemic is a short-term health hazard.

Today, we know that COVID-related variants and other airborne viruses are here to stay, and thus, looking more critically on their intended and non-intended consequences is critical for improving them to ensure that we continue to balance health and performance. This article contributes to the existing body of knowledge by incorporating and synthesizing the aforementioned understanding through a review of published work. That said, the chosen timeline serves to contextualize the study within a critical historical moment. The main contribution of this research is thus laying the groundwork for understanding how initial pandemic responses can inform and shape future IAQ research and policy direction over the next decade.

MATERIALS AND METHODS

The research method is based on a broad literature scan of works published by Scopus and CrossRef. The search parameters included “COVID” and “Indoor Air Quality” in the title of the publication or abstract. Variations in COVID, such as COVID-19, coronavirus disease, coronavirus, and SARS-CoV-2, were used to ensure coverage. The time span was limited to the period between March 2020 and August 2021. The aim was to find articles that answered the following research questions: What are the main recommendations within the academic literature on indoor air quality published in response to the pandemic? What are the consequences and implications of these IAQ recommendations on building design parameters, health, occupant well-being, energy efficiency, building performance, and use of technology? After reviewing recommendations on indoor air quality affecting the built environment, what gaps in the literature require immediate attention? Owing to the large number of publications on this topic, a filtering process was used, as described below.

The initial literature scan yielded 1078 results. Duplicates were eliminated from the database as a primary filtration step. Following this, the inclusion criteria were developed and used. They are: (1) the title of the article answered or linked directly to any of the listed research questions, (2) the article is in the English language, and (3) the article fell within the specified time frame (i.e., from the start of the pandemic) and scope (i.e., indoor air quality). Articles outside the scope of the study were excluded. For example, the filtration process eliminated articles discussing ambient air quality during COVID-19, the effect of lockdown measures on air quality, and air pollution.

To further focus the review, a relevance scoring was used to rate all included sources from 0 to 3, where 3 is significant research that must be included and shows rigorous methodological logic, and 0 is irrelevant and presents weak methodological work, redundant, or general works that could be eliminated. In consultation with industry experts, the research team carried out a rating based on scanning titles and abstracts. From this process, only 85 articles were retained for further analysis.

The 85 sources' introduction and concluding sections were read in more detail to retain only sources that focus on providing non-behavioral practical recommendations to improve IAQ in the face of the pandemic. At this stage, the team eliminated medical research articles (not addressing buildings or indoor spaces), articles that focused on issues such as mobility, air transport, or traffic, and studies related to the tourism industry (non-building related).

Following this process, the final list comprised 30 articles from the original 1078 results. These were mainly journal articles published in high-impact publications. Only a few non-journal publications were retained because of their relevance and significant contribution to the COVID guidelines and policy analysis. Moreover, in an effort to bring the review up to date, a couple of more recent articles were selected, published after August 2021, and referenced in the discussion and analytical sections.

The research team then divided the retained publications into three main topics and six subtopics: (1) the policy dimension: (1-A) General review, (1-B) COVID-specific policies, (1-C) Viral transmission, (2) air quality: (2-A) Ventilation, (2-B) Technology, and (3) indoor energy and building performance. Figure 1 presents a visual overview of this categorization.

