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Review

Prophylactic Architecture: Formulating the Concept of Pandemic-Resilient Homes

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Abstract: The lockdown instituted during the COVID-19 pandemic has drawn the world's attention to the importance of homes as integrated structures for practicing all aspects of life. The home has been transformed from a mere place to live into a complete piece of infrastructure accommodating all activities of life, including study, work, shopping, exercise, entertainment, and even telehealth. Although quarantines were necessary to protect against viral infection, we have faced social and psychological challenges due to the failure of the current home design to accommodate the new lockdown lifestyle during the pandemic. Thus, this study aims to set a foundation for the development and design of resilient homes in a post-quarantine world by establishing a comprehensive framework for quarantine-resilient homes. The framework was established on the basis of the relevant literature and proposals from architects and experts. It brings a perspective to the future requirements of homes so as to provide architects, stakeholders, and policymakers with the appropriate knowledge to mitigate the impact of lockdowns on mental health and well-being in residential buildings by focusing on the physical and architectural environment.

Keywords: COVID-19; SARS-CoV-2; coronavirus; pandemic; homes; housing; residential buildings; quarantine; healthy housing

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1. Introduction

In early 2020, the world witnessed the beginning of the SARS-CoV-2 (COVID-19) pandemic (coronavirus disease 2019) [1], which first emerged in Wuhan, China, in December 2019, and then spread to most parts of the world. At the time of this writing, it has claimed more than 6 million lives after more than 500 million confirmed cases worldwide [2]. Due to the extensive spread of the coronavirus, the resulting high death rates, and the limited capacity of hospitals to absorb patients, the World Health Organization declared COVID-19 a pandemic on 11 March 2020 [3]. Consequently, countries implemented home quarantines to prevent further spread of the virus. Thus, homes became isolated environments for infected patients during the acute stage of the disease [4]. At the same time, the world witnessed drastic changes in several areas—including digital technology and artificial intelligence—as evidenced by the transition to telelearning, telework, telehealth, and telemarketing, which are likely to continue even after the end of the pandemic [5].

At the time of the lockdown, people around the world found themselves trapped inside their homes, in full residence, carrying out all activities of life. A small number of people who had to go to work and mix with other people were exposed to the infection and transported it to their homes and families. At the end of the quarantine, and with the gradual reopening of society, the impact of the infection became apparent, as people got close to one another in public places, healthcare facilities, schools, restaurants, entertainment facilities, hotels, and apartment buildings [6]. Furthermore, home quarantine, which created a social and psychological challenge as a result of the long stays at home and the necessity to practice all areas of life in isolation, revealed that homes should be able to facilitate all daily activities, including living, working, shopping, and entertaining during epidemics and pandemics. This requires that more attention be paid to designing healthy futuristic homes by architects, planners and decision makers [4].

The experience of home quarantine during this period showed that controlling infectious diseases and preventing their spread is an important function of architecture. Intracing the history of epidemics and their impact on architecture and urbanism, we find that such events stimulate architecture to develop; thus epidemics and infectious diseases (such as the bubonic plague in the 14th century, yellow fever in the 18th century, cholera and smallpox in the 19th century, cholera epidemic in the mid-19th century, tuberculosis (TB), typhoid, polio and Spanish influenza in the 20th century) were the drivers of housing reforms and urban regeneration midway through the last century. However, the role of the human-built environments in treating infectious diseases has been held back by the advancement of antibiotics, immunizations, and antiviral drugs [7–13]. But now, with the lack of ready-made drugs to treat the newly emerging infectious diseases such as COVID-19 and the time needed to produce the appropriate vaccines for viruses and the resulting strains and study immunity and its side effects, there is a renewed interest in the role of physical spaces as means to counter epidemics [14].

As homes are among the types of building that have been most severely affected by the pandemic, this paper investigates the thoughts of architects, researchers, and stakeholders about innovative home designs that have been created as a response to COVID-19, drawing on peer-reviewed papers, specialist architectural web pages, expert opinions on web sites and blog posts, and assessing the expected changes in the sustainability requirements for these buildings.

Post-Pandemic Home: The Dilemma

The quarantine associated with the COVID-19 pandemic has shrunk our vast world to just a home. Hurst R. Neurotic, 2020, depicted the home as a pressurized environment during the closure, in which the living room became a conceptual public space, the annex rooms became productive work areas, and the inanimate objects became traces of our unexpected shrinking world. Kevin Lynch's elements have transformed from city, neighborhood, nodes and landmarks into house, room, place, and element [15].The rapid spread of COVID-19 has forced people to spend most, if not all, of their time at home in order to protect themselves and to prevent the risk of catching or spreading the coronavirus. The experience of living in quarantine, in addition to the expectations of viral outbreaks in the future, calls for rapid adoption of new lifestyles that ensure the achievement of safety measures [12]. The whole family stayed home for longer periods, college and school students stayed home to participate in remote classes, and parents stayed home to work while looking after their children instead of calling the babysitter. This unprecedented family gathering made us realize that our homes need additional spaces. Families with members infected with COVID-19 have realized their need for a quarantine room and private bathroom [16]. The problem appeared most clearly in multi-story apartment buildings, where tens or hundreds of people gathered in the public areas of the building, such as the lobby, elevators and laundry rooms [17]. The COVID-19 pandemic has drawn our attention to our physical world, particularly to our homes [16]. Most people have begun to adapt their current living spaces to accommodate remote work and study. These methods include making new uses of the existing spaces, reorganizing and redesigned the wasted spaces to accommodate workplaces and conference rooms, and reorganizing and renewing the storage spaces to put them to better use [16].

Peoples' attachment to their homes comes from the fact that the home is a place of refuge, security and stability, especially in times of crisis, which ensures it is filled with special moments of kinship, restoration and belonging as exemplary sources of psychological support. This is the pivotal role that the home must play during periods of closure. Moreover, people staying for extended periods of time at home during quarantine are poses many mental health-related issues. People were forced to change their lifestyles and, at the same time, opportunities for social interaction decreased, fears of job losses increased, as did those of the deadly and highly contagious infectious disease, a faltering economy, and an unknown future, all of which have many negative effects for both physical and psychological health [18].

In some countries during the lockdown, residents of entire complexes were infected as the infection was transmitted through shared surfaces such as doors, elevators, stairs, and other common facilities. Hence, these residential complexes were completely shut with their residents isolated inside, and obtaining food and medicine became very difficult despite its availability in nearby stores, which caused panic among the residents. In one case, welding shut the entrance door of a residential building provoked the discontent of one of the residents who tried to break the door and escape, which indicates that the residential buildings are not prepared at all for epidemics, not only due to the fact that they do not prevent the spread of the infection but also since they do not support self-sufficiency during the shutdown periods. It is worth noting here the description given to the closure of public housing as "confronting a crime scene" .The closure is a necessary measure, but it must be implemented in partnership with the residents and not as to detain them, and this is where architecture can make the difference [19].For communities to remain resilient and sustainable, changes must be made in the design of new apartment buildings; meanwhile, existing apartment buildings should be adapted to the new reality to make them self-sufficient and resilient to disease outbreaks so as to keep residents comfortable and productive in their homes and reduce the psychological impact on them [19]. Therefore, it has become necessary to review the additional spaces required for apartments at all levels [16].

2. Pandemic-Resilient Homes Concept

In a study conducted by Akbari et al., 2021 [20], to assess residents' preference for feeling satisfied during the COVID-19 quarantine, it was found that they prefer air quality and natural light primarily, followed by green landscapes and acoustics. These environmental factors are followed by spaces and activities (especially the kitchen for the former and planting for the latter). This showed the importance of the balcony, green spaces, and outdoor sports as factors affecting residents' satisfaction [20]. The study also indicated the effect of the availability of the balcony as well as its size on the mental health of the residents, as homes without balconies are associated with lower levels of mental health than those with a balcony, and mental health improves in homes with balcony areas of five square meters or more. In addition, the study indicated that the type of housing has an impact on mental health, as residents of private homes have better mental health than those who live in multi-story apartment buildings.

In another study that dealt with the population's preferences regarding healthy home indicators in Tehran after the epidemics conducted by Zarrabi et al., 2020 [4], it was found that the most important criteria were natural light, visual and acoustic properties, air quality, and open spaces, followed by the design of the house and the work space. The same study indicated that psychological effects on the population are more important than physical health effects, indicating the importance mental well-being standards. According to another concurring study, indoor residential environment quality (IREQ) standards have an impact on the psychosocial health of apartment occupants [11]. In terms of stressing the importance of mental health, Zarrabi et al., 2020 [4] pointed out the importance of providing qualitative standards in green rating tools such as LEED, BREEAM and other systems, which often provide quantitative standards, and emphasized making these qualitative standards mandatory or stimulating in systems Category.

In order to make homes suitable for the population during home quarantines, the World Health Organization has recommended improving home environments and reducing psychological pressure, which would help homes perform they role of providing comfort, privacy, security, all while protecting residents' physical and mental health [20].

