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Designing Post COVID-19 Buildings: Approaches for Achieving Healthy Buildings

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Abstract: The COVID-19 pandemic forced the accessibility, social gathering, lifestyle, and working environment to be changed to reduce the infection. Coronavirus spreads between people in several different ways. Small liquid particles (aerosols, respiratory droplets) from an infected person are transmitted through air and surfaces that are in contact with humans. Reducing transmission through modified heating, ventilation, and air conditioning (HVAC) systems and building design are potential solutions. A comprehensive review of the engineering control preventive measures to mitigate COVID-19 spread, healthy building design, and material was carried out. The current state-of-the-art engineering control preventive measures presented include ultraviolet germicidal irradiation (UVGI), bipolar ionization, vertical gardening, and indoor plants. They have potential to improve the indoor air quality. In addition, this article presents building design with materials (e.g., copper alloys, anti-microbial paintings) and smart technologies (e.g., automation, voice control, and artificial intelligence-based facial recognition) to mitigate the infections of communicable diseases.

Keywords: COVID-19; indoor air quality; green plant; healthy building; HVAC; ultraviolet germicidal irradiation; bipolar ionization; anti-microbial paint

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1. Introduction

The current COVID-19 pandemic has resulted in significant changes to every human life and caused economic crises and travel bans in most countries [1]. Further, these outbreaks, resulting from numerous forms of infections, have resulted in inferior living environments. This persisting situation can no longer be controlled by only employing a simple strategy, such as quarantining and physical distancing. This raise concerns over the effectiveness of the current strategies adopted to control the transmission of the. COVID-19 virus. Thus, it calls for a more contemporary, comprehensive, and innovative approach in dealing with COVID-19 virus/variants [2]. The COVID-19 infection is strongly linked to air quality, with proof that airborne transmission is possible [3]. COVID-19 pathogens are an aerosol size of less than 5 μm [4], which can be defined as ultrafine particles [5]. Since the ultrafine virus particles containing liquid are lightweight, they tend to be in the air in an aerosol form for about 30 min [6].

Recent investigations have demonstrated that people contract COVID-19 via indoor airborne transmission, especially in crowded and poorly ventilated environments [7]. Thus, maintenance of optimum air quality is required to eradicate the spread. This demands innovative changes to the existing indoor and outdoor infrastructure to positively impact the occupants in even the most densely populated spaces [8]. This also challenges the traditional design and construction approach to residential and public buildings in the post COVID-19 pandemic period [9]. Post COVID-19 architecture is a concept that is ongoing, which is applied to both future and existing building with healthy building aspects [8]. The healthy building concept mainly focuses on creating a comfortable and desirable indoor environment, which is measured in terms of the indoor environmental quality (IEQ) [10]. A healthy IEQ is expected to positively impact the occupants in most densely populated buildings in terms of physical, mental, and social aspects [11]. The IEQ refers to the quality of the living environment that exists within a building [12]. The level of indoor environment quality relies on several variables, such as thermal, visual, acoustic, and chemical [13–16]. The variables, which should be assessed individually and/or collectively, include indoor air quality, thermal comfort, ventilation, acoustic performance, lighting, and spatial layout [3,17].

A newly constructed or an existing building might not have the optimum levels of IEQ variables, as they can be altered during the usage of the building [18]. Buildings constructed without the required IEQ lead to unsafe buildings that ultimately cause poor health, learning difficulties, and productivity issues [19]. This is one of the major challenges during the COVID-19 pandemic that is present in most homes, schools, and workplaces. Thus, it is necessary to tune a building with a high IEQ level to ensure the health and well-being of its occupants [10,20].

Air quality is one of the factors that plays a major role in providing a healthy IEQ [21]. The quality of indoor air can be compromised by both outdoor and indoor sources of pollutants related to building materials, equipment, animals, and humans [22]. Indoor air can be contaminated with organic gases, such as volatile organic compounds, and inorganic gases, such as radon and ozone [23]. Furthermore, particulate matter, such as mold, asbestos, and silica dust, can also pollute the indoor air [24]. These indoor air pollutants result in a poor IEQ and induce health effects, such as asthma, throat pain, shortness of breath, and heart diseases [23]. Cancer, chronic lung diseases, and bronchitis are also some serious conditions caused by poor indoor air quality [25,26]. Moreover, these indoor air pollutants are often linked to mental conditions, such as increased negative feelings, intensified violent behaviors, degraded concentration, and mental exhaustion [27].

Thus, to improve the indoor air quality, the spatial layout should be considered during building design [28]. Spatial design is a conceptual design approach that accounts for both the interior design and service design. This requires the flow of people between interior and exterior environments [29,30]. Design decisions are typically made by the designers to promote social interactions in accordance with the sociability and well-being of the occupants [28]. Furthermore, biophilic design ideas are also used to improve the indoor air quality through the view of nature with indoor plants, fresh air, and natural sounds [31]. These indoor plants and natural sounds are widely encouraged for the interiors of hospitals to promote a speedy recovery of patients and decreased hospital stay [3]. Hence, it can also be assumed that maintaining a better IEQ can even be effective against many of the infectious diseases that are caused by different virus types similar to the COVID-19 virus [11,12].

As conditions, such as remote working and restricted access, will not be continued in the long run, reopening a country calls for innovative plans and more sustainable solutions. Therefore, this article presents in detail the information about current state-of-the-art emerging technologies and influencing factors of the healthy building concept. Remedies to transform the setup of a building to. a healthier space with enhanced air quality, incorporating various new technologies, are also discussed. Moreover, the environmental impacts, economic feasibility, and future perspective of the wider application of these techniques are analyzed. This paper aims to provide a comprehensive review of the application of building technologies to reduce COVID-19 transmission and achieve healthy buildings. It also provides conceptual approaches to adopting these technologies in the building construction industry by engineers, designers, and architects.

2. Method/Bibliometric Analysis

This work investigated journal articles to develop a detailed literature review of healthy buildings and their systems. Scopus and Web of Science (WoS) abstract and citation databases were used for identifying the journal articles to be reviewed. The search string utilized is shown in Table 1. Searches were limited to articles indexed from 2010–01-01 to 2021–07-31. This is because research on the healthy building concept existed prior to Covid-19. VOSviewer software was used to visualize the trend of the literature related to healthy buildings. A similar methodology was employed in [32] to analyze research on sustainable construction. A total of 148 journal articles in Scopus and 94 journal articles in WoS were identified. A network visualization diagram was generated in VOSviewer using a threshold of 105 keyword co-occurrences in Scopus and 20 keywords in WoS (Figure 1). In Figure 1, bigger circles represent the largest area of research conducted between the index dates of the search. Most research topics clustered around the keywords "COVID-19" and "ventilation". It is apparent from Figure 1 that other areas have not been the main focus investigated in healthy buildings. Therefore, this study provides a comprehensive review of the technologies to combat the transmission of COVID-19 disease in buildings.