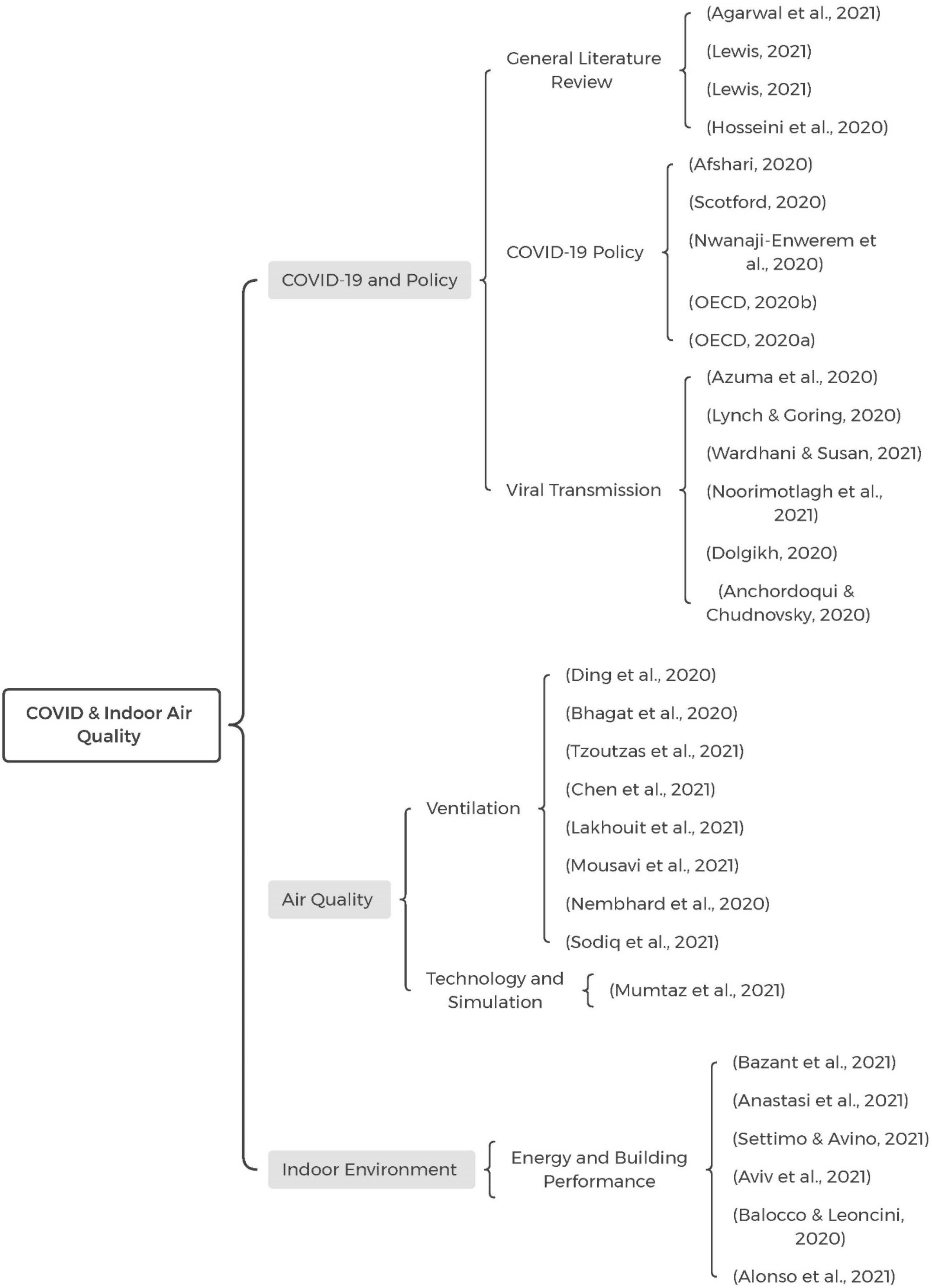

Figure 1. Literature review concept map.

RESULTS

The results of the literature review are presented in a table format listing the study titles, authors, and content summary (Supplementary Table S1). The table presents references based on the sub-topics proposed in Section 2 (RESEARCH PROBLEMATIC): general literature review articles (four references), COVID-19 policy (five references), viral transmission (six references), ventilation (eight references), technology (one reference), and energy and building performance (six references). Figure 1 presents a summary of the reviewed literature. The 30 articles are presented in the following subsections.

HVAC, Ventilation and Air Quality Guidelines

Heating, ventilation, and air conditioning (HVAC) systems play a crucial role in maintaining the indoor air quality and ensuring the comfort of building occupants. Effective HVAC systems should adhere to the guidelines that prioritize adequate ventilation rates, efficient filtration, and humidity control. Awada [7] noted that eliminating the transmission of airborne viruses, such as COVID, through HVAC is not possible. Instead, HVAC operations and ventilation should focus on developing appropriate measures to reduce the risk of infection. They identified four key HVAC parameters that are critical for this risk reduction: (1) ventilation, (2) filtration, (3) disinfection, and (4) proper operation and scheduling. As such, it is important to follow the correct HVAC operational guidelines, since if they are not applied correctly, HVAC can worsen viral transmission and become a source of contamination by itself [14]. From the four parameters listed by Awada [7], ventilation has received significant attention in the literature.

Agarwal [14] studied various ventilation recommendations by researchers and international organizations. For example, ASHRAE provides comprehensive standards, such as ASHRAE 62.1, which specifies minimum ventilation rates to ensure that sufficient outdoor air is introduced to dilute indoor contaminants. Research studies have also highlighted that depending solely on natural ventilation is impossible within enclosed environments, especially in office buildings with facades made of non-operable curtain walls [14]. However, this depends on the building design. Gil-Baez et al. [15] studied the effect of natural ventilation within classrooms in a Mediterranean climate and showed that it is possible to retain adequate ventilation levels, sustaining an acceptable level of thermal comfort under mild climate conditions. In addition, occupant behavior can affect the extent of indoor air quality. Tahmasebi et al. [16] studied window operation behavior and its effect on IAQ during lockdown based on real-time data, and recommended more stringent strategies to improve IAQ than relying solely on natural ventilation. Chen et al. [17] offered guidelines for ventilating indoor spaces to minimize COVID-19 transmission rates. They introduced a mathematical model to calculate the necessary ventilation rate for an indoor area based on the type of activity. Additionally, they suggested various methods to ensure that adequate ventilation rates were achieved [17]. Other studies have provided empirical validation for some ventilation rates and HVAC operation guidelines suggested by international organizations. For instance, Atkinson et al. [18] noted that the World Health Organization (WHO) recommends a ventilation rate of 288 m^3/h/person in healthcare settings, which can be accomplished using either natural or mechanical ventilation.

It is clear that no ventilation rate can completely eliminate the risk of infection; however, it can reduce the viral load in the droplets. Awada [7] pointed out that while many terms and suggestions from the reviewed guidelines are similar, the precise ventilation rate required to minimize the transmission of an airborne virus is not specified and requires further research [7]. As such, the recommendations of the different guidelines regarding the optimum ventilation rates vary significantly and depend on the building typology, the standard modes of ventilation in a specific region, and other human and cultural dimensions. As observed by Awada [7], this is one area of research in which more conclusive evidence needs to be found.

These findings stress that, as suggested by ASHRAE and REHVA [19,20], air recirculation in indoor environments is not recommended. According to ASHRAE's May 2020 guidance for building operations during the COVID-19 pandemic, it is recommended to reduce population density and maintain maximum outside airflow for two hours before and after the building is occupied [19]; is a needed measure to eliminate viral loads in buildings. Maintaining social distancing and reduced space occupancy are among the factors that would make lower ventilation rates in buildings acceptable [19]. Anand et al. [21] pointed out that while maintaining AHSRAE 62.1 standards specifications concerning required ventilation based on occupancy schedule and density may lead to energy savings with regard to HVAC operations; such specifications are not sufficient to reduce infection rates within enclosed spaces.