In conjunction with the previously mentioned studies, a healthy home has basic needs of proper ventilation and indoor air quality (IAQ), natural light/sunlight, proper sound insulation (particularly for multi-story apartment buildings),thermal comfort in the form of adequate cooling, heating and humidity [4,12,21], views (landscapes), and green spaces [21]. Building on the foregoing, the health-oriented design guidelines for pandemic-resilient homes concept proposed by this paper include the following: (1) indoor environmental quality (IEQ): air (natural ventilation, mechanical ventilation, filtration and purification), sunlight/daylight, natural views, domestic green spaces, and acoustics; (2) space: housing type, apartment size, layout type, home advanced technology (home automation, smart kitchen, finishing materials and touchless technologies), shared spaces (lobbies, stairs, elevators, laundry rooms, etc.); and (3) household environmental resources management: energy, water, wastewater, solid waste.

2.1. Indoor Environmental Quality Factors (IEQFs)

The following section will represent IEQ factors (see Figure 1).

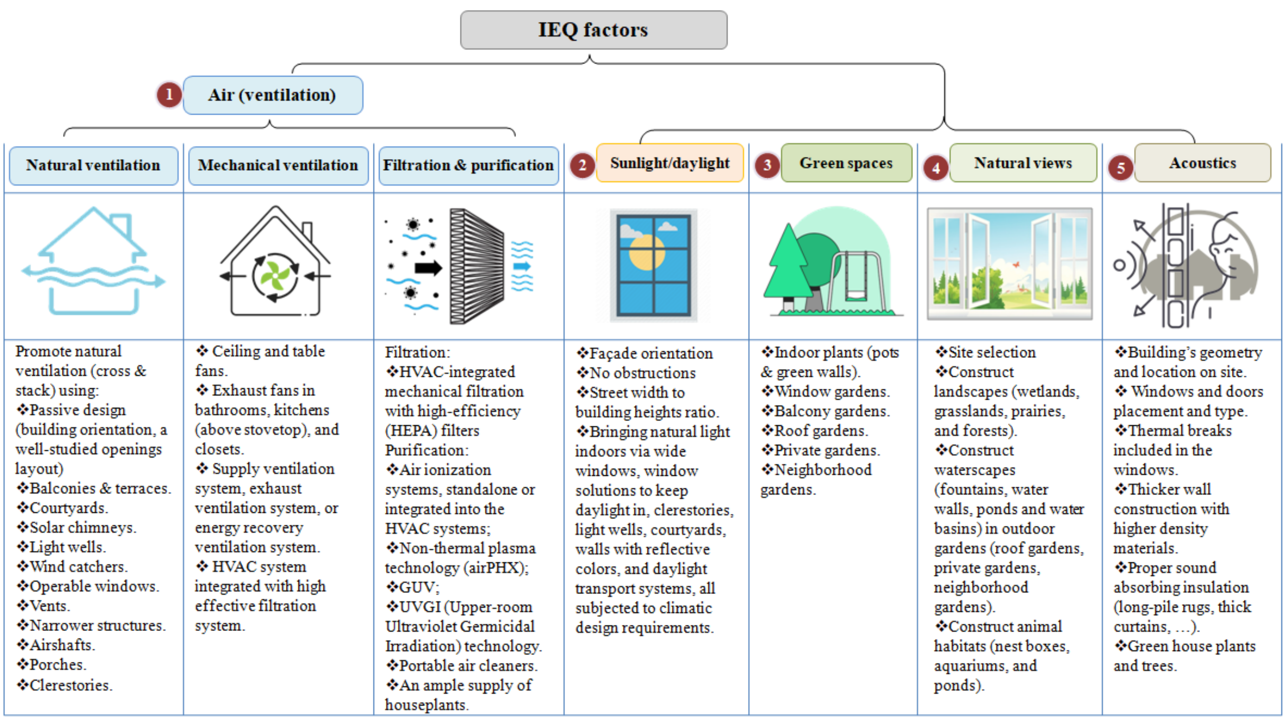

Figure 1. Indoor environmental quality factors in homes (IEQFs).

2.1.1. Air (Natural Ventilation, Mechanical Ventilation, Filtration and Purification)

COVID-19 is transmitted through aerosolized airborne droplets resulting from the mouth or the nose of an infected person when they breathe, speak, cough, sneeze, or sing in small liquid particles of different sizes ranging from smaller aerosols to larger respiratory droplets. People become infected when the virus enters their noses, mouths, or eyes following close direct contact with an infected person less than one meter away [6,17,22–28]. Airborne viral transmission indicates the presence of microbes inside the nuclei of droplets (which are smaller than 5 μmin diameter) that can remain suspended in the air for extended periods of time and can travel over distances of more than one meter. These aerosols (micro droplets) travel easily in enclosed, crowded and poorly ventilated spaces [6,17,24,28]. There is a lot of evidence indicating that the survival time of COVID-19 in aerosols ranges from 90 min to three hours, causing the risk of airborne infection [6,27,28] as stagnant air loaded with aerosol droplets in a room with poor ventilation may cause people who later enter the room to become infected [28]. This is valid with temperature ranging from 19 °C to 23 °C and humidity levels ranging from 65% to 88% according to Azuma et al., 2020 [6]. Although it is agreed that the recommended social distancing distance is 1.8288 m, one recent study has indicated that small infectious droplets can travel for up to 4 m in quiet, enclosed environments. Moreover, the risk of infection increases for young children and people of short stature [29]. Figure 2 shows the potential transmission methods in home environments.

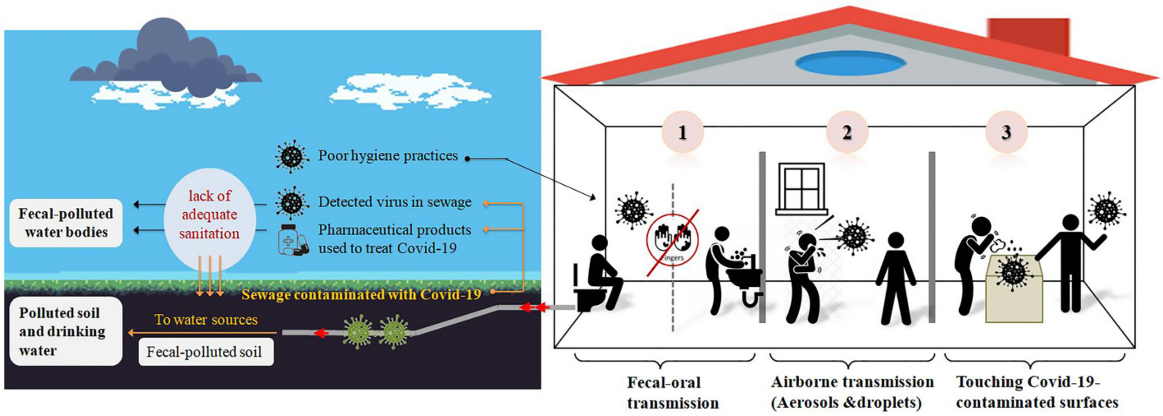

Figure 2. COVID-19 potential transmission methods in home environment.

According to recent research, there is a link between air pollution and the spread of COVID-19. Therefore, the most valuable mitigation strategy during the COVID-19 outbreak is practicing ventilation that would remove air particles that represent a favorable environment for the transmission of the virus [8,21]. Ventilation includes natural ventilation, mechanical ventilation (stand alone or as part of HVAC system), and filtration and purification systems. Natural ventilation is the flow of natural air through building openings such as windows and doors and the air is forced either by natural or artificially generated pressure differentials based on the layout design and positioning of the supply and exhaust vents [1,8,30,31]. Creating a pressure difference is carried out through the supply ventilation system (SVS) through fans that draw natural air from outside to inside the building, while the internal air leaks from the building through the openings in the building envelope. Or through the exhaust ventilation system (EVS), which is the intake of indoor air through exhaust fans (which are installed on the side of the building facing the air), which leads to a decrease in air pressure causing fresh air from the outside to flow through the air inlets, facilitating the removal of heat, odors, diluting pollutants and improving the indoor environment [1,8,25,30], or through an energy recovery ventilation system (ERVS) by introducing and exhausting approximately equal amounts of outdoor and indoor air [32].

Air flow patterns in indoor spaces can increase or reduce the risk of infection spread and transmission, both natural and artificial air flow [30]. To enhance natural ventilation, buildings are designed, for example, to encourage cross-ventilation by utilizing operable windows and shallow floors to encourage air circulation. With the adoption of air-conditioning systems that meet the indoor climate requirements, fixed windows have become a feature of most buildings, except for residential buildings. COVID-19 has now revealed, as has previously been revealed by Sick Building Syndrome, that HVAC systems encourage transmission of infectious diseases by enhancing transmission through virus-laden airflow [6,28,33]. In one air-conditioned restaurant in China, three families were infected with COVID-19, the infection having been driven by airflow generated by the air conditioning [27,31]. Hence, most HVAC systems are not equipped to limit COVID- 19 transmission. These systems can be improved by using more efficient filtration techniques (such as the HEPA filters integrated in HVAC systems, which remove 99.97% of contamination particles with a size of 0.3 μm-diameter while the size of a coronavirus particle is 0.1 microns) and purification techniques [30,31,34,35].