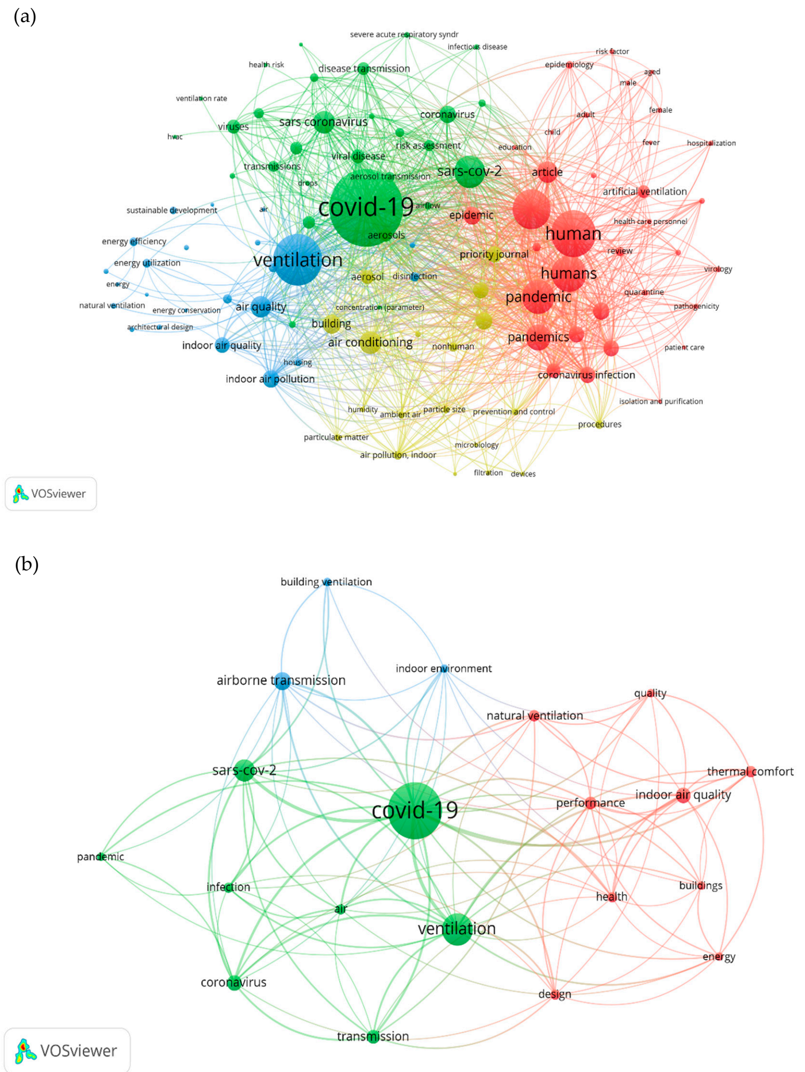

Figure 1. Network visualization based on keyword co-occurrence analysis: (**a**) Scopus data and (**b**) Web of Science data.

Table 1. The search string used in this review.

Year	Sources	Search String
2010–2021	Scopus (Title, Abstract, Keywords) and Web of Science (All Fields)	("Construction industry" OR "Building" OR "Built environment" OR "IEQ" OR "Modular construction" OR "Building open space") AND ("Covid 19" OR "Covid19" OR "COVID-19" OR "Covid") AND ("Healthy Building" OR "Indoor air quality" OR "Immunity level" OR "Indoor plant" OR "Green wall" OR "Green construction" OR "Bacteria killing plant" OR "Antimicrobial paint" OR "Bipolar ionization" OR "Ultraviolet radiation" OR "Air filter" OR "Plasma technology" OR "Non-porous material" OR "Interior design" OR "Adaptive reuse" OR Ventilation).

3. Existing Healthy Building Technologies

Most peoples' livelihood activities resided within buildings during the COVID-19 pandemic, except for the few people living in rural areas. In crowded places, the COVID-19 virus can be transmitted via air and via both direct and indirect contact with contaminated surfaces. Therefore, restrictions were imposed to limit access to large public areas such as shopping centers. Therefore, in order to ease these restrictions, this requires new innovative solutions for buildings. Engineers, architects, designers, and built environment specialists are now engaged in exploring many social and spatial implications in the built environment to achieve healthy buildings. This is expected to dramatically alter the nature of the infrastructure and design at present and also in the future to cope with communicable diseases. Thus, the building industry has focused on engineering control to rectify and redesign buildings to enable a healthy built environment (Figure 2).

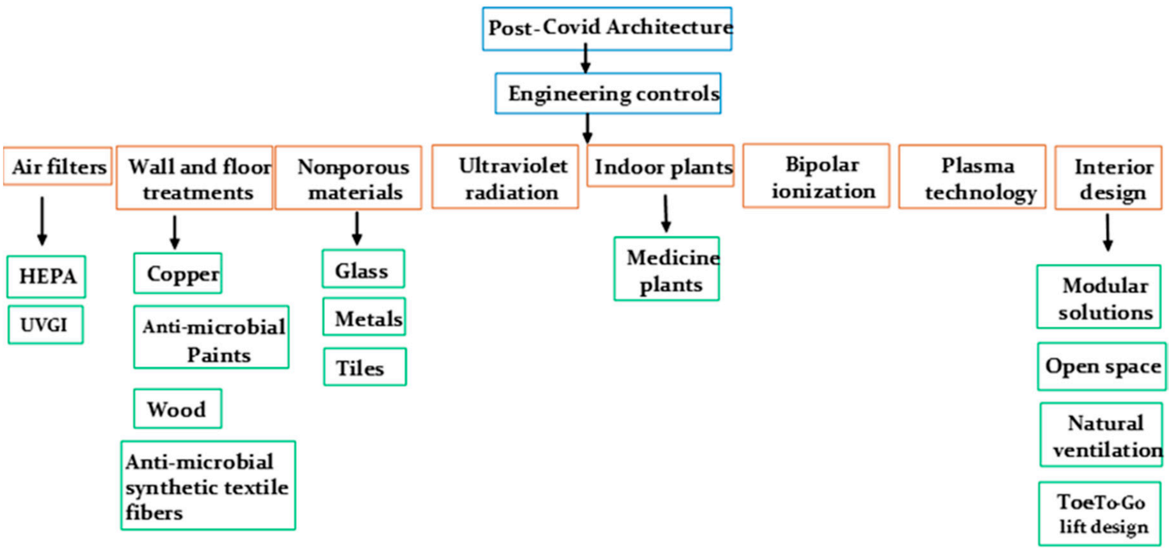

Figure 2. Engineering controls to reduce the transmission of the COVID-19 disease.

Healthy buildings are required to have innovative technology, which helps to increase the fresh air ventilation of buildings and consequently reduces transmission of the COVID-19 virus [8]. Currently, building construction in the USA, China, Australia, and the UK is applying various approaches to achieve healthy construction [3]. The most popular healthy building approaches are ergonomic furnishing, daylighting, operable shading, nature views, green scaping, and better indoor air quality [33]. The application of healthy building design approaches has become necessary for sustainable development. Residential, public, and commercial buildings are implementing some of the approaches in a way that allows higher intake of fresh air and increased natural ventilation [34].

The current COVID-19 pandemic highlights the importance of thinking forward to advancements in construction techniques that speed up the construction of emergency buildings (such as COVID hospitals and quarantine tents). Further, this COVID-19 pandemic has posed an enormous challenge to healthcare buildings, and demanded more building space with a healthy environment. Modular structures, adaptive reuse, lightweight and adaptive structures, and hygienic building materials have been used in healthcare buildings to help patients as well as to avoid further transmission [35]. The modular construction strategy has been successful in providing building for these kinds of pandemics or natural disasters while enabling decreased costs and faster construction. Furthermore, the use of parking lots and conversion of other buildings into emergency centers and temporary hospitals were also employed during the COVID-19 pandemic period [8]. This adaptive strategy is a possibility that can be set in place for future pandemics. Modular construction incorporates lightweight and adaptable structures for their fast and portable nature in response to the pandemic. These temporary structures are designed and installed to build emergency hospitals that can be transported and installed easily for COVID-19 patients.

It is important to consider every potential location and the risk of becoming a host for pathogens. Even with new technologies in place to reduce transmission, it also requires intensive and frequent cleaning of surfaces. The adoption of artificial intelligence and touchless technology would reduce the intensive cleaning frequency. Automation, voice control, and artificial intelligence-based retina recognition could be employed in the building environment during a pandemic to reduce transmission of a disease. Further, more than 80% of infectious diseases have been reported to be transmitted through contact with contaminated surfaces [36]. Thus, one should aim to use more contactless routes, such as smartphone lifts, eliminating the use of handles, keys, and automatic opening doors, etc. These contactless systems could be utilized in other applications, such as remote temperature control programs and remote-controlled automatic cleaning of pathogens.

Some of these emerging technologies were employed in the Chicago Office Tower (Fulton East), which claimed to be the "First Post-Covid Building" [37]. A 12-story, 8361 m^2 (90,000 ft^2) office and retail complex in Chicago is one of the first commercial buildings built during the COVID-19 pandemic. The building design introduced innovative features, which include touch-free lifts with foot-activated call buttons (the world's first new installation of MAD Elevator Inc.'s Toe-To-Go (T2G) hands-free lift system) [37] (see Figure 3).

