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Review

Designing IAQ-Resilient Post-Pandemic Buildings

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Abstract: The COVID-19 pandemic has led to significant changes to human life and habits. There is an increasing urgency to promote occupants' health and well-being in the built environment where they spend most of their lives, putting indoor air quality (IAQ) in the spotlight. This study fits into this context, aiming to provide useful information about the design, construction, and operation of an IAQ-resilient building in the post-pandemic era for it to ensure a good trade-off between energy- and health-related objectives. The PRISMA guidelines were adopted to conducting a systematic review obtaining 58 studies that offered relevant results on two main research areas: (i) the concept of resilience, focusing on its definition in relation to the built environment and to pandemic-related disruptions; and (ii) the building design strategies that are able to increase buildings' resilience, focusing on the preventive measures involving engineering control. In addition, the metrics and the decision-making tools able to make IAQ-resilient buildings attractive to the investors, focusing on the cost-benefit analysis (CBA) technique, were discussed. The research supported the transition of the building sector to a human-centered approach that is able to include IAQ resilience among the main priorities of future buildings to guarantee the occupants' health and well-being.

Keywords: COVID-19 pandemic; indoor air quality; IAQ-resilient building; occupant health; cost-benefit analysis; IAQ engineering controls

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1. Introduction

The outbreak of the COVID-19 pandemic highlighted the need for a comprehensive approach to human health, emphasizing the urgency of promoting this aspect, especially in the built environment [1]. This is further corroborated by the fact that, even before the pandemic, people used to spend more than 90% of their time indoors [2]. Now, with the changes of people's habits and the encouragement to work from home, more people are required to stay in the same confined space for extended periods. These considerations suggest how the design and operation of buildings require a profound transformation to guarantee optimal conditions for the occupants' health and physical, mental, and social well-being [3].

In the last few years, the construction of new buildings and the renovation of the existing building stock have been accompanied by the objectives of "efficiency" and, more recently, "smartness", aiming to reduce the energy and environmental impact of the built environment and to monitor and manage its energy performance. A paradigm shift towards a more human-centered approach to building design and operation was first explored within the 2018 revision of the Energy Performance of Building Directive (EPBD), which highlighted the importance of ensuring adequate comfort, well-being, and health conditions for occupants [4]. These aspects were further exacerbated by the recent COVID-19 emergency, which has highlighted how the indoor environment plays a crucial role in determining the risk of respiratory infections [5]. In fact, the pandemic emergency has emphasized the need to monitor the indoor microclimate not only in old cultural heritage buildings to prevent biodeterioration of valuable artworks [6], but also in all types of buildings to ensure the occupants' health and well-being. In line with this, the growing attention paid to the indoor environment and health is driving building professionals to seek increasingly innovative solutions for designing "healthy" buildings, characterized by the presence of innovative systems supporting people's physical, psychological, and social health, and ensuring a better quality of life [7]. According to [8], "a healthy building is one with an indoor environment that is optimized to positively impact the health, well-being and productivity of its occupants". Attention has been devoted to recognizing the positive impacts that healthy buildings can bring, focusing on the "effects of built environments on both individual and public health" [8]. For the sake of exemplification, together with reducing healthcare costs, as shown in [9], a healthy building can lead to various economic benefits, including increases in its market value, improvements in workers' performances (in commercial and office buildings), and reductions in healthcare and indirect costs (e.g., health savings as a result of the reduction in sick leave in commercial buildings). According to [10], the conceptualization of healthy buildings is based on the so-called "nine foundations of a healthy building", which cover all the criteria considered as crucial for guaranteeing the occupants' health. Among them, the indoor air quality (IAQ) represents a predominant factor [11], recognizing the major impact that it has on human health, as well as on comfort, satisfaction, and productivity. According to the Environment Protection Act (EPA) [12], the indoor air can be two to five times more polluted than outdoor air, thus leading to short-term health effects (e.g., headaches, fatigue, nausea, and irritation of the eye, nose, throat, and skin), as well as long-term effects (e.g., respiratory and cardiovascular diseases, lung cancer, and stroke). Even though the COVID-19 emergency has emphasized the need to pay attention to this area, it is important to mention that IAQ is an "old issue" and that, as well as the SARS-CoV-2 virus, other pathogens or contaminants (e.g., viruses, bacteria, particulates, etc.) can threaten human health [13]. However, if the current minimum IAQ standards have protected people from normal levels of contaminants, reducing healthcare costs and productivity losses, the COVID-19 emergency has highlighted that "buildings designed to such standards lack the resilience to protect occupants effectively during infectious disease outbreaks" [14].

The COVID-19 pandemic has emphasized the need for prioritizing design strategies to improve IAQ [15], working as a catalyst for the future transition towards the construction of healthy and resilient buildings. This is particularly valid if we consider that several studies have shown the more rapid spread of the SARS-CoV-2 virus in crowded and poorly ventilated environments, as offices, schools, public spaces, etc. [16,17]. For these reasons, according to the WELL Building Standard [18], ensuring a basic level of indoor air quality that contributes to the health and well-being of the building's users has now become a fundamental requirement for post-COVID-19 construction. Specifically, there is the need to rethink the built environment by proposing an IAQ resilience-based paradigm that is capable of ensuring healthier and more adequate living spaces, while adapting to the new occupants' needs derived from the COVID-19 pandemic (including working from home). For this purpose, in line with [15], a "holistic IAQ management plan" must become the priority of human-centered building design, giving relevance to passive measures, when possible, as well as to ventilation and filtration requirements, and to the control and regulation of indoor humidity and temperature, to protect occupants from the risk of airborne infections. However, together with the considerations regarding the need to update the existing IAQ standards to increase buildings' resilience to airborne infections, there is concern about the fact that the improvement in IAQ might lead to increased energy consumption in buildings [14]. Therefore, it is fundamental that the new IAQ-resilient design and operation strategies are aligned with the objectives of sustainability and climate change mitigation, finding the right balance between indoor air quality and energy consumption. Among the various measures, achieving carbon neutrality is the key to avoiding the worst consequences of climate change, as well as bringing benefits to the entire society in terms of reduced environmental pollution and improved human health. Some recent studies have examined the current decarbonization strategies of building operations have helped plan the carbon neutral pathway of future buildings.