Air purification systems cleanse the air of pathogens, either by air ionization integrated into the HVAC system [33] or standalone bipolar ionization systems, that are characterized by their low cost [35], by using non-thermal plasma technology such as airPHX, which reduces viruses, bacteria, and mold in the air and on surfaces by up to 99%[36], or by using germicidal ultraviolet (GUV) that can inactivate more than 90% of SARS-CoV-2 in indoor environments. But due to the harmful effects of UV rays on humans, it can be used when the rooms are not occupied. Otherwise, it is recommended to use UVGI (Upper-room Ultraviolet Germicidal Irradiation) technology which spreads radiation above the level of the occupants' heads to avoid direct contact [21,28,33,35,37]. Also of note is one of the safe air purification strategies for humans developed by scientists at Columbia University's Irving Medical Center. This new upgraded version of the air purifier using UV light (wavelength 245 nm) kills 99.9% of airborne COVID-19 particles [31].

Indoor air quality has attracted more attention since the outbreak of the COVID-19 pandemic. Indoor residential environmental quality (IREQ), with natural ventilation being one of its factors, is a strategic point for the development of a sustainable residential building. In apartment buildings, natural ventilation is preferred over mechanical ventilation and, according to ASHRAE recommendations [34], it is preferable not to use HVAC systems during infectious disease outbreaks. For multi-story apartment buildings, it is recommended to limit the ingress of air from neighboring apartments to reduce the possibility of cross-contamination. It is also recommended to seal the gaps around windows and doors to prevent the infiltration of air carrying viruses from other housing units. Air extractors (exhaust fans) can be used in bathrooms, kitchens and closets [12,27,34,37–39]. Despite the assurances that natural ventilation in residential buildings is preferable to mechanical ventilation, one study conducted on the sustainable design of courtyards and airborne diseases found that architectural design can improve air quality in the courtyard, but it cannot be based only on passive design; thus the adoption of mechanical ventilation measures and air purification systems are important requirements to reduce the transmission of infectious viral droplets and remove the resulting pollutants [40]. If HVAC systems are used in residential buildings to control indoor temperature and humidity for thermal comfort, it is important to upgrade the home-use forced-air system filters to high-efficiency filters and clean them under professional advice in order to ensure optimal air flow rates [17,34] and ensure mitigation of airborne transmission of SARS-CoV-2. It is also important that HVAC systems be evaluated by professionals to determine the necessary modifications, if any. Air flow rates should be controlled, as increasing air flow rates or air recirculation without introducing more fresh air can cause SARS-CoV-2 droplets to resuspend [17]. In addition, smart systems are also useful in automatically detecting and adjusting indoor air quality [12,36,41,42]. If HVAC systems that are not integrated with a filtration system are already exist, they can be combined with air purification systems to ensure the mitigation of pollutants [38,39]. Homes can also be equipped with lamps that use ultraviolet rays to kill viruses, harmful organisms and bacteria [39]. In naturally ventilated homes, and in cases where air filtration systems are a high-tech and expensive option, the simplest solution is to have an abundance of houseplants [43]. Plants can catabolize and absorb toxic chemical substances and purify the air, provided that the environment meets its needs in terms of lighting, climatic conditions, and appropriate growing media [35,41].

2.1.2. Access to Sunlight or Daylight

According to Azuma et al., 2020 [6], the exposure to sunlight quickly inactivates the coronavirus on surfaces. This indicates that the degree and intensity (illuminated-dark places) and the type of illumination (direct sunlight-daylight) determines the exposure risk. The half-life of the virus was found to be about 86 min in the dark, and in the summer sun [6,37] the infection concentration for COVID-19 decreased by 90% after six minutes, and in the winter and autumn sun, the infection concentration decreased by 90% in 19 min, which indicates the importance of the sunlight exposure intensity and duration factor as a mitigation strategy to reduce the possibility of aerosol transmission [6]. This brings us to the original strategies of sustainability related to building direction and orientation. Sustainability strategies include making the most of sunlight and daylight through proper orientation and selection of appropriate opening types that maximize the penetration of sunlight and daylight into the depths of the rooms, while also adopting light colors for interior surfaces in order to ensure maximum reflection. As people are spending more time at home during lockdown periods than at any other time, it is worth noting the importance of adopting a performance-based design approach in building codes to achieve daylight quality goals [37] by specifically developing standardized daylight levels for residential buildings with the residents' preferred lighting levels being taken into account. It should be noted that more research should be carried out on adjusted daylighting levels as they have become a key criterion in residents' satisfaction [11]. According to the results of their empirical questionnaire, Zarrabi et al., 2020, have put preventive measures into the architectural design in order to combat epidemic diseases, to support mental health, and to reduce stress. These measures include the use of large windows at rates higher than those specified in the regulations, reconsidering the light wells to treat problems related today light penetration, considering noise transmission and ventilation, rethinking of building orientation and provision of balconies to receive maximum natural light and natural ventilation and landscaping [4]. In addition to the aforementioned points, skylights, patios, and roof terraces are recommended [8]. However, the implications for the glass ratio of the building envelope, facade design, and climate considerations must be taken into account in order to ensure year-round thermal comfort [11]. Regarding relative humidity, most studies agree that the risk of transmission is greater in environments with low relative humidity [29]. Pinheiro et al., 2020 [44] and Navaratnam et al., 2022 [35] recommend maintaining relative humidity in the range of 40–60% to reduce the virus survival time associated with aerosolized particles.

2.1.3. Green Spaces and Natural Views

Measures taken by governments around the world to contain and reduce the transmission and spread of COVID-19 have had unintended adverse effects [42]. Long-term isolation by quarantine has negatively affected people's mental, physical and psychological health and well-being [12,41,45,46]. The negative effects of long-term social isolation associated with lockdown affecting the mental health of the population include post-traumatic stress, fear of financial loss due to lockdown, anxiety, confusion, depression, panic disorder, anger, mood swings, boredom, irritability, frustration, dullness, recurrent thoughts and dreams, poor concentration, and disturbed sleep [47,48]. Studies have shown that exposure to green spaces and providing a level of natural environment inside the home reduces the psychological impact of lockdown periods and improves the physical and mental health of residents, positively affects their energy levels and their well-being, and also aids in recovery from COVID-19 [11,12,41,45,46,49]. Moreover, evidence has shown that exposure to home gardens is not associated with complaints of physical and mental symptoms reported during lockdown, whereas it is associated with more positive feelings indicating the role of the home in promoting mental and psychological health [45,50,51].

Therefore, due to movement restrictions during lockdown and protection considerations, as well as the difficulties of going out for a picnic, and lacking adequate open green spaces for outdoor recreation and exercise in some cities [38,45], providing a certain degree of natural environment within home contexts is mandatory rather than optional [38,43,50,52], especially in economic housing buildings that accommodate large number of populations [38,43]. The different levels of providing home green space start from indoor pots, window gardens, balcony gardens, roof gardens (green roofs), private gardens, and neighborhood gardens respectively from small to large scale. Some design insights of indoor and outdoor domestic green gardens levels and the related functions and activities are shown in Figure 3. Vertical green spaces such as vegetable walls, living walls, and vertical gardens are recommended in limited-sized domestic spaces. In this case, it is recommended to provide solutions to reduce the cost of implementing vertical gardens to suit all housing levels.

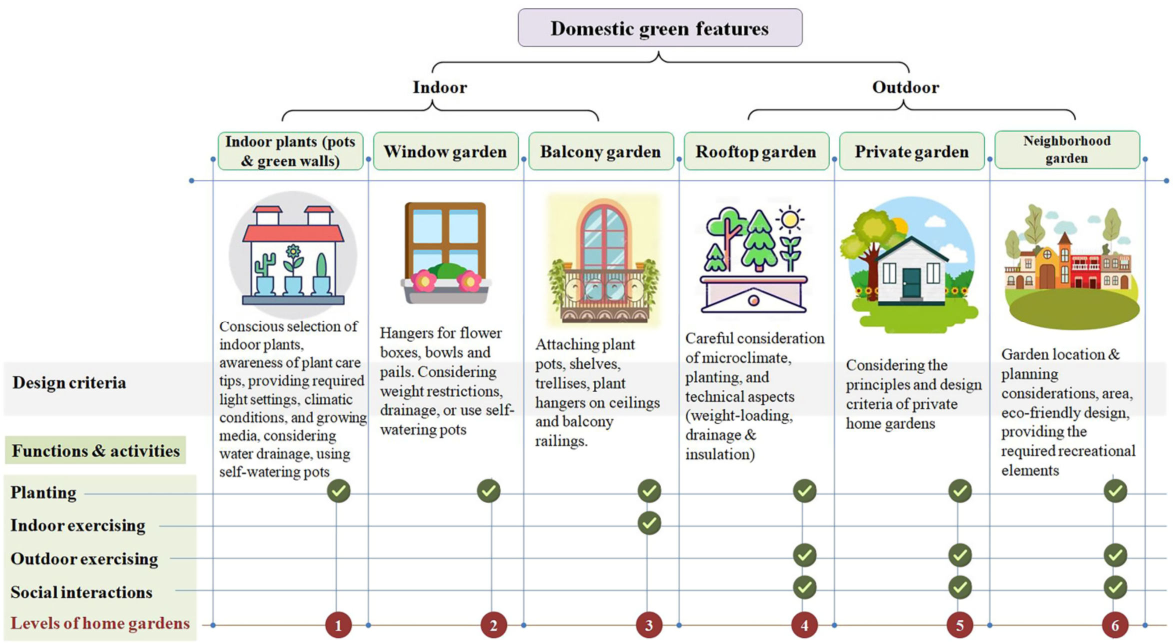

Figure 3. Domestic green aspects levels.