Non-thermal plasma technology (airPHX) that eliminates cross-contamination hazards and delivers cleaner air for employees was also installed in Fulton East [38]. This airPHX technology reduces viruses, bacteria, and mold by 90–99% both in the air and on surfaces [38]. This technology is currently being applied in commercial spaces, such as hospitals and dental clinics. The key benefits of using airPHX technology are shown in Figure 4. Fulton East building has a 985 m^2 (10,605 ft^2) floor plan to permit safe physical distancing and to enable customized space planning [37,38]. Figure 5 shows the techniques applied for Fulton East's post-COVID-19 design strategy.

The headquarters of Bee'ah represent another innovative building, which integrates a green design, displaying environmentally friendly approaches [39]. This building has a 7000 m^2 floor space and is made of a sequence of dunes. This led to two major dune-shaped buildings that fit with the desert landscape. The two central dunes of the headquarters building cross and join via a courtyard, an 'oasis' within the structure that maximizes indirect sunlight and enhances natural ventilation. The approaches applied include ultra-low carbon (100% renewable energy sources, ample high-quality daylight, natural ventilation, waste heat recovery from chiller to pre-heat hot water) and minimal water consumption in operation, and minimal material consumption in construction (maximum recycled materials from construction waste) [39]. Bee'ah has set an example by building a work atmosphere that provides sensible and long-term environmental solutions for healthy buildings. The concept of "contactless pathways" was applied in this building to reduce COVID-19 disease transmission [40]. Automated doors using motion sensors and facial recognition also reduce the number of contact points.

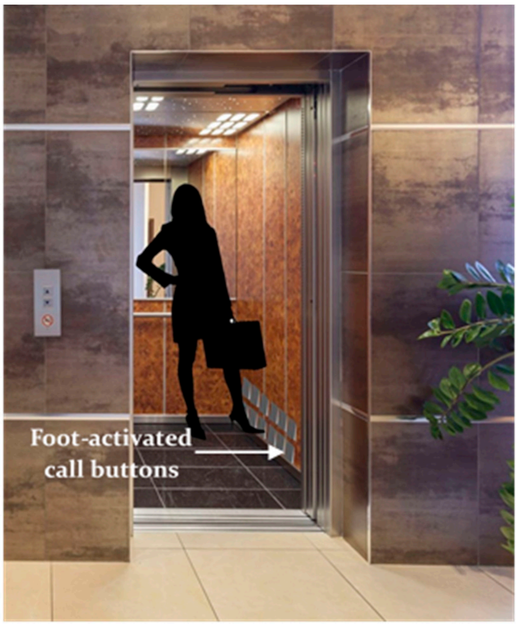

Figure 3. Toe-To-Go hands-free lift showing foot-activated call buttons.

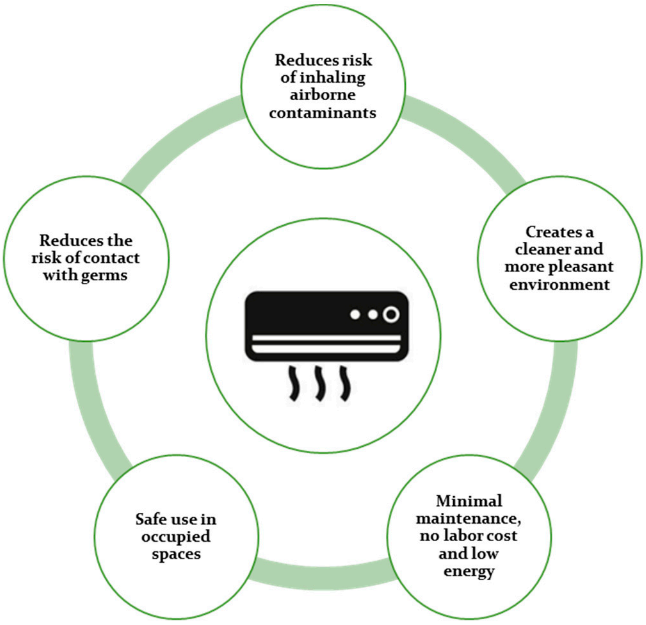

Figure 4. Benefits of using airPHX technology in buildings.

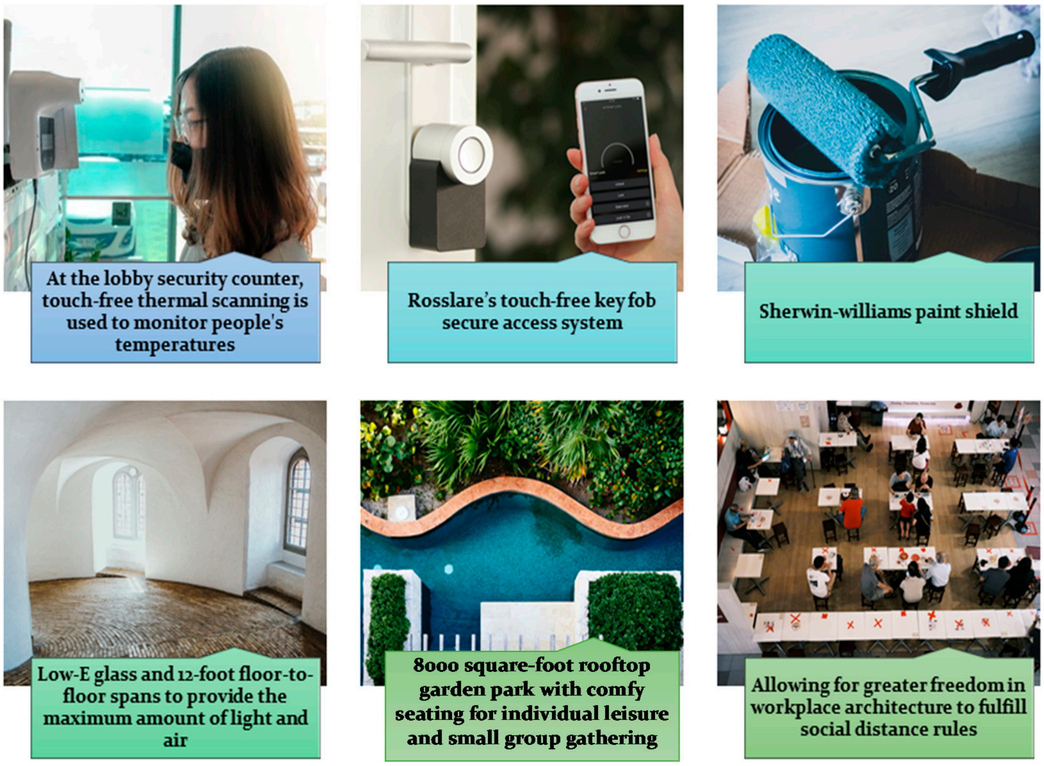

Figure 5. The techniques used to reduce the environmental risks for airborne transmission in Fulton East building [37,38] (photos: reproduced with permission under the terms of the Creative Commons CC0 license. 2021, published on Pexels website).

4. Overview of Engineering Controls to Reduce the Transmission of COVID-19

The lockdown is not a long-term remedy to limit the spread of COVID-19. Therefore, it is necessary to look into engineering controls to reduce the transmission of communicable diseases. Building ventilation design is closely linked with the engineering control method used to reduce transmission via air. Ventilation can be provided by opening windows (natural ventilation) or by operating fans (artificial ventilation) [41]. Heating, ventilation, and air conditioning (HVAC) systems play a major role in controlling the transmission of infectious diseases [7,34,42]. In pandemic situations, such as COVID-19, they can be modified to reduce transmission of the COVID-19 disease. Potential modifications include improving the efficiency of the central air filter, providing portable high-efficiency particulate air (HEPA) filters, and keeping the system running for longer hours. Additional potential modifications include increasing the volume flow rate of outside air in ventilation systems and opening the dampers fully to enable 100% outside air [43,44].