Xiang et al. [19] and Ma et al. [20] assessed the decarbonization progress of commercial building operations, considering the socio-economic impacts, the evolution of technology, and the climatic and end-use factors. In particular, among the various strategies for achieving carbon neutrality in commercial building operations, [19] identified the use of the district heating network for space heating and cooling in areas of high heat density, but the use of geothermal source heat pumps or hydrogen-based technologies for areas with lower heat density. IAQ-resilient buildings need appropriate engineering and architectural solutions that are capable of reducing the risk of airborne diseases and guaranteeing high levels of indoor air quality, while fulfilling the criteria of energy efficiency and thermal comfort. According to [14], engineering controls (e.g., ventilation-related interventions, and air filtration and purification technologies) are recommended for new and existing buildings to increase their IAQ resilience and to prevent the occupants from infection. However, despite their benefits, such solutions and strategies are characterized by high investment or maintenance costs, which might still prevent consumers from investing in them. Indeed, the design and operation of IAQ-resilient buildings is a "multifaceted challenge", involving several, and often competing, interests, stakeholders, costs, and potential benefits [21]. Their realization asks for adequate methods and tools that are able to make their benefits quantifiable and apparent to consumers, to support decision-making processes regarding energy investments.

The previous literature has mainly focused on the impacts of severe weather and natural disaster events (e.g., earthquakes, extreme winds, flooding, and fire) on the built environment. However, there is little understanding of resilient responses to the COVID-19 pandemic in the built environment, which represents the main focus of this review.

In the light of the above, this study aimed to understand how to design and operate an IAQ-resilient building in the post-pandemic era, looking at this challenge from diverse standpoints. By conducting a literature review, the study aimed to respond to the following research questions: (i) What does resilience of the built environment mean and how can the existing resilience definitions and features be extended to IAQ? (ii) Which strategies or technologies guarantee the design and operation of new and existing IAQ-resilient buildings? (iii) How can IAQ-resilient buildings become attractive to investors?

Attempting to respond to these issues, the article presents a state-of-the-art literature survey on two main topics: (i) the existing definitions of resilience for energy systems and buildings, focusing on the possible features of resilience to infection, which became relevant because of the COVID-19 pandemic; and (ii) building design strategies for designing and operating an IAQ-resilient post-pandemic built environment, based on the preventive measures involving engineering control that are able to mitigate the spread of COVID-19 by improving the indoor air quality.

2. Methods

The method of data collection for the present research was based on an analysis of the existing literature on the following two main topics: (i) definitions of the concept of resilience for the built environment, and (ii) building design strategies potentially adopted for supporting the targets of IAQ-resilient post-pandemic architecture. Initially, the available literature was collected from three different search platforms, including Google Scholar, Science Direct, and PubMed. These platforms provide access to a large database of journals in all fields (Google Scholar), as well as being recognized as being among the most authoritative of the scientific publications (Science Direct) and in the biomedical field (PubMed). Mainly journal articles, but also books and conference papers, were investigated.

First, the total number of articles containing the following terms, without including any restrictions, were searched for: "resilience", "resilient building", "resilient residential building", "built environment", and "sustainability" for the first topic and "design strategies", "post-pandemic architecture", "healthy building", "COVID-19", "hierarchy of hazard control", "engineering controls", and "indoor air quality" for the second theme. Figure 1 provides a graphical representation of the literature review results; in particular, for each of the search platforms, the results, as percentages, obtained for each term used for the bibliographic research are shown.