The balcony is one of the simplest ways to provide exposure to nature and green spaces [4,11,12,41,43,47,53]. Post-pandemic, the balcony is no longer just a place for clotheslines, storage, and accommodating air conditioning units and satellite dishes, it has become the most important space in the home as a result of the lockdown and the champion of design in the fight against the COVID-19 pandemic. This space has become the only space of freedom in the house in addition to being a source of sunlight and fresh air in the midst of the epidemic [46,51,54]. However, despite the role of balconies in achieving visual and thermal comfort in the indoor environment and reducing energy consumption, the climatic impact must be taken into account to reach the ideal balcony design [11,55,56].

Home gardening, which is provided by all levels of home gardens, improves residents' mental health as a result of the physical interaction of the inhabitants with live plants. Moreover, other expected benefits include healthy eating from personal home farming, acquiring agricultural knowledge gained from growing plants from seeds and creating food rations [39]. In addition, the process of monitoring plant growth per se leads to increased physical, social and psychological well-being [12,37], which results in enhanced social and economic sustainability as well. Based on the preceding, it will be necessary to determine the per capita share of private open green space according to the socio-cultural level in order to promote the mental health of the population [4].

If the purpose is to create a close visual connection between the living spaces and the outside world, this can be achieved with the balcony or through creating folding glass doors and wide windows [11,38], provided climatic conditions are taken into account so as to reach an environmentally friendly design. In the same context, the lowest degree of exposure to nature is to see the sky. Urban residential buildings in particular may face a challenge in obtaining direct views of the sky and landscape. Therefore, it is necessary to review building codes and urban densities in terms of building heights and street widths in order to obtain a clear view of the sky without obstructions [11]. Nature can also be brought into the home environment by building animal habitats such as nest boxes, fish tanks, fountains and water walls in terraces, in addition to creating ponds and aquariums in roof gardens and all of the above in private gardens and in neighborhood gardens [53].

2.1.4. Acoustics

Exposure to noise pollution can have serious long-term health effects [55]. Whether while sleeping, doing household activities, or working from home in the new home office style, especially during quarantine periods, noise pollution needs to be addressed [57]. Noise control starts from urban design and buildings' configurations. Urban noise control includes the geometric shapes of the residential clusters to control the sound waves' reflections and avoid the formation of flutter echo and sound foci, in addition to considering the distance from noise sources [57]. Also, one-story houses are better than multi-story houses in terms of reducing noise effects. Courtyard houses also provide acoustic privacy since the courtyard's design provides a shielding effect [58]. Noise control also includes the architectural design of the home. For example, rooms are arranged so that the most sensitive rooms are kept away from external noise sources, such as bedrooms, living rooms, and work and study areas. Reducing apertures is also one way to reduce noise, but since windows are the source of natural ventilation, daylight and natural views, some solutions must be adopted to suit this [57]. This includes the use of active noise cancellation (ANC) [56], the insertion of acoustic louvers [59], or thicker, densely woven, heavy curtains. It is also possible to use soundproof windows, considering their high cost [57]. Balconies are a cause of inconvenience if they are facing highways, but according to their importance as a source of access to the external environment, their arrangement must be addressed in order to obtain the desired advantages. Therefore, some measures can be taken, such as placing balconies in protected areas and using fences and solid walls to reflect noise to the outside [46].

2.2. Space

The space factors include: (1) housing type, (2) apartment size, (3) layout type, (4) advanced home technology (home automation, smart kitchen, finishing materials and touchless technologies), and (5) shared spaces (lobbies, stairs, elevators, laundry rooms, etc.). This factor will be highlighted in detail in the following section.

2.2.1. Housing Types: Houses, Not Apartments

As a result of urban expansion and the high density of urban housing, the vertical expansion of apartments has increased. The COVID-19 pandemic has shown that high-rise apartment buildings that are specifically designed to accommodate large numbers of residents face the challenge of reducing contact with shared surfaces in addition to the urgent need for fresh air and contact with nature, the latter being difficult to achieve in such places [11,43,55]. However, to compensate for the separation from the ground level and to create a relationship with nature for these types of buildings, balconies are required as private outdoor spaces. Green roofs also provide places for outdoor activities, connection to nature, agriculture and social interaction. The type of house, whether it is private or multi-story, and its height, whether it is short, medium, or tall, have a psychological effect on the population; the farther a person is from ground level, the more negative the physiological effect, especially for children. Therefore, from an epidemic perspective, low-rise and mid-rise dwellings of up to five stories are ideal from this perspective [20].

Perhaps the recent pandemic is exacerbating this trend, as migration away from crowded cities towards remote suburbs, small villages, and deserts has become an urgent development that requires the attention of planners, decision makers, and governments. Making a step back when it comes to urbanization encourages a change in the form and type of housing [11,43,55]. It has already been observed in recent years that horizontal expansion has increased by moving people into detached houses with fewer floors inside closed apartment complexes in the newly developed urban fringes [20]. Gated communities (or apartment complexes) are one of the new emerging housing trends that characterize modern and new cities. Their residents have demonstrated contentment and a sense of security during the pandemic. This is attributed to the controlled visitor access and strict adherence to preventive measures such as social distancing, sterilization, masks, etc., in addition to the lack of density and crowding. However, complaints of social isolation were noted in Asfour' study [60]. Accordingly, some strategies have been suggested to address this by improving communication with the external environment. In the same study, Asfour, 2022, [60] indicated that nearly half of the residents of non-gated communities who were surveyed would prefer to live in gated communities if they had the opportunity to do so. Gated communities may provide more safety during epidemics through access control, home design, and urban design.

2.2.2. Apartment Size

During the first half of 2020, the globally imposed lockdown policies have resulted in all family members gathering at home for longer periods than usual. Many families have found their homes too crowded and themselves unable to even reorganize their home spaces in order to accommodate the stressful juxtaposition of roles at the same time [4,41,61]. Although the purpose of the lockdown policy is to mitigate the spread of the virus abroad, these measures have had negative consequences for residential areas with poor housing conditions and with high levels of overcrowding and areas with multi-generational families where those areas have been associated with the highest COVID-19 infection case rates, especially among the elderly [20,42,61–67]. Some studies have shown a close relationship between home overcrowding and the transmission of infectious diseases such as COVID [68,69], as well as the emergence of mental illnesses associated with overcrowding, such as anxiety, distress, depression, unhappiness, social isolation, and reduced mental comprehension in children[37]. It can therefore be claimed that the benefit of general lockdown measures has been offset by amplifying transmission of COVID-19 as well as the mental damage to the residents in overcrowded housing and in housing with multigenerational families [4,41,70]. This necessitates reviewing the assumption of the home as a haven, as well as changing perceptions about the home size in light of the pandemic.

According to the World Health Organization, a home must provide sufficient privacy for its occupants and be of sufficient size for all persons to carry out the basic activities of daily life in a manner that meets the requirements of comfort and safety without special preventive measures. Since an adequate home size has a direct positive impact on physical health, mental well-being, productivity at work, and school performance, the failure to provide such spaces may represent a real source of risk, especially under lockdown conditions during epidemics and pandemics. The large size of a room facilitates the flexibility and adaptability of the home, as it makes the room divisible between several uses and accommodates the activities of multiple family members at the same time. This helps the family members adapt to living through a quarantine and also allows the house to grow as the family grows. In addition, the quarantine demonstrated the need for an additional space for a quarantine room and an attached bathroom for infected persons [12,41,56].

The balcony or the terrace, as previously discussed, is the simplest form of private outdoor space that can be provided to multi-story apartment buildings. The issue of providing such spaces is closely related to the size of the housing unit, and it is very important that such spaces do not come at the expense of interior space size. In apartments with limited sizes, residents resort to moving things to the balcony in order to obtain an additional space. Moreover, a balcony with a small area does not allow the addition of furniture or plants. For a balcony to be functionally efficient, it should be of sufficient size to accommodate daily activities including eating, exercise, gardening, and the required furniture. In light of this, building developers should not argue with providing usable apartment size along with providing a reasonably sized balcony [12,55,56] (no less than 5 square meters) [4].

Additionally, providing a space to work from home is one of the emerging trends required in pandemic-resilient homes. The COVID-19 pandemic caused millions of office workers to quickly move to working from home during the first half of 2020 in what has been called the "world's largest work-from-home experience" [71]. Many employees were forced to adapt some of their existing home spaces into temporary home offices during the quarantine period and beyond, such as converting their dining room tables into temporary home offices. But these new desks do not provide the comfort necessary for productivity [38,39], as their heights are unsuitable for clerical work and they are located in the midst of family noise, making them a poor substitute to an office[43]. Despite the end of the quarantine period and a return to normal life, there are many expectations for working from home to be the "new normal" after the COVID-19 pandemic [71]. So, it became necessary to change the spatial organization or allocate a dedicated place inside the home to do work [12,47,57]. Thus, there is a need to develop conceptual methods that allocate spaces inside homes as home offices or to attach them to private outdoor spaces to give residents a feeling of actually leaving their homes [38,39]. Allocating spaces inside homes (particularly existing homes) to create focused, health-enhancing home workplaces has several requirements. This includes a suitable work surface with dimensions of approximately 160 × 80 cm and an adjustable height [12,72]. For limited spaces, foldable and expandable wall-mounted desks can be installed [12]. Seats in the home office should be adjustable with regard to the distance from the screen (within 50–70 cm) and the positions of accessories such as the keyboard, mouse, camera, and headphone. Moreover, natural lighting [12,72] should be adjustable (500 lux for employees under 60 years old, 1000 lux for employees over 60 years old) and prevent unpleasant reflections and glare. The home office should have adequate temperature (around20 °C), humidity levels and ventilation [72] in a noise-free, soundproofed environment (max 45–55 dB) [12,47,73]. Additionally, for limited spaces, working from a tech-enabled kitchen may be suitable for home workplaces [70].