As proposed by Azuma et al. [22], controlling environmental quality parameters, such as temperature and relative humidity, is necessary to decrease the degree of contamination, whereby high temperatures and low humidity levels were shown to decrease infection rates [23–26]. Awada [7] pointed out that the multi-stakeholder group in charge of commissioning the building, including designers, architects, contractors, sub-contractors, and building operators, often have conflicting information and perspectives that hinder the implementation of the performance criteria that contribute to a higher indoor environmental quality, and the cost is often the final deciding factor. While IAQ and well-being standards offer some guidance, the extent to which occupants' health is considered the priority objective within such standards is not affirmative.

Wardhani et al. [13] reviewed the relevant literature on indoor health and comfort criteria that require revision to reduce COVID-19 infection rates within confined spaces. They analyzed the Greenship International Rating System in light of the pandemic and benchmark-published recommendations on IAQ to better adapt the Indoor Health and Comfort performance criteria [13]. The recommendations for adjusting these criteria include introducing outside air, stopping air recirculation, reducing the indoor user capacity, and reducing indoor biological and chemical pollutants.

Focusing more specifically on air purifiers, Mousavi et al. [27] examined their effects in parallel with mechanical ventilation in a dentistry clinic. The study indicates that while mechanical ventilation significantly dilutes pollutants, air purifiers also improve indoor air quality by lowering particulate matter (PM 2.5) and total Volatile Organic Compounds (tVOC). Sodiq et al. [28] further investigated the combination of air purifiers and HVAC operations and recommended innovative solutions such as integrating Ultraviolet Germicidal Irradiation (UVGI) with nanoporous air filters to effectively reduce the spread of COVID-19 and other harmful microbes in indoor spaces.

On a more practical note, other researchers offer recommendations for a “cleaning protocol” for the maintenance of HVAC systems in non-medical settings [29]. They stressed the importance of proper maintenance and regular inspection to ensure that HVAC systems operate efficiently and provide a healthy indoor environment. Additionally, they highlighted the role of High-Efficiency Particulate Air (HEPA) filters and the use of Minimum Efficiency Reporting Values (MERV) 13–16 filters, as recommended by ASHRAE [30]. Wu et al. [31] further evaluated filters in association with HVAC systems regarding particle-size removal efficiencies, confirming that MERV 13 filters are effective in removing small particles (0.1–1.0 μm in diameter). Consequently, maintenance and cleaning protocols, along with regular social distancing and facial mask measures, are essential to reduce the risk of viral transmission.

Viral Transmission

Closely tied to the study of HVAC system operation and ventilation methods is the means of viral transmission and the implications of HVAC operation in reducing or accelerating transmission [32]. The design and operation of HVAC systems are critical for minimizing the risk of viral transmission, particularly in the context of airborne pathogens, such as COVID-19. Anchordoqui and Chudnovsky [33] simulate droplets / COVID-19 virus in an aerosol form and tracked its motion within a room. The results of the simulation showed that (1) the virus can remain suspended in air for hours and (2) the HVAC operation can affect the movement of the virus particles, allowing them to spread beyond the recommended 6 ft of social distancing. They conclude that “inhaled viral load depends on the virus concentration in the air and the time of exposure”, where the varying concentration depends on several parameters—including: "the location of doors and windows, ventilators, heaters, movement of people, etc." [33].

In a more structured literature review, Bhagat [34] broke down many parameters influencing the transmission of the COVID-19 virus within an indoor space. This includes types of ventilation, airflow patterns, people's behavior or influence within a space, droplet size, and means of transmission. The discussion points are supported by mathematical models, computational simulations, or quantitative evidence. Important to mention However, this study lacked specific recommendations for building operators.

Their study of virus containment in nursing homes, Lynch and Goring [35] present depressurization as a practical containment technique. Their recommendations are simplified into five steps: converting a space into a negative air pressure zone to ensure that air does not flow outside the room when a door opens, thus keeping contamination contained. Noorimotlagh et al. [36] provided a systematic review of the literature discussing potential airborne transmission methods of COVID-19 in indoor environments. The authors' recommendations are summarized as follows:

- Provision of Ventilation Systems. Implementing systems, especially displacement ventilation.
- Redesigning Spaces. Increasing the existing ventilation rate and efficiency through spatial redesign.
- Stricter Policies in Hospitals. Applying more stringent air quality and ventilation control policies to COVID-19 patient wards to reduce infection rates. A recommended strategy is to "isolate COVID-19 patients with high viral loads in the exhaled air in the first weeks of infection" [36].
- Promoting Social Distancing. Adhering to the WHO's recommendations on social distancing and avoiding overcrowding.

Based on the reviewed literature, it can be concluded that improvements in HVAC and ventilation alone cannot eliminate airborne viral transmission. Evidence also indicates that the WHO's 6 ft social distancing recommendation is effective only when combined with appropriate HVAC and ventilation procedures.

Enhanced ventilation, using higher efficiency filters (such as MERV-13 or higher), and ensuring proper humidity levels (between 40%–60%) can reduce the concentration of viral particles in the air. Additionally, integrating advanced technologies, such as ultraviolet germicidal irradiation (UVGI), within HVAC systems can help inactivate airborne viruses. These measures, combined with good hygiene practices and social distancing, are vital for creating safer indoor environments.