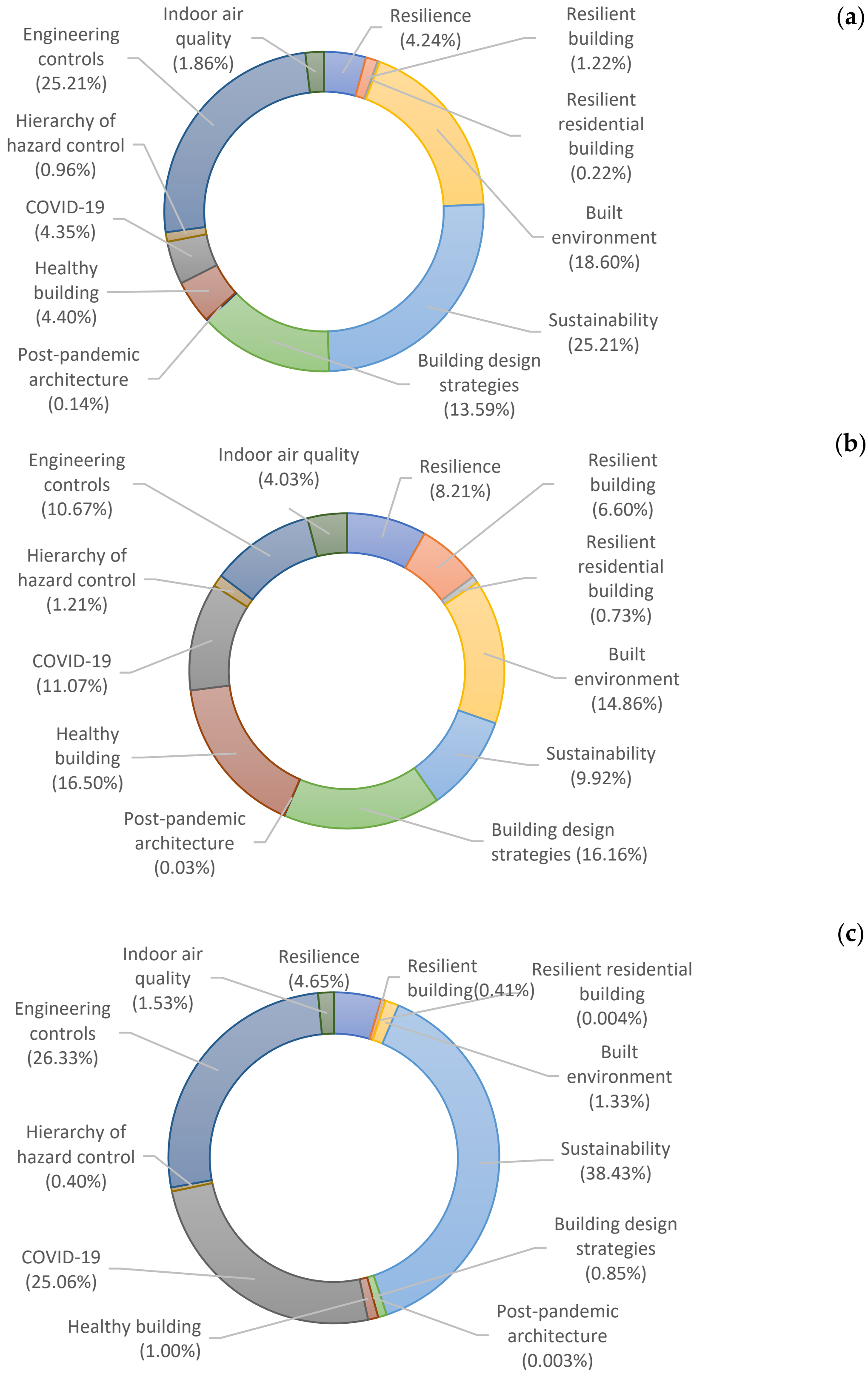

Figure 1. Graphical representation of the literature review results using different search platforms: (**a**) Google Scholar; (**b**) Science Direct; (**c**) PubMed.

Since the results of the above analysis showed too many findings, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were adopted for conducting a systematic review [22]. PRISMA outlines the following four stages: (1) identifying the articles for review, (2) screening the articles, (3) deciding on the studies' eligibility, and (4) finalizing the list of articles to include in the review.

To reduce the amount of irrelevant information for the purpose of this study, the search terms "resilience" OR "resilient" AND "built environment" OR "buildings" (for the first topic (T1)) and "buildings" OR "indoor air" AND "COVID-19" (for the second topic (T2)) were used in the three databases. In addition, the review was refined by searching for articles containing the above terms in their title and published between 2020 and 2022, as the research related to the period of the pandemic emergency. The search resulted in 2275 articles for T1 and 1197 articles for T2. All the duplicates were then removed, leaving 2154 and 2115 publications, respectively, for T1 and T2. The next stage was screening on the basis of inclusion and exclusion criteria. The inclusion and exclusion criteria in the screening stage for T1 can be seen below.

- The inclusion criteria were:
  (1) Published from 2020 and 2022 in accordance with the spread of the COVID-19 pandemic emergency;
  (2) Written in English;
  (3) Articles showing a definition of the concept of resilience in relation to the building energy sector;
  (4) Studies analyzing the relationship between the COVID-19 pandemic and the built environment.
- The exclusion criteria were:
  (1) Literature related to the concept of resilience without being linked to the built environment;
  (2) Study without any correlation between COVID-19 and the built environment;
  (3) The focus of the study was at the urban or city scale;
  (4) Not full-text content was available.

The inclusion and exclusion criteria in the screening stage for T2 were as follows.

- The inclusion criteria were:
  (1) Published from 2020 and 2022 in accordance with the spread of the COVID-19 pandemic emergency;
  (2) Written in English;
  (3) Articles describing the layers of the COVID-19 control hierarchy or the strategies of enhancing resilience in building designs;
  (4) Studies focusing on engineering controls in relation to IAQ and COVID-19.
- The exclusion criteria were:
  (1) Articles discussing building design strategies without any relation to the COVID-19 period;
  (2) Not full-text content was available.

According to the research objectives, 56 articles for T1 and 35 for T2 were selected and reviewed by reading the full text to assess their eligibility. After reading the entire contents of the literature in detail, 14 publications for T1 and 9 for T2 were excluded. Finally, the articles in the literature that were used for the purpose of this review numbered 32 for T1 and 26 for T2. The stages of the systematic review process using the PRISMA flow diagram are shown in Figure 2.