One of the spaces that require reorganization is the home entry area. The entrance of a pandemic-resilient home is no longer just an entry axis; it now acts as a defined sanitized entry area allowing for good indoor hygiene and functions as a decontamination chamber or a drop zone. In this case, the home entrance will be a clearly defined transitional space designed with adequate area to separate the polluted exterior from the clean interior. This transitional space includes space for the removal of shoes, hanging jackets and a small shelf for hand sanitizers to keep the home clean and safe (see Figure 4). This transitional zone also includes a bathroom close to the home entrance. It is possible to replace the bathroom with a large basin if the area is limited. This transitional zone and its annexes may already have been applied in most of our homes, but now it should be mandatory for all housing levels. This area can be applied outside or inside the boundaries of the house, or it can be divided into two parts, pre-entry and post-entry zones, if space permits. In this case, the outdoor area, the pre-hallway lobby, is dedicated to taking off shoes outside to keep the house clean and safe. The threshold of the hallway should also be expanded to accommodate a handling area with a delivery hatch for handling and delivering goods and services such as groceries and medicines through the door due to the greater reliance on online shopping during quarantines [4,40,43,47,57,58].

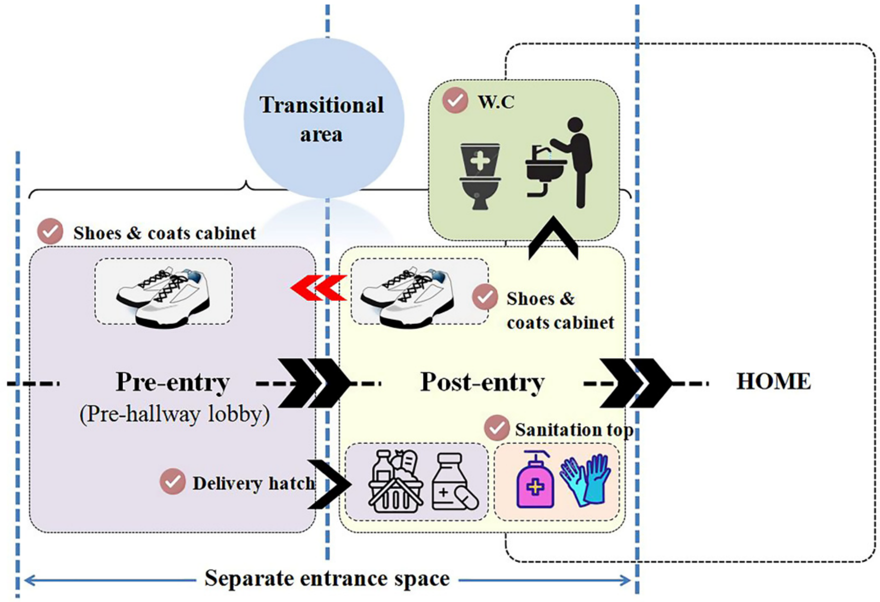

Figure 4. The home defined sanitized entry area.

2.2.3. Layout Type: Spatial Organization; Adaptable Layouts; Modular System

During the COVID-19 quarantine, people have found themselves forced to manage all aspects of their lives, including rest, leisure, work and food, in their homes. During the global COVID-19 crisis, the home has had to function as an office, school, gymnasium and restaurant. Many people resorted to adapting their existing spaces, but most of them found that the division of the current home spaces does not accommodate all of these activities [40,47,74]. The design of pandemic-resilient homes must adapt to and accommodate these new functions; this requires a realistic, flexible, and appropriate modification of home floor plans for all types of housing beyond considerations such as price, size, or type of tenure [43].

Adapting a home to new functions does not mean moving or removing walls as much as meeting the social aspect of architecture by achieving comfort and privacy for the residents. The social aspect could be achieved either through floor plans with fixed walls and an adjustment of the distribution of areas so as to achieve privacy and comfort, as suggested by ElZein et al., 2022 [46], by dividing the home into three zones: guest zone, family zone, and private zone. The guest zone is attached to the home entrance to include a lobby, guest bathroom, kitchen, reception, and dining room. The family zone includes a living room with a balcony, study or office room, and a bathroom shared with the private zone which includes bedrooms [46]. This fixed-wall floor configuration is only suitable for large sized homes. Alternatively, privacy, resilience, and comfort could be achieved through an open layout to facilitate the movement between different functions [12]. In Japan, for instance, home plans and room design without furniture are made to be multifunctional, allowing for quick transitions from one function to another aided by spacious storage areas in each room. In the West, they prefer open plans to achieve flexibility even though this layout does not provide privacy, especially with large families [43]. Despite the advantages of open floor plans they also necessitate adaptive furnishing, and a re-imagining in relation to the issue of privacy [16]. Another disadvantage of open-plan layout is the transmission of noise, since there are no obstacles in front of sound waves. To address this, carpets can be used in large areas, and thicker curtains can be used. Moreover, traditional walls should not be left completely bare.

Noise can be mitigated using wall decorations, plasterboard claddings and shelves. Also, growing green houseplants is an excellent noise absorber [57] (return to the acoustic factor for pandemic-resilient homes, Section 2.1.4).

Therefore, the design of pandemic-resilient home includes an adjustable open plan with a set of movable walls so as to create different spaces in order to accommodate a greater number of services and functions and to allow privacy. This plan will contain a home workplace, bedrooms, an entertainment area, and an exercise room to make it easier to spend more time at home. This concept, named AD-APT, was introduced by the architectural firm Woods Bagot as a modular system that can be adapted to suit different lifestyles. Also, the floor-plan includes fixed spaces including a balcony, a bathroom, an entrance hall, and a storage space. The modular system proposed by Bagot allows spaces to be rearranged throughout the day to meet residents' different requirements during work, learning, or entertainment. This system offers three different arrangements—daytime mode, nighttime mode, and play mode—each designed for specific times of the day (see Figure 5). The first is configured to provide ample living and dining space, a workspace, and a separate kitchen. In the next mode, the living room is compressed to create two bedrooms. In the third mode, the apartment is converted into a large open space for entertainment and playing sports. The modular design includes furniture that folds into the walls to save space and facilitate movement. In addition, Bagot suggests that the large balcony uses an aeroponic system to provide food, which eliminates the need for external systems, and also includes a space for outdoor entertainment and exercise [12,40,74,75].

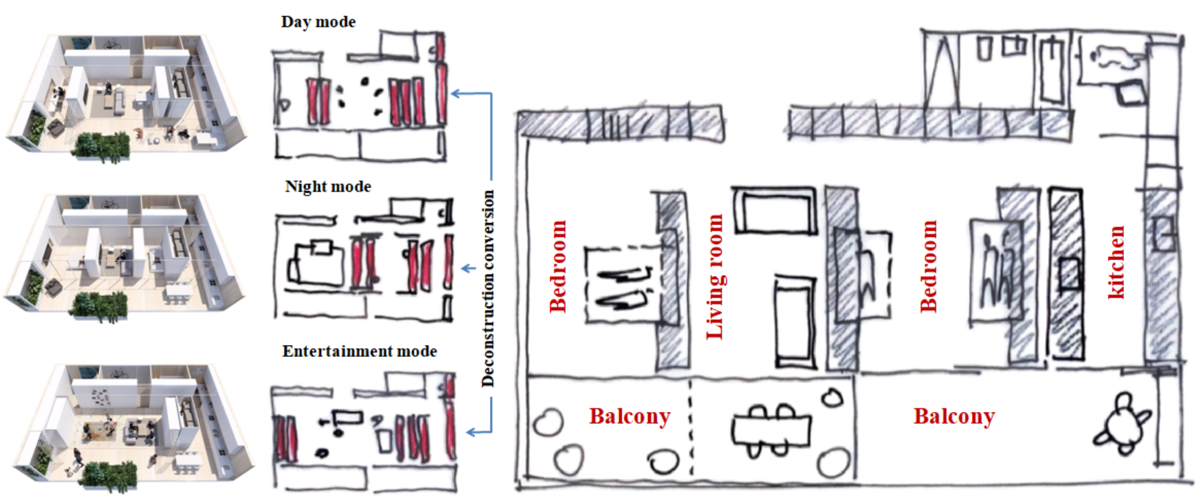

Figure 5. Split Shift Home proposed by Bagot to accommodate all daily lifestyles (© Woods Bagot). Arrows refer to that the proposed floor plan could be split into three modes.