Building Performance, Comfort, and Innovation

A key research area gaining attention within indoor air quality (IAQ) and COVID-19 discussion is the impact of high ventilation rates on HVAC energy efficiency and overall building performance. Settimo and Avino [37] highlighted the "dichotomy between indoor air quality and energy efficiency" during the pandemic. They argue that the debate over prioritizing human health by focusing on IAQ is not new, as evidenced by past discussions on sick-building syndrome. The authors proposed several high-level strategies and recommendations for governments to address this significant challenge. These strategies include optimizing the HVAC system operation to balance IAQ and energy use, adopting advanced technologies to enhance ventilation efficiency, and implementing policies that encourage energy-efficient building designs while maintaining high IAQ standards.

Alonso [38] studied the effect of international guideline recommendations for overventilation with a fresh outdoor air supply. They found that the recommendations applied to two classrooms in southern Spain during winter resulted in 60 percent of the operational hours outside thermal comfort conditions. Others, such as Balocco et al. [39] and Bazant et al. [40], also focused on educational settings. Most relevant to the discussion is the work of Balocco et al. [39], who studied the ventilation in a historical school building. The authors aimed to balance the energy savings and ventilation conditions to achieve an optimized indoor air quality scenario that ensures the sustainability of the school as a healthy building.

Anastasi et al. [41] elaborated on the challenges of achieving energy-efficiency measures and thermal comfort standards in smart buildings during the pandemic. In other words, they raise the question of balancing between meeting the HVAC ventilation standards, which consumes much energy, and simultaneously optimizing energy efficiency requirements. The author proposed simulation modeling to balance the energy efficiency and comfort parameters. They also proposed using new technologies, such as infrared cameras, to detect occupants and their movements and to operate HVAC systems accordingly. They experimented with thermal comfort thresholds to study the effect of natural ventilation, both separately and in combination with mechanical ventilation. Furthermore, Anastasi et al. [41] provided an overview of the available sensor technologies, including those detecting CO_2 concentrations, temperature, and humidity levels.

Bazant et al. [40] proposed an updated guideline aimed at mitigating indoor airborne viral transmission of COVID-19, building upon an existing standard and incorporating carbon dioxide monitoring. Their approach includes a mathematical model that allows the prediction of airborne transmission risk based on real-time CO_2 measurements [40]. Practical examples demonstrate how these data can be effectively applied to university classrooms and office spaces according to guideline specifications.

Pastor-Fernández et al. [42] developed a cost-effective device for monitoring carbon dioxide levels, designed to integrate with Internet of Things (IoT) solutions for dynamic monitoring in existing buildings. Mumtaz et al. [43] introduced an innovative mobile application prototype for monitoring indoor air quality. Their sensor system detects eight types of indoor pollutants and provides meteorological measurements, providing real-time results accessible via web and mobile applications. This solution offers advantages such as remote monitoring, scalability, and portable hardware capabilities [43].

Seeking practical solutions, Aviv et al. [44] advocated radiant heating and cooling systems as a way to decouple ventilation from thermal controls. Their findings indicated that traditional systems can double cooling costs when outdoor air is increased, whereas radiant systems can halve these costs by enhancing natural ventilation [44]. Ding et al. [45] emphasized the pivotal role of artificial intelligence (AI) and machine learning in optimizing ventilation and airflow control. They stressed the importance of expanding Computational Fluid Dynamics (CFD) modeling to achieve more rigorous and timely management of indoor environments.

Innovative control and sensing tools can significantly enhance the effectiveness of policies and guidelines, as underscored by OECD documents on COVID-19 [1,2]. Such digital innovations, developed in response to the pandemic, present a remarkable opportunity for policymakers to efficiently address the commotion created by the pandemic in an efficient manner [1]. Among such innovations are mobile applications that track individual locations and mobility patterns and aggregate personal and health data, although they also raise significant concerns regarding individual privacy rights [2].

High-performance buildings integrate advanced technologies to enhance occupant comfort while optimizing energy efficiency. Smart building technologies, such as automated lighting, climate control systems, and occupancy sensors, contribute to the creation of adaptable and comfortable spaces. These systems collect and analyze data to adjust environmental conditions in real time, ensuring optimal comfort while minimizing energy consumption.

ANALYSIS

The authors analyzed the literature on indoor air quality (IAQ) during the pandemic and related guiding documents and identified a range of consequential outcomes. These include spatial design, well-being and comfort of occupants, building performance, requirements for ventilation and energy efficiency, utilization of technology, considerations of health and social equity, and policy implications. These overlapping themes, which are recognized as consequences of recommendations on improving the management of IAQ during the pandemic, are discussed in the following section (refer to Figure 2).