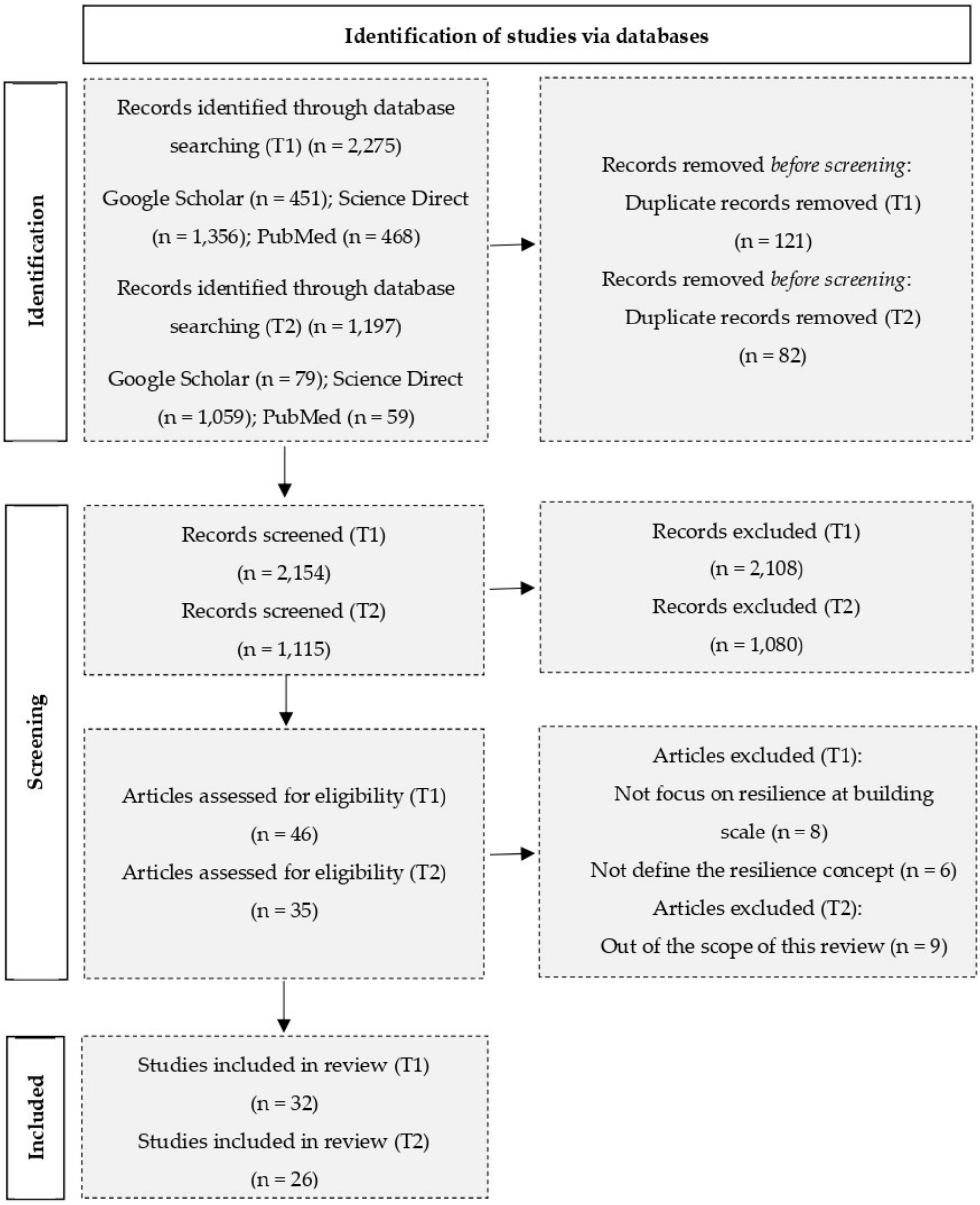

Figure 2. PRISMA flow diagram of the systemic review process, reworked from https://www.prisma-statement.org//PRISMAStatement/FlowDiagram, accessed on 20 December 2022 [23].

3. Results and Discussion

The following subsections show the main outcomes derived from the state-of-the-art survey performed to respond to the two research questions: (i) what does the resilience of the built environment mean and how can the existing resilience definitions and features be extended to IAQ? (ii) Which strategies or technologies guarantee the design and operation of new and existing IAQ-resilient buildings?

3.1. Definitions of Resilience for the Built Environment

The present section aimed to collect information on the existing definitions of resilience in the context of the built environment, and also concentrating on infection resilience.

The concept of resilience has been widely applied to diverse fields (e.g., the social, economic, organization, engineering, and risk management domains). However, even though some similarities arise in the definitions and concepts used in the different disciplines and applications, a clear definition is still missing [24]. According to [25], the term resilience can be used to express the "capacity to persist in the face of change, to continue to develop with ever-changing environments". Furthermore, [26] suggest that resilience can be defined as "a system's readiness in reacting towards disruptive events". A similar consideration was reported in [27], in which resilience was defined as "the ability of a system to recover from adversity", focusing on the energy domain. The International Energy Agency (IEA) has defined resilience in more detailed terms as "the capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the following concepts: robustness, resourcefulness, recovery" [28].

With a focus on the built environment, the concept of resilience for buildings or cities is taking hold [29], as suggested by Table 1, which summarizes some definitions of resilience derived from a literature review on the theme.

Table 1. Definitions of resilient buildings.