HEPA filters are effective at controlling the propagation of viruses in the operation of room air cleaners [45]. HEPA filters can be modified with natural lytic enzyme to immobilize the pathogen on fiber media. Then, this bactericidal enzyme will destroy the virus glycoprotein and thus inactivate the virus [46]. It eliminates the infectious agents in the building by providing efficient airflow patterns, with the mechanism being that it dissolves the indoor air near the source. The filtration grade can also be upgraded by using many other available products in the market, such as the semi-absolute filter ePM1 95% [47], PM2.5 filter [48], and photocatalytic oxidation (PCO) filter [49]. The use of movable vertical air filtration units is an option for minimizing the problems in retrofitting these types of different filters with HVAC [46].

All HVAC system modifications require proper functioning of the ventilation, which ensures prior operation before occupation. The Federation of European heating and air-conditioning associations (REHVA) suggested that the setpoint CO_2 concentration should be reduced to 400 ppm [44]. Further, the Society of Heating, Air-Conditioning and Sanitary Engineers (SHASE) of Japan also indicated that the CO_2 concentration should be reduced [44]. However, there is currently no consensus about the amount of ventilation required to minimize the risk of infection efficiently. REHVA recommended that to prevent resuspension of virus due to convection, return airflow should be stopped. The Chinese Association of Refrigeration (CAR) proposed recommendations that stop all convection devices, including fan coils to resuspend the virus [3,44] containing aerosols. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also suggested an upgrade of the filter to the minimum efficiency reporting value (MERV) 13 and to disinfect viruses in the air [50].

Other main parameters influencing the spread of virus include the indoor temperature and relative humidity. Many research studies have investigated the effects of the indoor temperature and relative humidity on COVID-19, and the results show that the right set-points are required to deactivate the virus [22,41,43,51]. The persistence of Corona virus can be influenced by both the temperature and humidity. SHASE suggested that the indoor temperature should range from 17 to 28 °C, and the relative humidity should range from 40% to 60% [44]. Thus, the setpoint temperature and relative humidity should be considered when designing buildings to meet these requirements. The temperatures required to inactivate the virus are reported to be 56 °C for 30 min and 65 °C for 15 min [52]. These temperatures and durations are not suitable for HVAC systems to heat the internal air. Alternative approaches to disinfection should be considered to reduce the virus spreading. ASHRAE recommended that the design and construction of HVAC should include an integrated design process during the early stages of construction. This will help to overcome issues related to the indoor temperature and relative humidity [41,53,54]. Apart from these methods, there are a number of other engineering controls that may be used to limit the risk of COVID-19, which are discussed below.

4.1. Materials That Offer Antimicrobial Protection for Walls and Floor

A study by Cortes et al. [55] highlighted how the survival of COVID-19 virus/variants on surfaces varies based on the material. The lifespan of coronavirus on various materials is depicted in Table 2 [56]. Cortes et al. [55] compared the stability and decay rates of the COVID-19 virus in aerosols, copper (99% copper metallic plate), cardboard, stainless steel, and plastic. Their study highlighted that after four hours on the copper surface, no detectable levels of the SARS-CoV-2 virus were found. The COVID-19 virus lasted on plastic, stainless steel, and cardboard for 3, 2, and 1 day, respectively [56].

Copper alloys contain antiviral and antibacterial ions that may kill over 99.9% of germs in just two hours [55]. Thus, coper has the capability to destroy the ribonucleic acid (RNA) of the virus. Thus, antimicrobial copper surfaces could be used to help minimize the spread of respiratory viruses and protect people in communal areas and at mass gatherings [55]. Moreover, copper has antibacterial characteristics that are more effective than silver, which requires moisture for activation [57]. Thus, copper can be recommended as a much better construction material than other traditional materials for post COVID-19 buildings. Copper-incorporated construction products and elements will help to prevent the spread of infectious diseases. The use of this metal in alloys on hotspots, such as elevator buttons and door handles, might help to decrease contamination and the spread of pathogens [57].

However, copper is not cheap, and it is difficult to maintain as it has high maintenance costs. Unlike copper, stainless steel and plastics are widely used in many building applications due to their affordability and clean-looking surfaces with low maintenance costs. Thus, plastics can be combined with copper, silver, and zinc to produce a substance with antimicrobial properties, where the viruses are not eliminated instantly, but it prevents the multiplying of viruses and they eventually disappear [57]. Silver nanocoating, gold nanocoating, titanium-based coatings, and carbon-based coatings also have potential to enable antiviral coatings [58].

Table 2. Survival of coronaviruses on surfaces near room temperature (adapted from Marzoli et al., 2021) [56].

Surface	Virus	Viral Titer ($TCID_{50}$)	Temperature (°C)	Survival (d)
Steel	HCoV, MersCoV, SARS-CoV, SARS-CoV-2	$1.4 \times 10^3 - 1 \times 10^6$	20–24	2–>28
Copper	SARS-CoV, SARS-CoV-2	1×10^3–1×10^4	21–23	0.17–1
Aluminium	HCoV	5×10^3	21	0.08–0.5
Wood	SARS-CoV, SARS-CoV-2	5×10^5–1×10^6	RT–22	1–5
Glass	HCoV, SARS-CoV, SARS-CoV-2	1.4×10^3–1×10^6	20–25	2–>28
Cloth	SARS-CoV, SARS-CoV-2	6.3×10^4–1×10^6	RT–22	1–>5
Paper	SARS-CoV, SARS-CoV-2	5×10^3–1×10^6	RT–23	0.02–>28
Ceramic	HCoV	1.4×10^3	21	>5
Soil	SARS-CoV	1×10^6	RT	4–5
Vinyl	SARS-CoV-2	3.38×10^5	20	>28

RT = Room temperature.

Furthermore, fabric covering, commercial vinyl wall coverings, upholstered panels, as well as cork wall coverings can also be used to reduce the rate of germs [57]. These products can be used for post COVID-19 buildings as wall treatments. The main criteria for hygienic coatings and coverings are cold-cracking, heat-aging resistance, crocking, scrub-ability, and chemical resistance. One of the latest examples is hygienic cladding, which is easy to clean, cost effective, and resistant to chemicals [59]. Another viable solution to kill or inhibit the rate of germs on the walls and floors is the application of antibacterial paints [59]. These kinds of paints have the ability to resist mold fungus and bacteria. Biocote is one of the most effective antimicrobial paints on the market, with over 99% microbe's resistance with antimicrobial technology [60]. Australian researchers have created a solar paint that can convert water vapor into hydrogen and oxygen, allowing for improved indoor air quality [61].

Another option for preventing virus spread would be the use of hygienic flooring. Different flooring materials exist, such as bamboo, cork, and engineered timber. Wood contains extractives, such as flavonoids, tannins, aldehydes, phenolic acids, terpenoids, alkaloids, terpenes, etc. These wood chemicals enable antimicrobial actions against microbes [62].

4.2. Ultraviolet Radiation

Type C ultraviolet (UV) rays are capable of destroying bacteria and viruses, commonly known as pathogens [63]. It is particularly successful in decontamination as it breaks the molecular connections that keep viruses' and bacteria's deoxyribonucleic acid (DNA) together. This UV light is known as a germicidal ultraviolet (GUV) [53]. GUV now attracts attention as a passive sanitizing design feature that can be used to minimize transmission risk within buildings. Vranay et al. [64] stated that by using germicidal sources to disinfect transported air, more than 90% of the SARS-CoV-2 virus produced by humans in an internal environment can be inactivated. This contaminated indoor environment can be disinfected by applying the germicidal sources. UV radiation at a wavelength of 265 nm is most effective for use in air disinfection [65].

Pathogens sensitive to UV radiation are expressed as an inactivation rate constant (m^2/J) [66]. The value for SARS-CoV-2 in air is 0.08528 m^2/J. It is reported that a dose of 27 J/m^2 UV radiation is sufficient to inactivate 90% of SARS-CoV-2 [64]. However, UV rays are harmful to people's eyes and skin. Therefore, direct exposure of humans should be avoided. The upper-room ultraviolet germicidal irradiation (UVGI) technology can be used in buildings in which humans are present to avoid direct exposure [67]. UVGI technology uses UV rays to disinfect viruses and bacteria by creating an irradiation field above the heads of the room's occupants [68]. One of the advantages of UVGI is that the UV field does not affect the room's inhabitants. Further, UVGI can be mounted as part of specifically designed fittings on walls and/or ceilings. UVGI does not require a specialized technician and it can be easily installed in existing buildings [69].