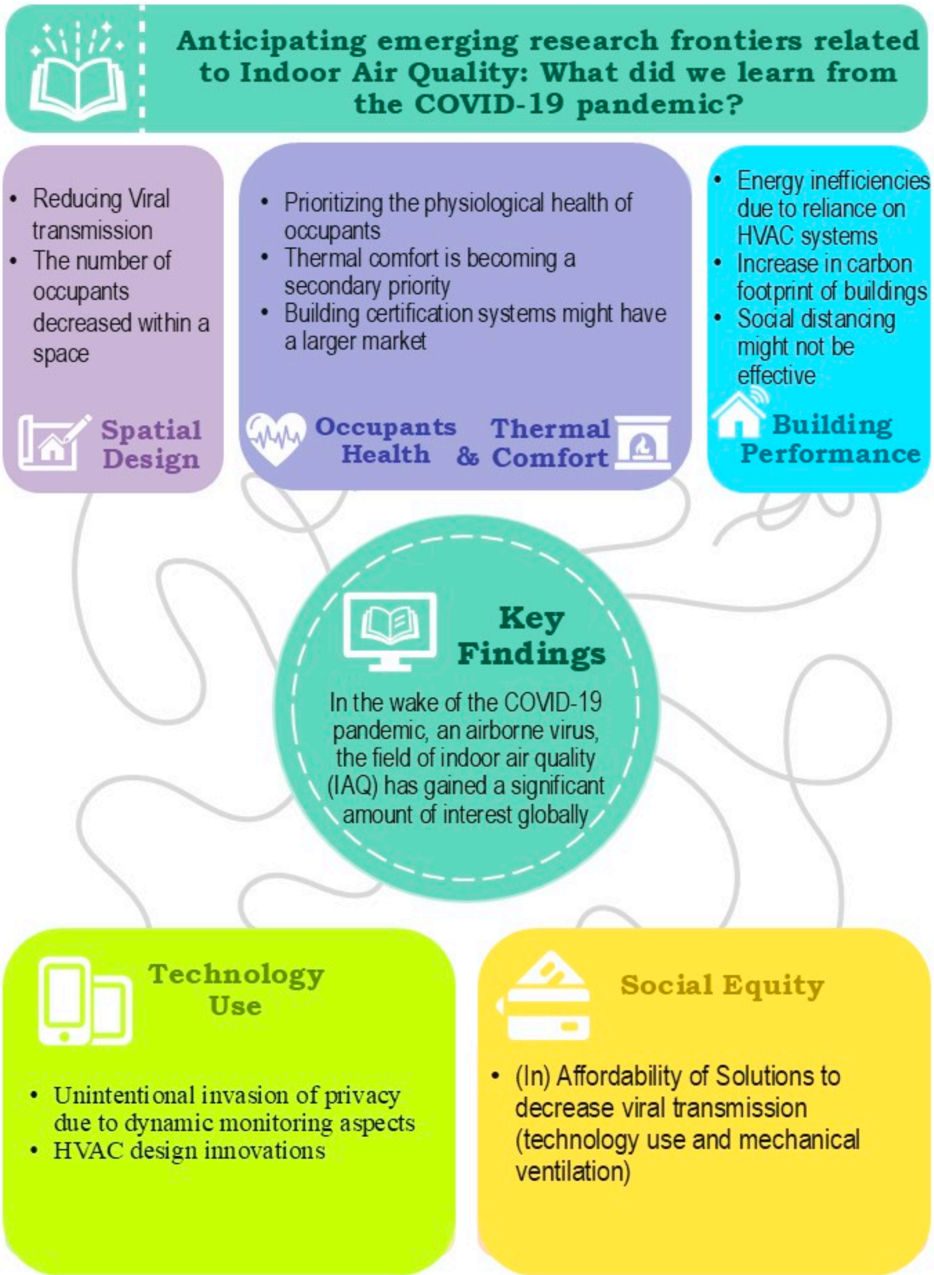

Figure 2. Key findings—IAQ recommendations instigated consequences.

The consequences of COVID on indoor air quality in a built environment were analyzed based on intentionality and impact. In other words, whether such consequences were indeed taken into consideration when the recommendations were published to combat the pandemic or unintentional in that they were a quick response to exponential health hazards without evaluating their effects on the built environment and its occupants. Furthermore, the impact of such consequences is conceptually categorized as either short- or long-term. The short-term refers to the consequence that a future addendum can quickly remedy IAQ recommendations. Alternatively, the long-term impact is on the other end of the spectrum, with a conceptual timeframe of >10 years. The researchers, in consultation with industry experts, analyzed the extracted consequences (Supplementary Table S2).

If we metaphorically analyze these consequences along a spectrum, the short-term intended consequences are characterized by a low impact level. Researchers are actively exploring alternative solutions to alleviate these perceived impacts. For instance, the challenge posed by the ineffectiveness of social distancing in indoor environments that rely on mechanical ventilation has been addressed through diverse research approaches. To name a few: simulating the extent of virus transmission through Computerized Fluid Dynamics (CFD) modeling [46], finding the optimal seating arrangement within an indoor space to reduce viral transmission and achieve thermal comfort [47], experimenting with aerosols to increase the efficiency of air purifiers [31], and other technical innovations and experimentation in the fields of psychology and behavioral sciences. However, at the other end of the spectrum, there were long-term, non-intended consequences. This category has the potential for disruption. For example, HVAC design innovations with the purpose of reducing viral transmission and increasing the efficiency of mechanical ventilation systems will propel the whole industry towards technological advancements—from now until the unforeseeable future. Although such technical advancements are perceived as a non-intended consequence, the impact is generally positive. HVAC design innovations will inevitably try to balance the diverse parameters of energy, environment, and socioeconomic parameters. From an energy point of view, HVAC innovations will aim to increase the energy efficiency of the designed systems to align with the 100% fresh air intake recommended by ASHRAE [44]. With regard to the environmental objective—linked to the carbon footprint—an interesting question is how such HVAC innovations will impact the carbon footprint of buildings in the long run. Another probing investigation is the extent of affordability of the proposed solutions (technically innovative mechanical ventilation) for use by the wider public to safeguard their health and comfort. These are just some examples of instigated consequences related to IAQ deduced from the reviewed literature, which sets the tone for future research.