Reference	Definition
[30]	"A resilient built environment as one designed, located, built, operated, and maintained in a way that maximizes the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate the impacts of threats"
[31]	"Buildings resilience could be seen as an ability to withstand the effects of earthquakes, extreme winds, flooding and fire, and their ability to be quickly returned after such event"
[32]	"A building's ability to withstand severe weather and natural disasters along with its ability to recover in a timely and efficient manner if it does incur damages"
[33]	"The capacity of the city (built infrastructure, material flows, etc.) to undergo change while still maintaining the same structure, functions and feedbacks, and therefore identity"
[34]	"A single building is resilient if it has the ability to quickly adapt to changes in conditions and continue to function smoothly"
[35]	"The building is defined to be resilient if it is able to prepare for, absorb, adapt to and recover from the disruptive event"
[36]	"A resilient building is a building that not only is robust but also can fulfill its functional requirements during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts"
[37]	"A resilient built environment will ensue when we design, develop and manage context sensitive buildings, spaces and places that have the capacity to resist or change in order to reduce hazard vulnerability, and enable society to continue functioning, economically, socially, when subjected to a hazard event"
[38]	"Resilience in buildings [. . .] is framed as the ability of the building to serve the occupants' needs in times of crisis or shocks. [. . .] The capacity of a building to sustain atypical operating conditions in disaster situations, rather than succumbing to building failure, is the critical measure of its resilience"
[39]	"The ability of a building to prepare for, withstand, recover rapidly from, and adapt to major disruptions due to extreme weather conditions"
[40]	The concept of resilience in the built environment is understood as "the ability of any urban system, with its inhabitants, to maintain continuity through all shocks and stresses, while positively adapting and transforming toward sustainability"

According to [41], buildings must be resilient to several disruptions or emergencies, including air pollution and pandemics. The literature review suggested that the resilience of buildings to various hazards, ranging from natural disturbances (e.g., earthquakes, high winds, floods, etc.) to energy supply interruptions and to "atypical operating conditions" (including pandemics), is usually associated with the concepts of adaptation, recovery, and resistance. Specifically, reductions in damage are linked to the level of resistance of the buildings, as well as the recovery time being influenced by the extent of the damaged components. Many sources highlighted how the adequate design and construction of resilient buildings is enabled by four key factors: robustness, redundancy, resourcefulness, and rapidity [42]. Furthermore, in [43], the concept of resilience was linked to that of preparedness, the authors stating that "the response of a society, city or system to future challenges depends on their preparedness, i.e., preparedness of social actors and their capacity to learn from past experiences [44,45]".

As previously mentioned, an increase in the hazards of buildings asks them to be not only sustainable (reducing their impact in terms of energy and the environment) but also resilient. Some authors have discussed the possible links or divergences between the concepts of resilience and sustainability [46–50]. As reported in [44], "sustainability focuses on future stability, while resilience represents readiness for the potential disasters of the dynamic and unpredictable future". Lizarralde et al. [46] discussed how the consequences of climate change have forced the built environment to adopt both the sustainability and resilience paradigms, highlighting the differences between these objectives; indeed, the authors reported that "whereas sustainability encourages reduced impacts on the environment to avoid changes, resilience encourages adaptation to change" [46]. In the context of climate change, [51] defined and summarized the most applied resilient qualities of buildings to mitigate the impact of climate change, suggesting the introduction of a holistic approach that combines different assessments, resilient characteristics, and qualities. According to Tokazhanov et al. [48], the COVID-19 experience calls for new requirements and discussions in relation to the design and renovation of sustainable and resilient buildings, which should guarantee the objectives of health and safety, reduced energy consumption and environmental impact, and the occupants' comfort and well-being. In this regard, it is interesting to note that some authors have discussed the need to introduce new criteria to ensure their readiness for addressing buildings' sustainability (and resilience) in the post-pandemic era [49]. In [52], the authors provided solutions for the built environment to foster resilience to multiple crises; among them are (1) green and healthy infrastructure, (2) adaptable infrastructure, and (3) equitable and inclusive infrastructure.

Even though the literature on the resilient built environment is mainly related to natural hazards, pandemics are included among the possible disruptions that can affect the built environment [53]. The COVID-19 emergency has shown that traditional spaces within a residential building are inadequate for the new demands associated, for instance, with work-from-home arrangements. In post-pandemic cities, an extensive overhaul of the design of buildings and public spaces is needed, as well as reconsidering the ways they are used, integrating indoor spaces for educational and work-from-home needs and outdoor spaces for mental and social well-being [54]. Therefore, the design of buildings and public spaces needs to experience a profound change, with the goal of increasing their resilience [54]. Specifically, since the COVID-19 pandemic has increased people's awareness of the health hazards they are exposed to in indoor spaces (e.g., pathogens, indoor pollutants from manufactured furnishings, etc.), this study devoted attention to the extension of the resilience concept to IAQ and health-related issues.