4.3. Air Cleaning Plants

Plants in indoor environments promote healthy and comfortable living by absorbing pollutants [70]. Plant evapotranspiration helps to decrease the temperature in the surrounding environment. Thus, it may be used to regulate air cooling and humidity. Further, plants have the ability to reduce volatile organic compounds (VOCs). This helps to maintain a person's mental health by reducing the sick building syndrome effect [71]. Plants also have potential to purify indoor air through a phytoremediation process in which plants absorb and catabolize various toxic substances [70]. Using indoor plants to purify air may be a cost-effective and energy-efficient option to promote healthy buildings. However, more research is needed to establish standards and regulations before adopting this strategy.

Plants that can be used inside buildings must meet certain criteria, such as light settings, climatic conditions, and growing media [72]. As a result, medium- and low-light plants as well as inorganic growth media are recommended, since they are easier to regulate in terms of nutrients and adaptability [72]. Living walls are another strategy of green buildings that allow plants to grow on a vertical surface, such as a building facade or an interior wall, which is known as "vertical gardening" [73]. Vertical gardening has gained attention recently, owing to its economic, environmental, and social advantages. Therefore, it has potential to be included in both traditional and new zero-emission green buildings in the near future [74]. Vertical greening systems are used inside buildings for indoor air purification and biofiltration [71,75]. Therefore, designers, architects, and engineers are interested in the application of this technique to avoid the "sick building syndrome".

4.4. Bipolar Ionization

Needlepoint bipolar ionization (NBPI) is used to purify air by producing ions [7]. This technique scatters positive and negative ions thorough air, which eliminate pathogens, such as viruses, mold, and bacteria, in air [76]. In addition, the filtration effectiveness is enhanced by particle assembly induced by NBPI. The system oxidizes foul-smelling gases by separating them into basic compounds free of any smell. It was discovered that through NBPI, about 84.2% of the virus can be inactivated within 10 min, whilst about 92.6% and 99.4% of the virus can be inactivated after 15 and 30 min, respectively [77]. NBPI can give many of the same advantages as UV radiation as well as odor control and VOC reduction.

NBPI produces reactive ions or reactive oxygen species in air. This reacts with airborne pollutants including viruses [76]. A virus cannot mutate, grow, or reproduce without hydrogen bonding [78]. Therefore, this technology helps to deactivate hydrogen bonds by releasing groups of OH (hydroxyl) radicals using electrostatic interactions [76].

The bipolar ionization technique has been adopted in hospitals, schools, hotels, airports, and office buildings to improve the indoor air quality [76]. Currently, an advanced bipolar ionization system has been introduced with particle reduction and pathogen control. This is a feasible method used to control coronaviruses in buildings [79]. This technique could provide an optimal solution to reduce the transmission of viruses via aerosols inside buildings.

4.5. Disinfectant Fogging Systems

Fogging technology has been used in the pharmaceutical and food processing industries to remove air and surface pollution. Recently, this system has been used in hospital environments to disperse the fine particles of liquid sanitizers or disinfectants to decontaminate an entire volume [80,81]. In hospitals, hydrogen peroxide fogging is widely used to minimize or remove air and surface pollution in unoccupied patient rooms [82]. Fogging uses an antiviral disinfectant solution that easily and efficiently cleans and sanitizes large areas of a building. This has the ability to destroy viruses and other biological agents in aerosols and on surfaces [83]. Fine mist is sprayed from a spray gun that is then left to evaporate, usually for six hours, while the room is not in service [83].

4.6. Other Technologies

Good indoor air quality can be achieved using building materials that are certified as no or low-pollutant-emitting products [3]. The U.S Environmental Protection Agency (EPA) identified the primary sources of indoor air pollution, which include furniture and appliances, floor and wall coverings, paints, coatings, adhesives, sealants, wall coverings, wood, textiles, insulation, and cleaning products [19]. Therefore, protocols for chemical emission testing have been developed to ensure that the test results can be converted into applications for real-world product use. Consequently, "smart" construction materials and coatings are now being created, with the intention to minimize indoor air pollution through a research program for advanced construction materials [84].

Green building materials (GBMs) containing non-toxic, natural, and organic ingredients have potential to improve indoor air quality and lower health risks [85]. One GBM is a bio composite, which is composed of biopolymer and natural fibers that can minimize indoor air pollutants [85]. Thus, the use of green building materials helps to maintain a healthy built environment. Photocatalytic creative covering applications for the depollution assessment (PICADA) project represent a new initiative that developed coatings and "smart" building materials containing titanium dioxide (TiO_2) [86]. Nitrogen oxides (NO_x) and organic compounds in the atmosphere diffuse through the porous surface of the materials and coatings that adhere to TiO_2 nanoparticles. Optimum antibacterial activity can be achieved by exposing the TiO_2 surface to radiation-intensive ultraviolet lights with a range of 10 mW cm^{-2} for a duration of 30 min to a few hours. UV-A-induced photocatalysis of TiO_2 is highly promising for pathogen disinfection systems [87]. TiO_2 photocatalyst and UV lighting systems jointly represent a mitigation strategy for the propagation of viruses. The acidic products produced by this process are washed away by rain and/or neutralized by the materials contained in alkaline calcium carbonate. These new building materials will help reduce the concentration levels of NO_x that cause respiratory problems and cause the development of smog, as well as other harmful substances (such as benzene). The outdoor air quality can be substantially improved by photocatalytic materials under field conditions [86]. Surfaces covered with a photocatalytic cement-like material decreased the NO_x concentration by up to 60% at the street level [86]. Thus, the application of photocatalytic materials to building surfaces will improve the outdoor and indoor air quality [88].

Further single treatment techniques, such as mechanical and electrical filtration, adsorption, ozonation, photolysis, photocatalytic oxidation, biological processes, membrane separation, plasma-catalytic hybrid systems, hybrid ozonation systems, and biofilter-adsorption systems, are effective means of ensuring healthy buildings [89].

5. Recommended Solutions for the Post COVID-19 Buildings

5.1. Existing Buildings

The COVID-19 pandemic has had an impact on building construction techniques as it forced modification of the architectural design of buildings [8]. Our existing buildings are neither designed nor constructed to effectively reduce the transmission of communicable diseases. Thus, it is important to consider new solutions to overcome such a situation in the way of adaptive reuse. This can be achieved in many ways, such as engineering controls and retrofitting of existing structures or improving the indoor air quality [9,21].

The holistic approach is the best way to control and minimize the impacts of the current COVID-19 outbreak [90]. This approach attracts people to work in buildings by considering their physical, mental, and social environments. Creating a healthy environment by retrofitting green plants inside building walls could be one of the best options to improve buildings' health (Figure 6). Plants are capable of absorbing and catabolizing many harmful environmental chemicals [70]. Therefore, the use of indoor plants might be one of the most environmentally friendly air-purification techniques, with minimum energy use and a low cost. However, more specific research is still required to define the standard requirements for an indoor plant. The creation of indoor portable green walls is another solution used to achieve healthy buildings. This technique uses botanical biofilters and bioreactors, which neutralize pollutants through an active biofiltration process. In this process, the contaminated pathogens are moved into the biological active region, which is installed behind the wall system (Figure 7).

Cortes et al. [55] reported that the use of copper helps to prevent the transmission of coronavirus. The creation of antimicrobial copper touch surfaces within existing buildings can help to reduce the spread of coronavirus. This can be achieved in many ways, such as retrofitting and/or replacing door handles and handrails of doors and windows, lift surface, and control buttons with copper alloys products. This action requires an additional cost as copper is an expensive material and it require expenses to maintain [91]. These issues can be avoided by using "cold spray technology". Hutasoit et al. [92] investigated the use of a cold-spray process to manufacture copper coatings onto steel plates. This can shorten the coronavirus's lifespan to less than 5 h. Therefore, this cold spray technique could represent an option to replace contact surfaces in a building. The cold spray technology is one of the most promising solutions for creating a hygienic built environment in post covid buildings.