DISCUSSION

The discussion section aims to delve deeper into the identified areas and provide insightful observations, fostering a thorough exploration of multifaceted research frontiers surrounding indoor air quality (IAQ). Under each heading, is a pointer providing the analytical framework summary (Table 1 to Table 5) represented in Figure 2 in the analysis section above.

Spatial Design

Table 1. Spatial design*.

Anticipating Concerns Regarding Spatial Design Requirements Post-Pandemic	
Reducing viral transmission	Long-term impacts—with respect to the architectural and spatial design of indoor environments—involve reducing the transmission of viruses, meeting the intended goal, with an intentional consequence to sustain reduction in transmission is expected.
Number of occupants decreased	Long-term consequence is met with a decrease in occupants per footprint presumably by the adaptation of building standards to improve health and wellbeing. This is a non-intended consequence, which may lead to more permanent change in spatial use and design.

*Identified research area regarding instigated consequences of IAQ recommendations.

What we are sure to perceive during the upcoming research agenda in the architectural design discipline is the focus on spatial layouts that are conducive to the health and well-being of occupants. This focus on the healthy design of spaces stems from the recommendations postulated by pandemic-urging architects to design and retrofit spaces in order to reduce viral transmission between occupants. A questionable hypothesis is that the greater the square footage of space per occupant, the less possibility airborne viruses are transmitted, that is, social distancing. In other words, social distancing and occupancy reduction requirements are manifested in an isolated zoning program of architectural spatial that aims to increase air permeability and reduce air recirculation.

This conceptual understanding of space segregation and isolation has already begun to unfold across different building typologies: office spaces, educational facilities, medical settings, and commercial spaces. For instance, office spaces are shifting from open-plan layouts to private or enclosed offices, designed for single occupants or small groups. Likewise, schools and educational facilities are moving towards smaller classroom sizes to accommodate fewer students per room. In medical settings, large open zones, whether in waiting areas or wards, are being reconsidered for more segmented designs. This trend also extends to commercial spaces like restaurants and retail centers, where designs that incorporate outdoor elements are increasingly favored. This shift also occurs in residential buildings, where changes in behavioral patterns are also observed. Alhusban et al. [48] contemplated "How the COVID 19 pandemic would change the future of architectural design", and communicated insights regarding the future of interior design. The study confirmed the need for indoor environments that promote occupant health and echoed biophilic design principles, such as increasing daylight permeability within residences and integrating open green spaces whenever applicable. The study commented on the behavioral changes post-pandemic, where the home office would be an important element of zoning activities. The move towards incorporating biophilic design elements and adopting standards that prioritize occupant well-being is rapidly accelerating. For example, the number of certified buildings from the two major standards, WELL [49] and Fitwel [50], has increased nine-fold in the last three years [51]. By August 2021, there were over 960 projects worldwide certified by WELL and Fitwel, with an additional 1431 projects either in the process of certification (Fitwel) or pre-certification (WELL). During the pandemic, both organizations introduced significant new rating standards to address disease transmission risks, leading to an additional 7684 properties achieving these ratings [52].

That said, the logical concept of increasing building permeability and reliance on both natural and mechanical ventilation would move designers away from the characteristically airtight standard smart buildings trend, if not make amendments to the building envelope to adapt to IAQ guidelines. Thus, the design discipline is challenged by a complex agenda of competing priorities to be achieved within a given space: zoning to provide safe and healthy spaces, improving IAQ requirements, and increasing the permeability of buildings while optimizing performance.

Recent blog reports have highlighted the major design strategy trends influenced by the pandemic [53,54]. These include innovation to tackle real-time challenges, promoting resiliency and human-centered design, and emphasizing future-proofing and scenario planning as fundamental tools in the design process [54]. Additionally, there is a focus on smart design, the adoption of technology, and increased attention to hygiene. Other trends include fostering a stronger connection to outdoors and reimagining collaboration in commercial and workspaces [53].

Occupants' Health and Thermal Comfort

Table 2. Occupants' health and thermal comfort*.

Anticipating Concerns Related to Occupants' Health and Thermal Comfort Post-Pandemic	
Prioritizing physiological health	Indoor environments design are foreseen to optimize for prioritizing the physiological health of occupants, which is an intended consequence to published IAQ recommendations.
Thermal comfort as a secondary priority	In the short term, thermal comfort may be compromised for the sake of health. It is however, an non-intended negative consequence to published IAQ recommendations during COVID. Building certification systems might have a larger market in the future. The shift in spatial design perceptions and objectives, together with the health priorities of occupants is expected to give 'rise of new rating systems' that achieve such objectives. It is a non-intentional consequence to published IAQ recommendations during COVID.

*Identified research area regarding instigated consequences of IAQ recommendations.

The literature has presented cumbersome evidence linking IAQ status to occupant health and thermal comfort. What we observed, however, is "health over comfort" is the underlying motto of the reviewed literature. Prioritizing comfort and leveraging technology in building design not only improves occupant well-being but also contributes to long-term sustainability goals Many studies—following the IAQ recommendations posted during the pandemic—reported on occupants' thermal discomfort in indoor spaces, especially in the winter season [22,38].