According to Pinheiro et al. [55], few studies have analyzed the relationship between the pandemic and the built environment. Even though mainly behavioral actions were undertaken (e.g., protective masks, social distancing) to reduce the spread of COVID-19, "the built environment (buildings and urban areas) can also make a valuable contribution that must be researched and analyzed" [55]. In line with this, Megahed et al. suggested that a more "human-centered design" can help future buildings to better protect the occupants from future epidemics [15]. Focusing on IAQ resilience, in relation to the pandemic's disruptions, Tokazhanov et al. [50] discussed the resilience of residential buildings and their ability to "withstand future pandemics' social, economic, and health-related challenges" in quantitative terms, defining specific resilience metrics to evaluate buildings' readiness to face potential future health-related threats. Similarly, in [21], the concept of infection resilience was described, defined as a set of measures and strategies to make buildings capable of resisting possible future pandemics or diseases. Indeed, a white paper discussed the importance of "looking ahead" beyond the COVID-19 emergency and introducing long-term improvements in buildings to "create indoor environments that support our health and wellbeing" in the face of various and possible future air-transmittable diseases (e.g., epidemics, pandemics, seasonal flu, etc.), through which the risk of infection could be reduced with a more resilient design [21].

3.2. Hazard Control Measures of IAQ-Resilient Buildings

In this section, possible strategies for supporting the construction and retrofit of IAQ-resilient buildings are presented, focusing on the engineering controls that might be adopted in new and existing buildings to increase their IAQ.

As previously mentioned, COVID-19 has emphasized the urgency of designing IAQ-resilient buildings by prioritizing design strategies that are capable of improving the IAQ. As reported in [48], building design is crucial for protection against environmental threats and should be based on strategies that are able to increase the IAQ resilience of indoor spaces, which, to be resilient, need efficient design control measures that are able to mitigate the spread of contaminants (including the SARS-CoV-2 virus). Strategies of enhancing resilience in building design can be classified as active or passive. The former category includes the use of heating, ventilation, and air-conditioning (HVAC) systems to dynamically respond to external threats (e.g., "pathogens, pollution, wildfires, seasonal conditions, etc.") [56]. Passive measures are instead related to the provision of environments that are "easily cleanable, free from harmful materials, and full of wellness-promoting features such as natural light, views, access to exterior areas and clean air" [56]. Leng et al. [57] suggested that passive designs must be complemented with proper ventilation strategies and with the use of appropriate air cleaners to remove pollutants and pathogens from indoor spaces. In [58], the authors proposed a classification of IAQ improvement strategies, dividing them into engineering controls (e.g., ventilation and air purifiers) and non-pharmaceutical measures (including the use of face masks, social distancing, and lockdowns). These considerations were enlarged on in [15,59], presenting a wider set of measures for hazard mitigation (against COVID-19) allowing the elimination of and/or reduction in the risk of infection to maximize the occupants' safety. In detail, the hierarchy of hazard controls was composed of four layers of defense that guide the selection of control measures for confined spaces, with their efficacy increasing from the bottom to the top (i.e., measures higher up on the hierarchy are more effective in reducing the risk of infection in indoor spaces) [60,61]. Each layer of the COVID-19 control hierarchy is described in the following bullet list, from bottom to top:

- *Personal protective equipment (PPE).* These measures are related to the personal protection of individuals, and include the use of masks in indoor spaces while also encouraging the adequate sanitization of the devices.
- *Administrative controls.* These include activities to educate people on how they should interact in enclosed environments to reduce opportunities for close contact with each other. Some of these control measures may include: (1) requiring people with COVID-19 symptoms to stay at home; (2) ensuring cleaning and disinfection actions; and (3) staggering entry and exit times from workplaces.
- *Engineering controls.* These refer to strategies aiming to redesign or modify the building's systems to mitigate the risk of infection. Among these actions, preventive measures including the ventilation of the building have proven to be the most effective in reducing the risk of the SARS-CoV-2 virus spreading.
- *Elimination and substitution.* In the context of COVID-19 pandemic, these control measures included all the actions that eliminated the potential for SARS-CoV-2 exposure, such as: (1) isolating infected persons from others,(2) eliminating or reducing person-to-person interactions, (3) reducing the occupancy in indoor environments, and (4) moving activities to outdoor spaces.

In this study, attention was given to engineering controls, given the role they play in reducing the risk of infection. Indeed, the previously cited definition of resilience to infection explicitly referred to the deployment of engineering controls within buildings to reduce the risk of airborne infection, aiming to create a healthier built environment [21]. Generally, engineering controls refer to several short-and long-term strategies intended to control and limit the transmission of airborne diseases, which are thus capable of increasing the IAQ in buildings [54]. In [15], three strategies were identified to improve indoor air quality: "source controlling, designing ventilation systems, and air cleaning". The building's ventilation design as well as air cleaning and purifying technologies represent the focus of most engineering controls to reduce the transmission of the SARS-CoV-2 virus [54,58,62].

Ventilation-related strategies are recognized as the most effective in diluting and removing indoor air contaminants through indoor–outdoor air exchange [59], as well as for guaranteeing the occupants' comfort and health within the building [46]. Proper ventilation rates can be provided naturally (e.g., through windows) or mechanically, using HVAC systems, to reduce the risk of infection. During the COVID-19 emergency, several building control authorities and associations at national and international levels suggested the following measures to correctly operate ventilation strategies [63,64]:

- Running HVAC systems on 100% outside air. Recent research has shown that the risk of COVID-19 infection increases in closed environments with recirculated air, which was therefore not recommended [59,65,66]. As pointed out by [67,68], the air must be treated if recirculation is applicable.
- Maintaining a high ventilation rate despite variations in occupancy. As [66] showed, it was recommended to extend the operation times of mechanical ventilation systems by keeping the ventilation on 24/7.
- Opening windows was a key recommendation to rapidly increase the IAQ during the COVID-19 pandemic period [69].
- Introducing CO_2 monitoring to assess the adequacy of ventilation in the indoor environment. This type of measure allows the occupants to act when the CO_2 level exceeds a certain threshold by opening a window or reducing the occupancy [70].