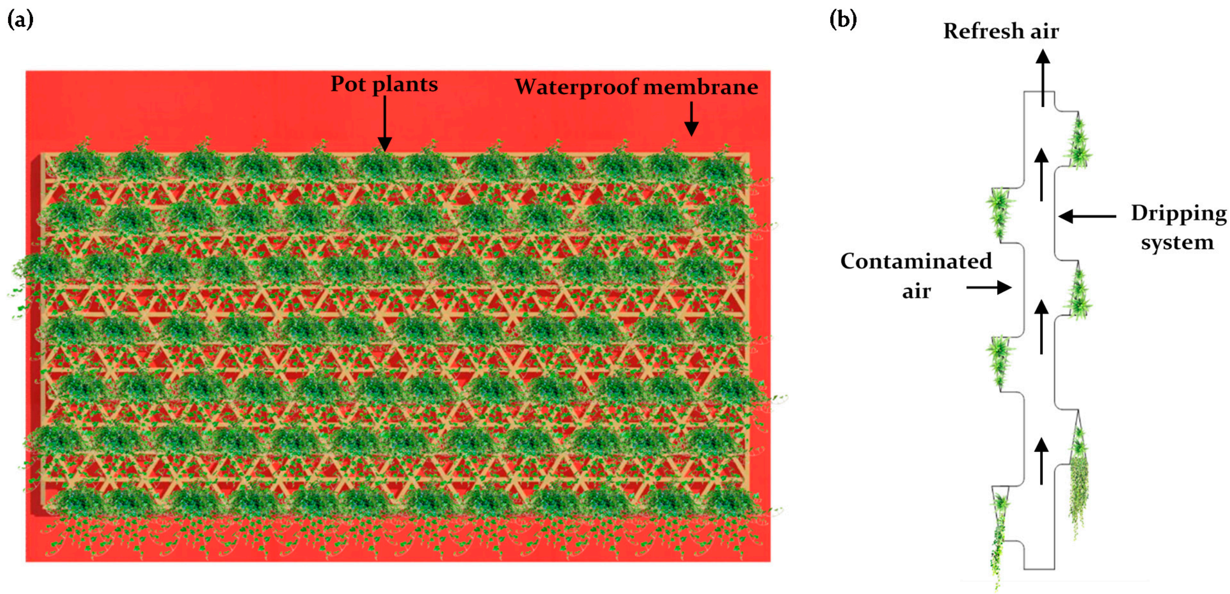

Figure 6. Retrofitting of green plants in a wall: (**a**) plan view and (**b**) sectional view.

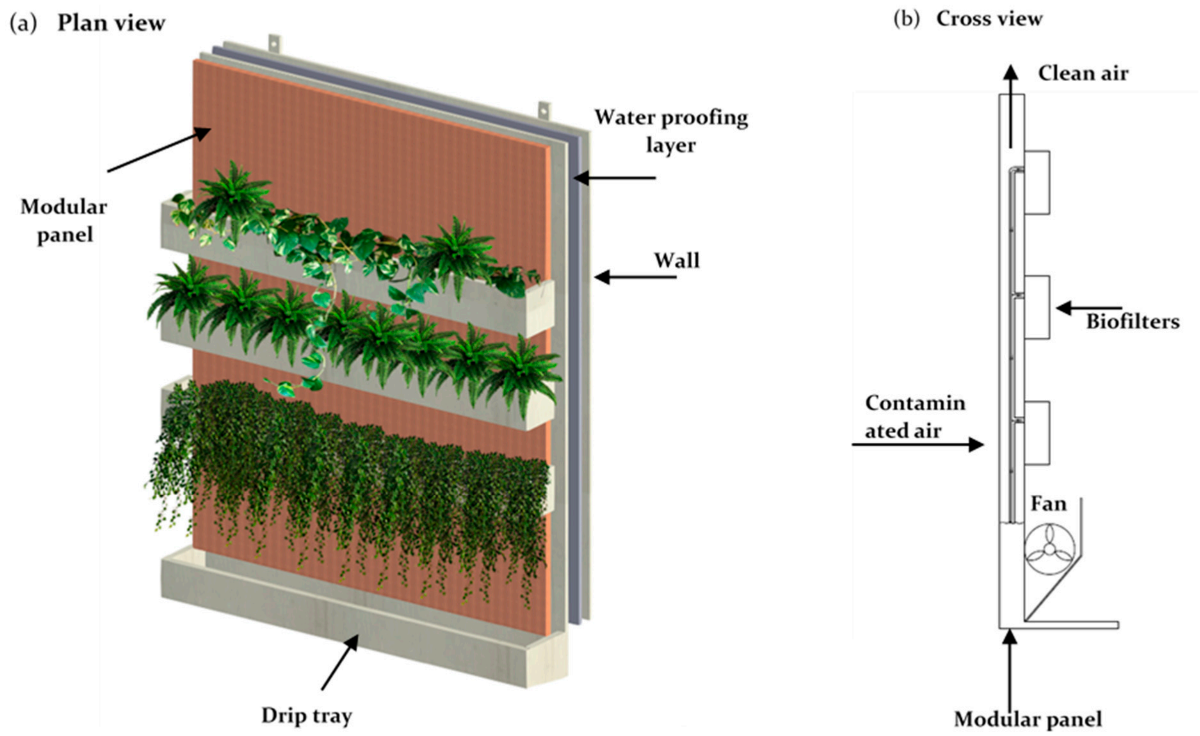

Figure 7. Prefabricated green wall: (**a**) plan view and (**b**) sectional view.

Another potential solution to reduce the transmission of COVID-19 disease is the application of surfaces with antimicrobial paint. These paints can destroy bacteria and viruses that come into contact with the surface of the paint [93]. However, commercialization of this paint requires an understanding of the nature of paints and their endurance. Incorporation of antimicrobial particles into regular paints before application to building surfaces is another method that reduces the transmission of the disease. Silver ions and glass ceramic ions can be used as antimicrobial particles mixed with paints, which have the ability to reduce the growth of harmful bacteria and coronavirus [93]. Further antimicrobial chemicals, polymers/composites, and nanoparticles (i.e., with antibacterial, antifungal, and antiviral action) can be directly applied to existing building surfaces or integrated into coatings to reduce the spread of coronavirus [94].

The air cleansing technique using air ionization, which includes the injection of ions into a room, has the capability to improve the indoor air quality and reduce the transmission of coronavirus [76]. Bipolar ionization appears to be one of the most commonly utilized ionization techniques to avoid the spread of the virus in air. Bipolar ionization devices have been recommended by many engineers due to their low cost regarding initial purchase, installation, maintenance, and materials expenses. Another advantage in this system is the low pressure drop for the air handling equipment [76,79]. This system can be installed in any existing building at any location without causing any disruption (Figure 8).

Installation of the UVGI technology in existing buildings (Figure 9) is another direct approach to preventing airborne transmission [7]. This technology is considered to be applicable for large buildings (Figure 10) to reduce virus concentrations by utilizing human-safe UV radiation intensity. UVGI has the ability to provide considerable protection at a low cost and is particularly well-suited for retrofitting older buildings. However, further research is needed to improve this technology in a safe and commercially viable manner. In the absence of people, mobile UVGI devices (Figure 10) can be used to clean surfaces and indoor air, and passageways. This device can also be placed on the floor, pulling air at lower levels, and it contains a G4 filter that removes particles to keep the UV lamp clean inside. However, before utilizing a mobile UV device, one should ensure the surrounding are not exposed to UV radiation as it harms the inhabitants.