2.2.4. Home Advanced Technology

- Home Automation and Smart Homes

Homes during quarantine have been tested for adaptability and resilience. Practicing all areas of life from home—whether work, study, physical activity or entertainment—means that the Internet, Wi-Fi networks, and automation play a pivotal role in designing smart home and supporting the requirements of living comfort. This change in lifestyle means flourishing information and communication technology (ICT), Internet of Things (IoT), and artificial intelligence (AI) which are used in communications to facilitate learning and work from home as well as home information management, energy management and healthcare fields, where it is expected to continue as long-term policies, even after the end of the epidemic. Examples of IoT devices and smart developments include smart, remote control of lighting, curtains, temperature and humidity (heating, ventilation, and air conditioning devices) through mobile devices such as smartphones, automatic control of closing and opening doors, windows and shutters.

These innovative systems include advanced computer systems equipped with sensors such as temperature detectors, motion sensors and power sensors that have shown strong sales growth in Australia in 2020 [12,41,76,77]. In the field of communications, to help people reassure their distant family members who cannot visit them due to the restrictions of COVID-19, Amazon has introduced one of the smart developments, the Alexa Care Hub, which uses echo devices to share files between separated family members for this purpose. In the field of health care, there are some applications through smartphones that guide occupants about their current health. There are some other voice-operated applications that will detect the symptoms of COVID-19 through voice signals for individuals. IoT systems are also used to analyze the health profiles of smart home residents by detecting fever, coughs and sneezes in order to determine the home residents' health status [78].

Although smart home technologies have been addressed in much of the literature over the past two decades, it is recommended to expand the study of smart home technologies related and their related social issues, especially considering the current boom in home companies' revenues [78,79]. In addition, despite the necessity for Internet and Wi-Fi, with the development of information technology systems, there are concerns about the propagation of electromagnetic waves resulting from 5G technology in particular in communication between wireless devices, and the associated health effects. Therefore, it is recommended that the scientific evidence regarding the potential health risks of exposure to 5G technology be reviewed as more data becomes available regarding its public health impact [37].

- Smart Kitchen Design

During quarantine, the family once again gathered together at the dining table, kitchens have replaced restaurants and the time people spend cooking and eating at home has increased, turning the kitchen into a functional gathering space. The increased importance of providing storage space in the kitchen has been noted due to the increased time people spent in their homes, along with the restrictions that prevented people from going to stores during the lockdown. As a consequence of the importance of the kitchen as a functional gathering area, the importance of natural lighting has emerged as one of the design elements related to a healthy kitchen due to the fact that individuals stay longer periods in the kitchen, whether for eating or working [11,16]. Moreover, the advent of hands-free thinking implies the use of contactless technologies such as voice activation technology and remote control of lights, appliances and faucets, making smart kitchen design even more important [38].

- Fomite Transmission and Touchless Household Technologies

Another method of indirect infection with COVID-19 is touching surfaces—such as tables, handrails, and door handles—that are contaminated with the virus when infected people touch, sneeze or cough on them and touching mouths, noses or eyes afterwards with contaminated hands [6,17,22–28]. On one cruise ship, traces of the virus were found in COVID-19-infected passengers' rooms for up to 17 days after evacuating the cabins [6,17], with the virus detected on the bed pillow, the phone, the TV remote, the seat arms, the floor around the toilet, the toilet seat, and the flush button [6]. The duration of survival of the coronavirus on surfaces varies depending on the type of surface [35], the amount of biological fluid, the initial concentration of the virus, air temperature, and relative humidity [4,41,80]. The coronavirus settles for a longer time period on surfaces at lower temperatures, in conditions of low and high relative humidity (the period is shorter at moderate humidity levels of 40–60%), and in dark places [81]. COVID-19 can last for several days on certain materials such as plastics (PVC, Teflon, PTFE), ceramics, silicone rubber, glass, and stainless steel [6,82].

The virus remains longer on stainless steel and plastic than on copper and cardboard (see Figure 6). Porous surfaces such as cardboard cause the virus to stick and dry up. Copper and copper alloys such as copper-nickel, brasses, bronze, and copper-nickel-zinc alloys can kill the virus by disrupting its vital functions within about 4 h [35]. Copper also outperforms silver in its ability to kill bacteria, as it does not need moisture. Therefore, it is recommended to use copper as a building material and as a material for making high-touch surfaces (such as doors and windows handles, light switches, and elevator buttons) for post-COVID-19 buildings. However, due to its high price and difficulty in maintaining, it is possible to mix copper with other materials such as silver and plastic to produce a material that prevents the reproduction of viruses [35].Alternatively, the cold-spray technique can be used to quickly paint copper on steel surfaces instead of replacing the steel with a new copper surface. According to the study conducted by Hutasoit et al., 2020 [73], the lifespan of the virus was reduced to less than five hours on copper-coated samples. Other germ-resistant strategies such as antimicrobial polymer surfaces [6], and some types of coatings such as carbon-based, titanium-based, and gold nano-coatings could also be used [35,83]. The above indicates the importance of environmental factors such as exposure to sunlight, temperature, humidity levels, and material type for reducing the virus's survival.

Some examples of innovative finishing materials that are currently being offered on the market and function as antimicrobial materials areLapitec®, KRIONTM, and Richlite [12]. Lapitec® is a mixture of ceramics, porcelain, quartz, and granite that offers interior solutions for floors, bathrooms, and kitchens [12,74]. KRIONTM is a natural stone-like material consisting of aluminum trihydrate and a small portion of high-resistance resins [75]. Richlite is an alternative material to stone and metal for its durability and is used to construct worktops, furniture, wall panels, and building facades [12]. Despite the increasing prevalence of antimicrobial additives in building materials to prevent the spread of COVID-19 on surfaces, it is worth noting that there are trends against these additives on the grounds that they do not guarantee the preservation of health and the environment [12,76]; in addition, there is no evidence of their resistance to viral loads[37].

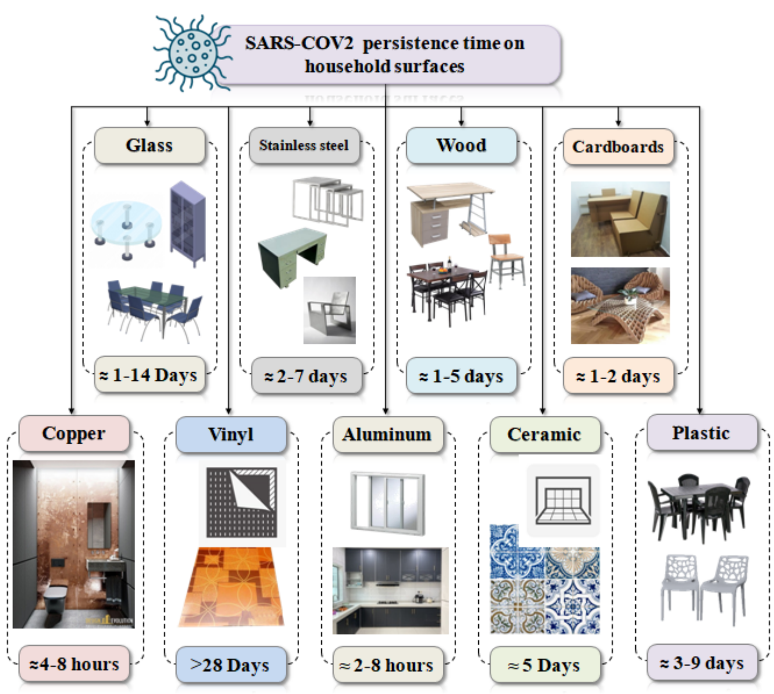

Figure 6. Persistence of COVID-19 on various home surfaces (it varies with viral titer and temperature). Source: Drawn by author after [6,17,21,77,80,84–87].

The Healthy Building Network has stated that antimicrobials are used as additives in building materials to protect them from damage or mold, but they do not reduce infection. Moreover, the widespread use of these substances may increase the microbial resistance to these agents. Some of these substances, such as quaternary ammonium compounds, have negative effects on human health and lead to cancer and endocrine disruption [88]. Even antimicrobial mattresses and fabrics are warned about sincethey can promote human pathogens [89]. There is also evidence of the possibility of such materials moving into the natural environment, finding their way into the sewage system. The false sense of security that our use of these substances creates can also cause a laxity in hygienic practices such as hand washing, cleaning, and sanitizing of surfaces [88]. Daniela et al., 2020 [37] stated that the absence of antibacterial materials can be easily compensated for by careful, regular, and continuous cleaning and disinfection of surfaces, especially surfaces that are frequently touched such as doors and door handles, window shutters, tables and desks, chairs, keyboards, light switches, faucets, toilets, and cell phones. Other non-washable surfaces such as carpets, mattresses, and upholstery must be sterilized using steam. In all cases, indoor environments must be naturally ventilated during and after cleaning in order to ensure healthy environments. However, more scientific research is needed in this regard.

Another trend in managing fomite transmission is the use of contactless technology to deal with surfaces frequently touched by the public during daily life, such as elevators, doors, and faucets. Elevators, blinds, and lighting can be controlled by a smartphone. Doors can be opened automatically using facial recognition systems and motion sensors [12,90]. Self-cleaning mechanisms for domestic and public toilets can be an effective disinfection method. In general, voice control, keycard swiping, and facial recognition technologies will be effective when dealing with contaminated surfaces [12].