In addition to physiological health, occupants' psychological well-being is an issue of concern brought about by the lockdown experience and isolation activities endured during the pandemic. Accordingly, it is another important item on the policy-making agenda, as well as on the scientific researchers' community. The implications of isolating spaces are yet to be explored, including the risks of increasing anxiety, stress, and depression among the occupants. Safeguarding an occupant's health, well-being, and comfort is a multi-layered endeavor in the context of IAQ.

The question then becomes: How can we maintain an acceptable IAQ status within a given space while optimizing occupant comfort, health, and well-being in various indoor settings, and how can design interventions address these factors?

Guidelines can be considered a form of soft policy intervention, and the IAQ guidelines published during the pandemic have long-term implications. Guidelines continue to be written under the assumption that they are temporary based on the belief that the pandemic is a short-term health hazard. Little consideration is offered to the possibility that the pandemic may continue for an extended period. A key takeaway from the pandemic is the ease of viral transmission in enclosed areas. In that light, guidelines must be written in a much clearer language to account for long-term affordable solutions that can be universally applied.

Green building rating systems serve as supplementary guidelines. Current certification systems such as LEED primarily prioritize energy performance rather than ensuring that buildings meet the recommended standards for healthy ventilation relative to indoor air quality (IAQ) guidelines. This is in contrast with the current emphasis on creating healthy environments for occupants in the post-COVID-19 era. Alternative standards, such as the WELL Building Standard [9], which focuses more on occupant well-being, may see increased adoption. Nevertheless, there is a growing indication that existing green building certification systems will evolve to address the health and comfort needs of building occupants in the near future. There is also the potential for new rating systems to emerge, potentially introducing a new label for buildings that prioritize airborne safety, although it is too early to predict their widespread adoption. Balancing these health considerations with financial concerns, particularly energy savings, presents a complex challenge as discussed in the following subsection.

Building Performance and Ventilation

Table 3. Building performance and ventilation*.

Anticipating Concerns Regarding Building Performance and Ventilation Post-Pandemic	
Energy inefficiencies	It is an impact perceived in the short-term due to excessive reliance on HVAC and dual modes of ventilation. It is a non-intended consequence to publish IAQ recommendations.
Increase in carbon footprint	As a result, increase in carbon footprint of buildings is perceived as a short-term impact, which is yet another unintentional consequence to published IAQ recommendations.
Effectiveness of social distancing	Short-term impact suggests social distancing may not be effective in mechanically ventilated environments—especially relying on centralized units. Though the use of HVAC systems of increased fresh-air percentages is an intentional best practices measure, studies show that it does not eliminate viral transmission.

*Identified research area regarding instigated consequences of IAQ recommendations.

The literature on indoor air quality (IAQ) recommendations during the pandemic proposes various methods to maintain occupant health and comfort. These include optimizing HVAC units, increasing ventilation rates, and adopting advanced air-purifier technologies. However, the implementation of these practices often conflicts with the energy-efficiency goals of building operations. Consequently, there is a growing need for HVAC design advancements that strike a balance among energy efficiency, air purification, and filtration.

Furthermore, the prioritization of occupant health necessitates a critical reevaluation of centralized HVAC systems. Studies suggest that viruses can spread over longer distances than the recommended 6-foot social distancing guidelines when centralized HVAC units are used. This underscores the urgency of rethinking HVAC strategies to effectively mitigate airborne transmission risks.

In the reviewed literature, significant attention has been paid to assessing the effectiveness of mechanical ventilation in reducing viral transmission rates, especially in high-risk environments, such as medical facilities. IAQ recommendations emphasize the importance of relying on air purifiers and mechanical ventilation systems to enhance indoor air quality and minimize infection risks.

The increased reliance on mechanical ventilation inevitably leads to higher energy consumption patterns. Discussions on ventilation's role in improving IAQ highlight concerns about energy inefficiency. Ongoing innovations aim to mitigate these challenges, but another consequential outcome is the potential increase in buildings' carbon footprints due to the demand for dual ventilation modes and enhanced operational requirements. The main takeaway is that whenever the design permits, optimization for IAQ will tend to incorporate advanced HVAC systems with high-efficiency particulate air filters and the use of bio-filters to reduce pathogens, as well as reduce pollutants such as volatile organic compounds [55]. The question then turns out to be how to optimize energy efficiency when using such ventilation system technologies.

Technology Use and Energy Efficiency

Table 4. Technology use and energy efficiency*.

Anticipating Concerns Regarding Technology Use and Energy Efficiency Post-Pandemic	
Invasion of privacy	A long-term impact due to innovative technological solutions developed during the short-time frame of the pandemic. Data privacy measures are perceived to be more stringent in the future. It is yet another unintentional consequence to the pandemic.
HVAC design innovations	In the long-term the HVAC industry would foresee exponential rate of innovation in technology development to improve efficiency, filtration, and purification systems. It is a positive unintentional consequence to published IAQ recommendations.

*Identified research area regarding instigated consequences of IAQ recommendations.

The importance of decreasing viral transmission and improving the energy efficiency of installed ventilation systems suggests that this technology will play a more powerful role in monitoring IAQ parameters.

A key technological application can be found in the use of artificial intelligence (AI) dynamic sensors. These sensors apply the notions proposed in discussions pertaining to smart buildings and follow occupant movements. This enables them to monitor IAQ and the energy efficiency of ventilation systems, as well as whistle-blowing if contamination is detected. However, it is important to consider the possible consequences of such a technological direction, primarily within the scope of open-access data and its implications for social privacy.