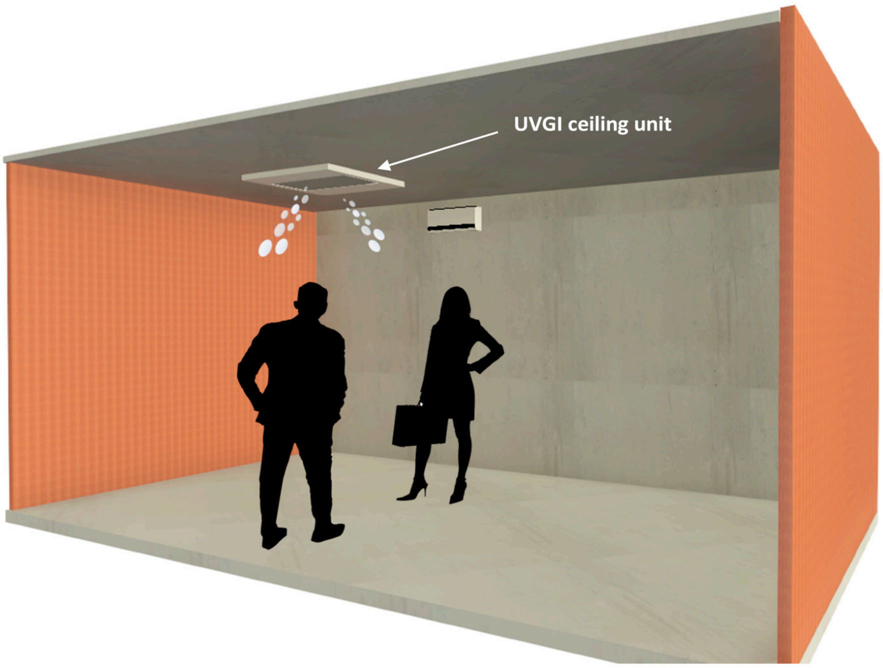

Figure 8. Potential application of a bipolar ionization device inside existing buildings.

Recently, a smart Soterius Scout bio sensor was induced to detect viruses in buildings [95]. This can deliver results in under a minute, giving someone the green light or alerting them to the need for a test and self-isolation. The sensor is small enough to be placed on a personal fob card, and it is simple to use. A simple swipe over the sensor can help to detect the presence of a virus. This represents a crucial tool that can be used to combat COVID-19, allowing for precise early identification.

Separation of a large open building space with a plastic barrier with a zipper door (Figure 11) is another option that could be used to reduce disease transmission. This system contains a particle counter, portable HEPA filter, aerosol generator, and pressure gauge. This strategy is more suitable for use in offices, hospitals, schools, and university buildings. Adapting this system to existing buildings will help to reduce the cost and activity induced by workplace capacity limits imposed during the COVID-19 pandemic.

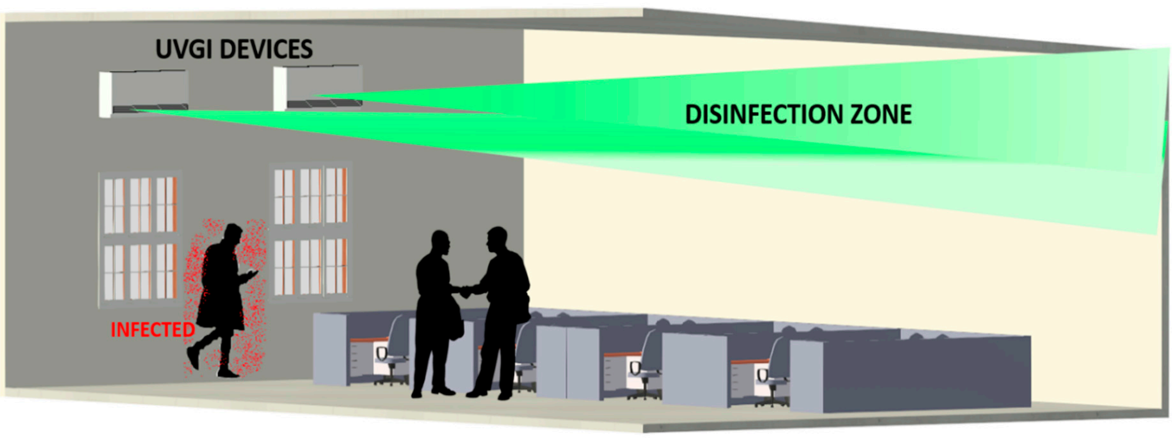

Figure 9. Potential application of ultraviolet germicidal irradiation (UVGI) technology.

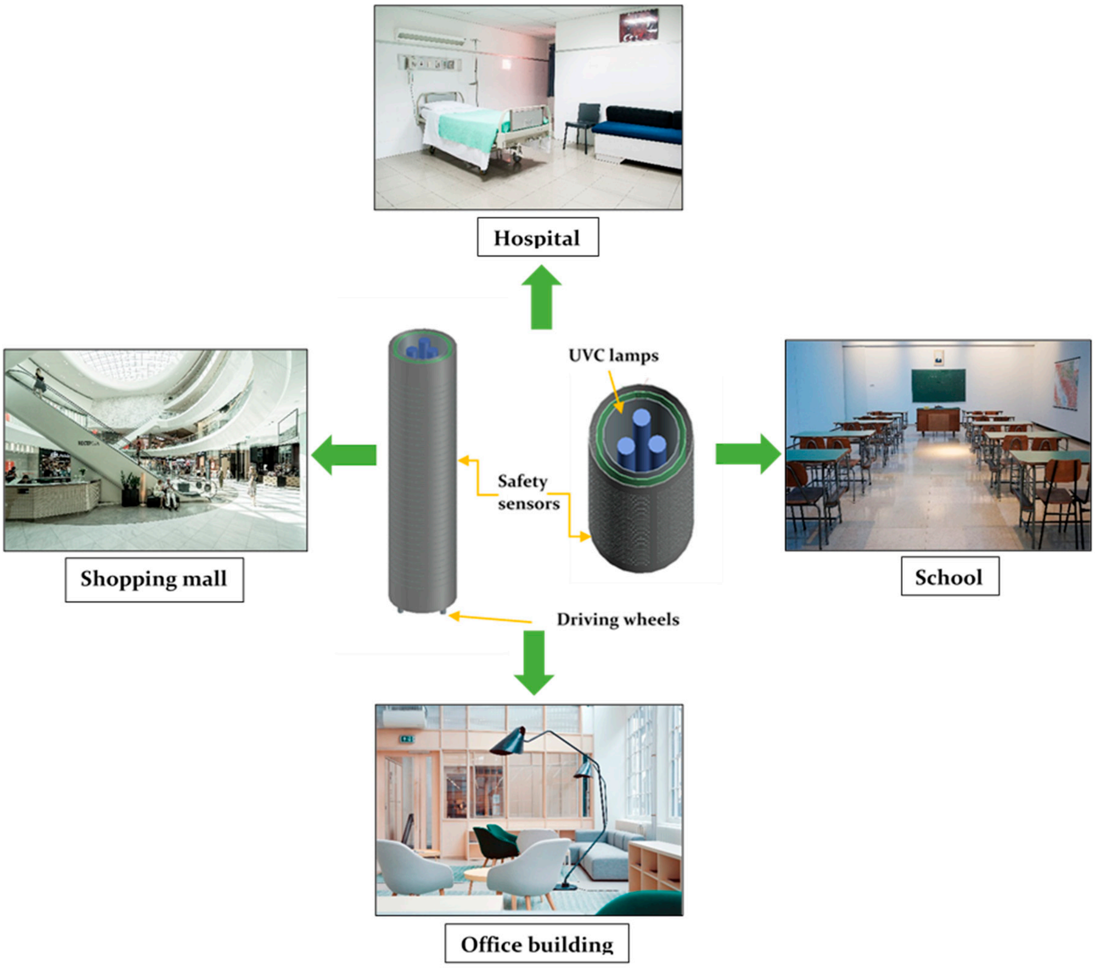

Figure 10. Mobile UVGI device and its application in different places (photos: reproduced with permission under the terms of the Creative Commons CC0 license. 2021, published on Pexels website).