The first strategies could be labelled as emergency or short-term measures to reduce the risk of airborne transmission; indeed, even though they are effective in minimizing health-related threats, they have a non-negligible impact in terms of energy consumption and costs, and are surely unsustainable in the long-term. For instance, several authors have explored the impact that outdoor air treatment and supply has in terms of energy, as well as extended schedules of operating HVAC systems, which were introduced during the emergency period [71–73]. These considerations highlighted that, with the aim of designing and operating buildings to be healthier and more IAQ-resilient, it is fundamental to consider long-term strategies that could be put in place without reducing buildings' sustainability and energy efficiency, representing a good compromise between energy- and health-related objectives. For this reason, in mechanically ventilated buildings, air filtration (e.g., mechanical filtration using filters or biofiltration technologies) and other purification techniques (e.g., UVGI systems and bipolar ionization) should be adequately installed in HVAC systems to protect the air handling units from viral and bactericidal agents, and to maintain a healthy indoor air quality for the occupants [59,74,75], reducing the potential for airborne transmission of diseases.

In detail, mechanical filtration is widely used in HVAC systems to improve the indoor air quality using high efficiency particulate air (HEPA) filters, as well as filters treated with antimicrobial agents. HEPA filters are recommended because of their ability to remove airborne particles less than 0.3 μm [76]. Nevertheless, airborne microorganisms can remain viable and proliferate on the filters' media if not adequately cleaned, thus making the filter itself a source of contamination [77–79]. In response to this problem, as emphasized by the COVID-19 pandemic, the demand for antimicrobial filtration technologies has increased. As demonstrated by [80], the use of a tungsten trioxide (WO_3)-based photocatalyst placed on a filter's media allowed the researchers to observe a reduction in the infectious load of SARS-CoV-2 by 98.2% 10 min after treatment, reaching 100% abatement after 30 min. Similarly, a titanium dioxide (TiO_2) photocatalyst combined with UV lighting seemed to be the optimal strategy for mitigation of the SARS-CoV-2 virus [81]. In addition, another type of air filtration system that is becoming increasingly widely used for its economic, environmental, and social benefits is biofiltration technology, also known as plant-based technology [54]; because of its capability to absorb CO_2, NO_2 and SO_2, the system is widely used in polluted environments to improve the occupants' health and productivity [82].

Focusing on air purification, these systems "can inactivate the germicides as well as remove the pollutants with high efficiency" [58], capturing airborne dust particles and allergens [83]. The most common techniques used in confined spaces are represented by ultraviolet germicidal irradiation (UVGI) devices and bipolar ionization. The former technology uses Type C ultraviolet light (UV-C), also called germicidal UV, which is able to efficiently inactivate bacteria and viruses [84]. Recently, several studies have demonstrated the efficiency of the use of direct UV-C against the SARS-CoV-2 virus. According to [85], a small dose of UV-C irradiation (3.7 mJ/cm^2) is sufficient to inactivate COVID-19 in an indoor environment. Another study conducted by Vranay et al. [86] has shown that more than 90% of the SARS-CoV-2 virus can be inactivated by UV-C sources. Despite its evident benefits, this technology is still under development to avoid health risks to human eyes and skin. Finally, another emerging air purification technique, which is effective against viral and bacterial pathogens, is represented by the bipolar ionization, also called needlepoint bipolar ionization (NBPI). This system can be installed into HVAC systems to purify the air by generating ions that react with airborne contaminants (e.g., viruses, mold, and bacteria) and thus remove them from the air by the electrostatic force [87].

4. A CBA Decision-Making Tool to Boost IAQ-Resilient Buildings

Decision-making processes regarding energy investments are still profoundly shaped by financial considerations. Among the four layers of the hierarchy of hazard controls, engineering controls are the most expensive measures, thus still requiring significant economic investment by the building manager. However, to give value to their capacity to render buildings healthier and more IAQ-resilient, there is a need to include externalities (i.e., health-related factors caused by the improved IAQ) in their assessment and evaluation, to better balance their costs and benefits using proper decision-making tools. For this reason, the cost-optimal analysis introduced by Directive 2010/31/CE (EPBD II) [88] allows the users to take not only energy-architectural variables but also financial ones into account (in terms of investment and operating costs), which has been overtaken by the proposal of the cost-benefit analysis (CBA) [89], which is a method allowing the introduction of additional externalities beyond the costs, such as the occupants' increased well-being and health in the buildings. For this reason, the tool appears to be in line with the transition to a more human-centered approach to building design and operation. Moreover, CBA has proven to be an effective method that is able to support decision-making processes, demonstrating that the energy and socio-economic benefits that innovative solutions or strategies (i.e., engineering controls) can guarantee could repay their higher investment in the long-term [90]. The final objective of a CBA is to support the design of a building characterized by a reasonable investment cost, high energy performance and a high level of the occupants' comfort and health; for this reason, it can be identified as a key tool to make IAQ-resilient buildings more attractive to several stakeholders, allowing users to quantify and monetize the wider benefits they can guarantee. This is particularly valid nowadays, since, because of the COVID-19 pandemic emergency, people are even more sensitive to health and well-being issues, being pushed to prefer technologies that can guarantee a higher level of hygiene and safety. For this reason, there is an increasing demand by industrial companies to enhance these innovative technologies in the market, demonstrating their socio-economic benefits in terms of increased healthcare savings and reductions in productivity losses, despite their possible higher investment costs.