Privacy remains a crucial issue in the context of big data analysis for indoor air quality (IAQ) monitoring. The practice of tracking user movements both inside and outside buildings to control infection rates has raised concerns among human rights organizations worldwide. However, from a research standpoint, the accessibility of these innovations and accurate real-time data are essential for protecting the health of occupants.

It is important to note that the recommendation of blasting air conditioning (AC) systems along natural ventilation requirements, in particular, results in energy inefficiencies [37]. At first glance, building ventilation requirements are perceived as a dichotomy between mechanical and passive ventilation. However, maintaining the dual mode of ventilation in the complementarity mode maximizes clean airflow and circulation.

Health and Social Equity

Table 5. Health and social equity*.

Anticipating Concerns Regarding Health and Social Equity Post-Pandemic	
(In) Affordability of solutions	Affordability of solutions in favor of public health—such as web and mobile applications, and HVAC technologies—in the long term. It is yet another positive unintentional consequence to published IAQ recommendations posted during the pandemic.

*Identified research area regarding instigated consequences of IAQ recommendations.

Relying on technology—particularly forms that are not yet affordable—to improve IAQ and mitigate viral transmission has often-neglected implications on social equity. The fact that spatial requirements lean more towards individualistic spaces supports the argument for the lack of social equity, as these spaces may not be an affordable option for the larger community.

The issue of social equity affects not only residential areas but also various types of buildings. For example, during the peak of the pandemic, hospitals became overcrowded, making it difficult to maintain high-quality standards in all areas including isolation wards and ICU units. This overcrowding hinders the ability to provide adequate care and maintain proper conditions throughout the entire hospital.

CONCLUSIONS

An improved level of IAQ is a key priority for safeguarding the health and comfort of occupants. This review presents a snapshot of urgent IAQ topics being re-investigated in light of the pandemic: spatial design considerations, occupant health and comfort, building performance and ventilation, technology use, energy efficiency, and health and social equity.

Many guiding documents were issued during the pandemic, with the underlying assumption that the pandemic is short-lived. However, in the sense of reflection, airborne viruses remain [56]. This means that IAQ recommendations within new guidelines, the newly introduced addenda to existing guidelines, as well as COVID recommendations suggested in academic publications, should be assessed considering their implications in the long run and revised accordingly for future adoption.

Notably, the instigated consequences of such recommendations vary in terms of both the severity of impact and intentionality., the pandemic, has left much room for academics and practitioners to reassess their take on managing and controlling indoor air. The key findings and expected future research directions from this review are as follows.

- Building codes and standards are anticipated to see changes related to the zoning of spaces that will be catered towards a lower occupant density, and segregation of spaces to reduce viral transmission effectively.

- The HVAC industry is witnessing a jump in the scale of technological innovation to check off several parameters: higher energy efficiency performance, stringent air purification and filtration mechanisms, automated sensors to detect the exact occupant's density, greater reliance on fresh-air intake, and consideration of the thermal comfort of occupants.
- Prioritizing occupants' health and well-being is a heavy responsibility that facility managers are now aware of. To some extent, the Key Performance Indicators (KPIs) for IAQ monitoring include measuring the physiological health of the occupants.
- The tracking and monitoring of users for health, comfort, and well-being monitoring-related applications will inevitably occur through IAQ monitoring mechanisms. This raises ongoing concerns regarding data privacy and the need for robust data protection measures.
- An increase in the carbon footprint of buildings is yet another issue that unfolds in the current new norm—post post-pandemic. Whether the high ventilation rate of HVAC systems along with the natural ventilation requirements as recommended by ASHRAE will be a long-term solution to improving IAQ; is an inquisition that remains uncertain. It is certain that the percentage of recycled air in airtight buildings should be reconsidered.
- Questions on affordability and equity of utilizing advanced technology, including mechanical ventilation solutions, to achieve improved IAQ levels open wide room for discussion among policymakers to ensure equitable access to healthy indoor environments across different socioeconomic groups.

These are just evolving trends in IAQ research, which remains a work in progress. Future research work is suggested to tackle IAQ dimensions by adopting a multidisciplinary perspective to provide accurate and actionable recommendations that address the complexities of maintaining acceptable IAQ and IEQ in the post-pandemic world. Examples of topics include balancing between occupants' health, wellbeing, and environmental qualities of the built environment; providing dynamic IAQ monitoring applications and benchmarking technologies to optimize building performance, which can be further processed via machine learning technologies; and utilizing innovative solutions to enhance the overall carbon footprint of a given indoor environment by increasing its energy efficiency performance.

SUPPLEMENTARY MATERIAL

The following supplementary materials are available online at https://doi.org/10.20900/jsr20240050. Supplementary Table S1: Literature review summary; Supplementary Table S2: Instigated consequences related to IAQ and COVID-19 reviewed literature.

Supplementary Table S1 presents a summary of the reviewed articles and their main findings and recommendations; Supplementary Table S2 presents the analysis of perceived consequences to published IAQ recommendations and addendum during the pandemic, and categorizes the perceived consequences based on impact and intentionality.

DATA AVAILABILITY

All supplementary data is available online. This research has received the Institutional Review Board (IRB) approval letter (Case# 2022-2023-010).

AUTHORS' CONTRIBUTIONS

Conceptualization, FS, KT, SG; methodology, FS and SG; software, FS; investigation, FS; resources, FS; data curation, FS; writing—original draft preparation, FS; writing—review FS, SG, KT; supervision, SG, KT; project administration, SG, KT; funding acquisition, SG, KT. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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