2.2.5. Shared Places: Stairs, Elevators, Corridors and Lobbies

As an opportunity to encourage physical activity, attention should be paid to designing stairs in multi-story apartment buildings as an alternative to elevators, as they are considered an ideal and healthy alternative. This can be achieved by improving natural lighting, adding music, and adding comfortable seating on each floor. With regard to elevators, restrictions must be placed on the number of elevator users at one time [54,91], and touch buttons should be abolished and replaced by contactless technology (hands-free elevator systems such as T2G) [36]. Air purification systems such as GUV or HEPA should be used in elevators as well as in lobbies and public spaces. Corridors between housing units should be widened to increase the area of circulation and to work as interior public areas wherever possible. Otherwise, corridors should be made unidirectional if possible, such as in corridors that contain elevator cores, to maintain safe distances between residents. If the lobby width is less than six feet, specifically in long corridors, pause points must be created to enable residents to pass one another and to act as rest points as well [54,91]. Residential shared facilities such as shared kitchens and dining rooms, laundry rooms, recreational areas (activity rooms and exercise rooms), pools and hot tubs, and shared bathrooms pose challenges with regard to social distancing. The necessary measures include restricting the number of people allowed, ensuring at least two meters between people, and especially the provision of PPE [11,92] (see Figure 7).

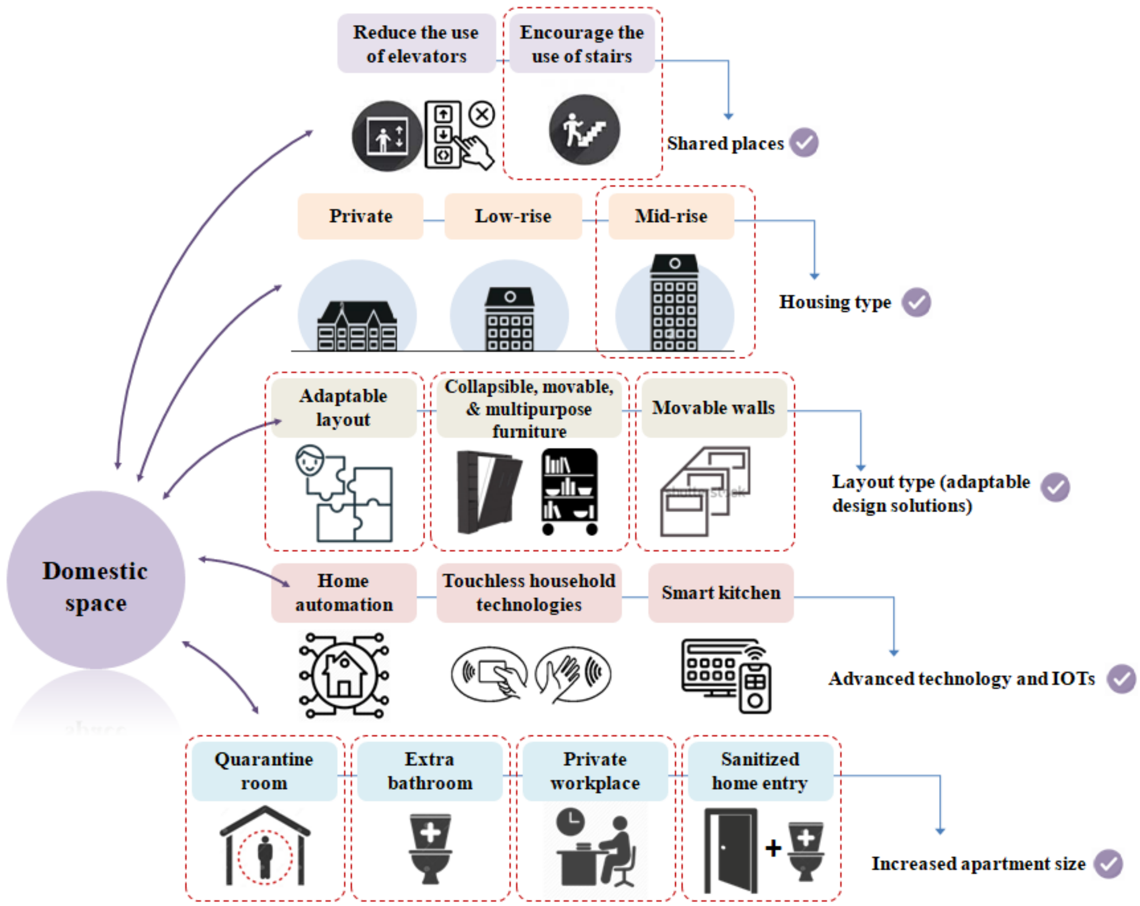

Figure 7. Household space factors of pandemic-resilient homes (red dotted rectangles refer to the minimum requirements).

2.3. Household Environmental Resources Management

The COVID-19 pandemic and the associated lockdown measures, particularly with the adoption of remote work and distance education, have had an impact not only on the built environment but also on infrastructure services including food, potable water, waste management, and energy [13,93]. The role of the home during the lockdown period has been transformed from merely a place of living to a seat of infrastructure and place of work, which has increased pressure on electricity and water resources. Hence, the house has become a source of hazardous waste via infected people living at home [93]. Thus, the epidemic had dangerous effects on the economy and society as a direct result of the lockdown as there was a challenging choice between closing for the sake of personal health or reopening for the benefit of the economy [13]. Therefore, in order to achieve sustainability, epidemic-resilient homes, both new and existing, should take into consideration how to control the consumption of natural resources and how to reduce the environmental impact of these facilities in compliance with sustainable development goals (see Figure 8). Therefore, issues related to energy, water, and waste in the post-pandemic reality should be addressed.

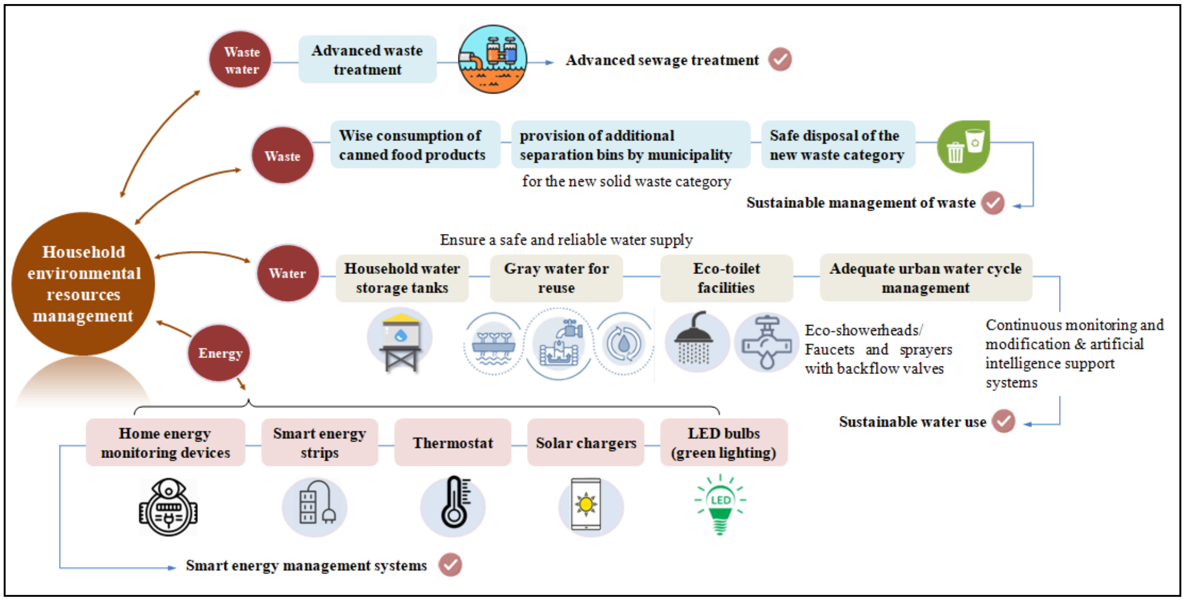

Figure 8. Domestic environmental resources management in pandemic-resilient homes.

2.3.1. Energy

During quarantine, household electricity consumption has increased in parallel with the increase in time spent at home [69,78]. This increase in consumption may be induced by the increased use of ICTs for work and distance learning, increased cooking, increased energy consumption from refrigerators due to frequent access, increased household energy consumption for entertainment (TV), and increased energy consumption from washing machines and frequent washing [12]. On the other hand, although the energy consumption of municipal buildings during the first closing period was reduced by about half according to a study conducted in Florianópolis, Brazil, half of the energy was consumed in unoccupied buildings. This entails reviewing building management, the efficiency of energy systems, and the installation of more energy-efficient systems, as well as raising awareness and changing behaviors in this regard. Whether in homes or public buildings, there is a need to make energy management policies more stringent [3]. In residential buildings, in addition to promoting the adoption of renewable energy sources [4], it is recommended to use smart methods to reduce energy consumption in homes such as solar chargers for electronic devices, LED bulbs for lighting, smart energy strips devices that cut off power automatically when the devices are not used, energy monitoring devices, and thermostats that automatically control the temperature [37]. Independence from the outside world has become an objective so as to reduce risks in the event of a complete lockdown. Therefore, providing the home with secure sources of heat, energy, and water will keep it safe from the threat of complete closure [39].