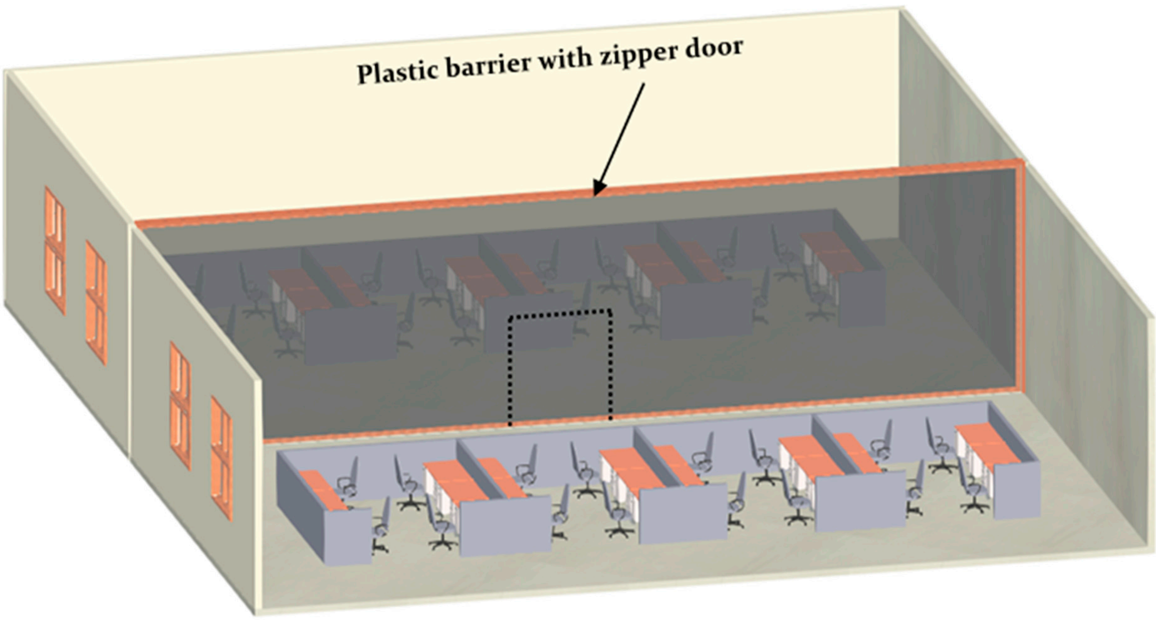

Figure 11. Separation of a large open space in an office building with a plastic barrier.

5.2. Future Buildings

The post pandemic period highlights the importance of thinking forward to advances in construction techniques that speed up emergency building development. Effective ventilation is an essential part of engineering solutions for future buildings. The most cost-effective method that provides fresh air is natural ventilation. This can be considered at the building design stage. While it may appear that leaving windows and doors open to facilitate a continual flow of fresh air into a structure is a viable option, to construct healthy buildings, the building must be re-evaluated for appropriate ventilation.

The modular construction strategy has been successful at coping with pandemics or natural disasters and producing cheaper and faster-built construction [96]. Parking areas and other structures are converted into emergency centers and temporary hospitals during pandemic. These adaptive strategies will be beneficial for future crises [35]. Lightweight and adaptable structures are also preferable for their speed and portability in response to a pandemic [96]. These temporary structures are designed and installed by designers to build field hospitals that can be moved and installed easily for COVID-19 patients.

It is important to think of every potential location and the risk of becoming a source of pathogens inside the building at the design stage. More cleaning strategies focused on new technologies could be implemented by post-pandemic architecture. Virus transmission can also be reduced by applying touchless technology on potential contact surfaces of buildings. The use of Toe-To-Go elevator systems in future buildings is one innovative technology that will avoid contact with operating lift keys. This technique was recently adopted in a Chicago building [37]. Further, automation, voice technology, and artificial intelligence-based facial recognition can be adopted in the design of post Covid architecture [3]. Post Covid building design principles should aim for more contactless routes, such as smartphone control lifts, door and window locks, and automatically opening doors with face identification. These systems could include other space temperature control programs and clean them automatically to destroy pathogenic substances, viruses, and bacteria. Even though there is an additional expense associated with incorporating these techniques into future buildings, it will improve occupants' health and provide value regarding the money being used.

In Australia, residential houses are constructed with a hip end roof [97]. Part of this roof cladding can be designed with UV filter glass with a transparent solar panel (Figure 12) in post COVID-19 pandemic building design. This enables sunlight to travel into the building, which helps the growth of indoor plants and boosts vitamin D levels for humans. This glass roof has the capability to produce power, which can reduce electricity costs and greenhouse gas emissions. Thus, this proposed roof design could be an option to improve the health and quality of built environments.

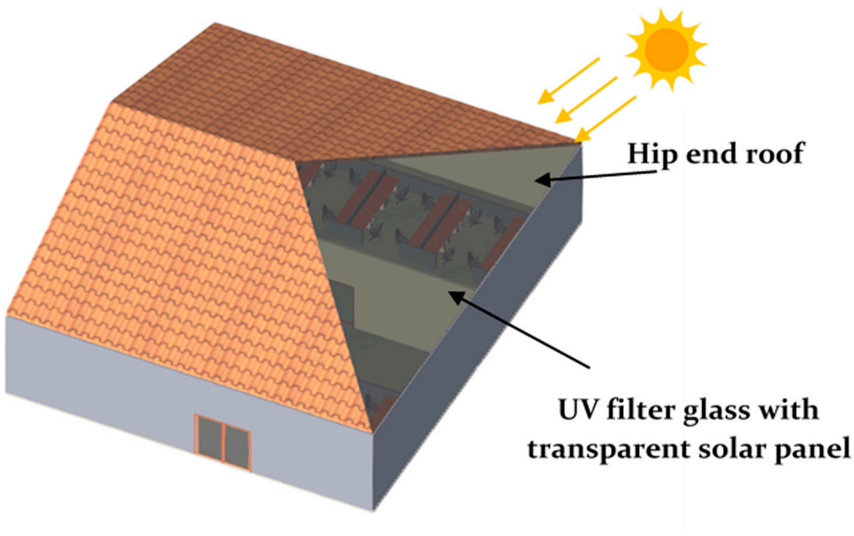

Figure 12. Roof structure with UV filter glass with a transparent solar panel.

Post COVID building design should consider the use of bipolar ionization systems, UVGI technology, building products with copper alloy, and antimicrobial paint. Further, the interior and exterior building design should adopt indoor plants and vertical planting strategies. These approaches will enable fresh air and improve occupants' health, thus controlling virus spread. Consequently, this may reduce lockdowns and improve the economy of a country.

6. Conclusions

The COVID-19 global pandemic brought significant changes in lifestyles, working environments, travel patterns, and economics, etc. The pandemic resulted in isolation and limited access to workplaces, hospitals, schools, and other facilities. Thus, scientists, engineers, and governments have identified all potential strategies that reduce disease spread and proposed protective measures. COVID-19 viruses are transmitted via aerosol and about 80% of infectious diseases spread by contact with contaminated surfaces. Thus, improving air quality and reducing contact surfaces in buildings could reduce the spread of disease. Buildings with good indoor air quality could effectively mitigate the transmission of communicable diseases. This article proposed the following more sustainable engineered techniques to enable healthy buildings and reduce the transmission of diseases:

- Installation of HVAC systems (in existing and future buildings) with UVGI and Bipolar ionization, which improve the indoor air quality and reduce the transmission of communicable diseases.
- Increased contactless routes, such as smartphone control lifts, touchless door and window locks, and automatic opening doors with face ID.
- Application of antimicrobial paint and particles to existing and future buildings, which disinfect pathogens in a short period to reduce disease transmission.
- Utilization of antimicrobial copper alloy-coated touch surfaces (e.g., door and window handles, wall, etc.).
- Modification of the geometry of roofs, introducing more open space and separating open spaces of building designs with UV filter glass.

Overall, these proposed techniques can be used alone or in combination. However, more research studies are required to identify more sustainable ways to adopt these technologies in existing and post COVID-19 buildings.

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAR	Chinese Association of Refrigeration
DNA	Deoxyribonucleic Acid
EPA	Environmental Protection Agency
GBM	Green building material
GUV	germicidal ultraviolet
HEPA	High-efficiency particulate air
HO	Hydroxyl
HVAC	Heating, ventilation, and air conditioning
IEQ	Indoor environmental quality
MERV	Minimum efficiency reporting value
NBPI	Needlepoint bipolar ionization
PCO	Photocatalytic oxidation
REHVA	Federation of European Heating and Air-conditioning Associations
RNA	Ribonucleic acid
SHASE	Society of Heating, Air-Conditioning and Sanitary Engineers
UV	Ultraviolet
UVGI	Ultraviolet germicidal irradiation
VOC	Volatile organic compounds
WoS	Web of Science

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