However, the quantification of co-benefits is not always an easy task [7]. Indeed, the quantification and monetization of non-market impacts (e.g., health-related benefits) is ambitious, requiring adequate methods for their evaluation [7]. According to the literature, for this purpose, several economic evaluation techniques exist for monetizing non-market impacts (quantitative methods), which can be divided into three main approaches known as the “stated preference”, “revealed preference”, and “benefit transfer” methods.

The stated preference (SP) technique uses surveys for establishing people’s preferences. Among the survey-based economic methods, the contingent valuation method (CVM) [91] and choice modeling (CM) [92,93] appear to be the most used for evaluating a non-market good in monetary terms. Both approaches specifically use questionnaires through which the respondents are directly asked about their willingness to pay (WTP) for a certain good or service or their willingness to accept (WTA) a certain outcome.

The revealed preference (RP) method is used for analyzing individuals’ preferences by revealing their purchasing habits. The main evaluation techniques are represented by the hedonic pricing (HP) [94] and the cost of illness (COI) [95] methods. The latter is usually used in the healthcare field to measure the economic burden of a particular disease, allowing an evaluation of the health-related benefits in terms of avoided costs [96]. According to [97], COI identifies and measures all the costs related to a disease, including the direct costs (e.g., healthcare costs related to specialist visits, diagnostic procedures, hospitalizations, etc.), the indirect costs (e.g., absenteeism, loss of productivity due to morbidity), and the intangible costs (e.g., cost of pain). While the intangible costs are difficult to quantify and are often overlooked, the indirect costs can be calculated by using two main methods: the human capital approach (HCA) [98], which estimates the productivity lost by employees’ absence from work for the period between the beginning of the disease and the return to work activity, or the friction cost method (FCM) [99], which considers the hours until another worker takes over the sick patient’s work.

Finally, the benefit transfer (BT) method is based on the transfer of available information from completed studies to estimate the economic value of non-market goods, including health-related benefits [100].

Although not used in the CBA analysis, it is interesting to mention some methods used in the healthcare field for quantifying health-related impacts; even though they do not allow the monetization of such impacts, they could be used to boost the spread of engineering control measures as the foundation of an IAQ-resilient built environment. Such methods, as the disability-adjusted life years (DALYs) and the quality-adjusted life years (QALYs) [101], are usually used in cost–utility analyses to measure the generic health consequences of a disease by considering the effects of both mortality and morbidity [102]. In detail, the DALYs represent the sum of the years of life lost (YLLs) due to premature mortality and the years of life lived with the disability (YLDs) [103]. The QALYs, a measure of the value of health outcomes, combines two different benefits of treatment: the length of life and the quality of life [104].

5. Conclusions

The COVID-19 pandemic has emphasized the need to guarantee adequate IAQ conditions in indoor spaces, prioritizing strategies of building design and operation that are able to increase buildings’ resilience to future pandemics and accelerating the future transition towards the construction of healthy buildings. This article discussed the importance of using the COVID-19 experience as a catalyst to rethink the built environment, boosting an IAQ-resilience-based paradigm that is capable of ensuring healthier and more adequate living spaces, while adapting to the new occupants’ habits and needs. Bearing in mind the attention given to sustainable practices, which aim to reduce the environmental impact of the building sector, the IAQ resilience paradigm for buildings should go together with the objectives of sustainability and climate change mitigation, seeking the right balance between energy- and health-related aspects, without neglecting the economic burdens.

Given the points above, this research involved a systematic review, conducted in line with the PRISMA guidelines, aiming to explore how to design and operate an IAQ-resilient building in the post-pandemic era and to collect insights on two main topics: (i) the existing definitions of the resilience of the built environment, concentrating on infection and IAQ resilience, exacerbated by the COVID-19 emergency; and (ii) the possible strategies for supporting the design and retrofit of IAQ-resilient buildings, focusing on engineering-based control measures, which have proven to be the most effective in reducing the risks of infection in confined spaces. Among these measures, attention was devoted to differentiating among emergency or short-term actions and long-term strategies, recognizing the latter as the core elements of the IAQ-resilient building paradigm, which should guarantee buildings to be prepared for and resilient to future health-related threats. Despite the benefits that engineering controls (i.e., ventilation-based strategies, the use of air cleaners) offer for allowing improvements in indoor air quality, their costs are still high. Therefore, to give value to their capacity to render buildings healthier and more IAQ-resilient, there is a need to include externalities in evaluations, using proper decision-making tools. With the goal of understanding how such solutions could become more attractive to consumers, the study explored methods allowing the quantification and monetization of non-marketed goods (e.g., the health benefits associated with improved IAQ in buildings), identifying the cost–benefit analysis method as an attractive tool for boosting energy investment decisions, as it is capable of integrating the full set of the costs and benefits of these solutions.

The limitations are related to the search restrictions used in the literature review process. For this reason, as it is a topic of great importance in the current pandemic period, a further in-depth investigation is required. Future literature research should shift the focus from single buildings to a building cluster and exploring the resilience of the city. In addition, starting from the features of IAQ-resilient buildings, future work should consider the application of CBA and related methods to quantify and monetize the energy- and health-related benefits associated with the adoption of specific engineering controls in non-residential buildings (e.g., schools, offices, etc.), focusing on long-term strategies (mainly the adoption of air filtration technologies within air handling units).

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