2.3.2. Wastewater

The COVID-19 pandemic has revealed the value of public health-related services such as sanitation [94], hence the presence of coronavirus genetic material in wastewater has been identified. Its concentration has been observed to increase with the increasing prevalence of COVID-19 infection and vice versa [95]. Improper disposal and treatment of wastewater from people infected with COVID-19 affects both water and soil and thus the environment and living organisms, where this waste can end up in the soil, in sources of drinking water and in oceans, causing deadly effects on living organisms of all kinds. The impact of waste resulting from COVID-19 may reach a serious gravity and exacerbate important environmental issues such as global warming [96]. In addition, this sewage system can transmit infectious particles and expose the population, especially sanitation workers, to infection [17,97]. In addition to the genetic material of the virus, wastewater is expected to contain concentrations of special pharmaceutical products used to treat people infected with COVID-19 which may leak into fresh water sources [94]. Fecal-oral transmission is yet another risk [27]. Moreover, among the problems related to the sewage system is the formation of large masses of solids resulting from new, unfavorable COVID-19-related practices. These practices include throwing toilet paper and face masks into toilets, which can clog sewage systems, release odors, damage pumps, and disrupt pumping stations [94]. Therefore, it is important to use advanced wastewater treatment in addition to spreading awareness of proper waste disposal behaviors as well as the importance of designing on-site wastewater treatment systems for homes with toilets not connected to central sewers [37].

The COVID-19 pandemic has demonstrated the importance of wastewater in tracking the COVID-19 virus, mapping its spread, and detecting infection mutations, in addition to bridging the gap between observed and actual cases. Therefore, it can be said that the virus has demonstrated the advantage of using wastewater as being a tool for collecting epidemiological data on common drug products consumed and excreted in wastewater systems and an important tool for monitoring human health [94,95].

2.3.3. Solid Waste

A new type of solid waste has emerged during the pandemic, namely medical waste contaminated with virus such as single-use masks, gloves, and goggles, leading to the advent of a new category of solid waste classification that requires the provision of dedicated bins to reduce the possibility of viral transmission [77,80]. After separation, these wastes should be sterilized in a manner similar to that used for medical waste; this explains the suspension of waste recycling and reuse practices during the pandemic in many countries. In addition to this new type of medical waste, the generation of organic and inorganic household waste has increased as a result of the increased use of canned foods [12,37]. In this regard, it is advisable to provide garbage collection areas protected from pests and rodents [37]. Ayer et al.,2021 [77] suggest in their study to use automation in waste separation to decrease human intervention and to use UV for sterilization.

2.3.4. Water

The consumption of fresh water in residential buildings increased during the quarantine due to the recommendations for frequent hand washing, doing laundry, and cleaning homes for the purpose of protecting against infection and spread of COVID-19. This increasing consumption of fresh water necessitates the provision of technologies to facilitate the sustainable consumption of water. One such technique is the use of eco-friendly showerheads for bathing. Also among those sustainable alternatives is the treatment of gray and black water, but it faces new challenges in terms of advanced purification and purification processes. Although COVID-19 has not been detected in drinking water, there is general agreement that traditional water treatment methods using proper filtration and disinfection can inactivate the virus. However, some views advocate the increased use of chlorine in drinking water during distribution as an additional precaution, even though these treatments pose additional costs. Although the virus has not been detected in drinking water, improper treatment of sewage contaminated with the virus may lead to the contamination of fresh water sources. To prevent the spread of the virus through sewage, it is recommended to use well-maintained plumbing infrastructure including sealed bathroom catchments and faucets with backflow valves. On-site wastewater treatment systems should also be designed for homes with toilets not connected to a central sewer. Along with sustainable consumption techniques, it is important to ensure a safe and reliable water supply with adequate urban water cycle management as well as continuous monitoring and modification along with artificial intelligence support systems [41,54,98].

3. Discussion

Although rigorous measures have been taken worldwide to prevent the spread of COVID-19 and its relevant advanced strains along with the development and delivering of various anti-COVID-19 vaccines, there are persistent concerns and warnings about the emergence of new viral infectious diseases in the future [94,99]. Given the epidemics that have broken out in many places in the world during the past 20 years (SARS in 2002, H1N1 in 2009, MERS in 2012, coronavirus in 2014, Ebola in 2014, Zika in 2016, and COVID-19 in 2019) [13], it is highly expected, with the development of science, technology, and global transportation, that new zoonotic infectious diseases will be inevitable in the future[100]. These projections are attributed to climate change, and the rapid urbanization that associated with the encroachment on wildlife habitats and the spread of wild animal products in some areas around the world leading to the transmission of diseases from animal species to humans [14,45]. In order for our buildings, more specifically homes, the quarantine residences, to cope with the prospective pandemics of tomorrow, their architectural engineering must be ready to resist the spread of infectious diseases via its physical elements and indoor air.

The COVID-19 pandemic has alerted us to many challenges, such as climate change, over-development, a lack of affordable housing, and inequality. Now, we must seize the opportunity to assess and re-imagine our built world. The COVID-19 crisis should be seen as an opportunity to revise housing standards so as to provide healthy living conditions for all individuals, including citizens of low socioeconomic status. Therefore, some housing-related issues which have become imperative in the aftermath of COVID-19 will be highlighted in the following paragraphs.

3.1. Socio-Economic Inequity

The pandemic has exposed a socio-economic gap in housing levels with a marked impact on the poor, the elderly, and immigrants. The low quality of urbanization, the lack of affordable housing for low- and middle- income people, and the risk of infection transmission in inadequate housing with little access to daylight, sunlight, and nature were the main dilemmas [98]. The COVID-19 crisis and the accompanying forced home-confinement have raised the issue of needing to improve living standards for low- and middle-income families and to reduce socio-economic gaps [46,101]. This calls for improving the residential environment and adapting it to new standards [98].

For the most part, housing levels are classified, according to income, into low-, middle-, and upper-income housing, which in turn is reflected in the classification of the housing unit by size and type of finishing [102]. Some studies [103] have shown that the level of income and the associated housing level have an impact on lifestyle during epidemics and pandemics.

The biggest housing challenges, which have emerged largely during the quarantine period, are in low- and middle-income areas. An important issue is the poor distribution of housing units, meaning that high-income people have a large housing surplus, while low- and middle-income people live in housing conditions that are not adapted to the new standards [102]. People with high incomes have greater opportunities to engage in physical activities due to the availability of physical and social spaces provided by their environments, which positively affects their health. Detached housing, less densely populated areas, and more green areas are what distinguishes high-income housing, which low-income people severely lack, presenting a major challenge in the face of epidemics and pandemics.

This strongly indicates the need to reach or define a minimum component of the housing indicators that affect the mental health of the population for the lower-income housing levels to ensure a reasonable level of mental health for low- and middle-income families [20]. In this context, some housing policies that can be adopted are the use of integrated, low-density, nature-related planning. Future studies should focus on such solutions that support sustainable architectural and urban design that ensure healthy living in the midst of a wide range of challenges, including epidemics and climate change, especially for low- and middle-income families. The need to develop housing policies and bridge the socio-economic gap raises the issue of balancing housing costs and at the same time achieving adequate housing environment, health, and welfare [20]. This calls for designing sustainable solutions at affordable prices, guaranteeing coexistence with the contemporary conditions the world is witnessing.

Goal 11 of the Sustainable Development Goals seeks to achieve social justice in the housing sector without discrimination, which means providing all segments of society with safe, sustainable, flexible, and decent housing equipped with safe and affordable basic services to ensure that it keeps pace with rapid urbanization. In Egypt, based on the recommendations of the Global Housing Strategy, and in light of the 2030 sustainable urban development goals, the Egyptian Housing Strategy was prepared to increase the supply of affordable housing. The efforts and integration of the various economic, environmental, and social sectors have combined to achieve the maximum benefit from spatial and material resources in order to ensure the maximum degree of social justice. Also, according to the Egyptian constitution, adequate, healthy, and safe housing is part of the state's plan to improve the quality of life for citizens, including low-income groups such as slum dwellers. Also, according to human rights, every citizen has the right to an adequate standard of living so as to maintain his and his family's health and well-being, including housing [102].

The COVID-19 crisis and its many repercussions, including the inability of the current homes to play their roles as safe and healthy places to be in during quarantines, point to the need to keep pace with contemporary new types of challenges posed by epidemics. Therefore, it is important to develop strategies taking into account changing conditions, to guide the housing sector effectively and flexibly. In addition, sensitizing local authorities to emerging requirements and defining roles is important for achieving sustainable development goals in the housing sector. The new approaches and policies in housing must be especially addressed to the most vulnerable and marginalized groups such as slum dwellers, the homeless, the poor, migrants, and refugees [101].

3.2. Housing Real Estate Market

The COVID-19 crisis has had a shocking impact on the housing real estate markets across the world due to the upheaval in the construction industry [104,105] and its impact on tenants, landlords and businesses. Most governments around the world have adopted some changes in their real estate policies to mitigate those negative effects as an attempt to reduce the burden on renters and owners in the housing sector. These attempts include tax exemptions for mortgage borrowers, temporary suspensions of evictions, introducing support for vulnerable families, increasing housing allowances, providing affordable housing through investment initiatives, improving disadvantaged areas, and easing restrictions on land use. Maintaining these relief measures for a long period may create barriers that restrict the movement of labor and population, discourage the expansion and maintenance of the housing stock in the long term, lead to unintended inefficiencies and difficulties in achieving recovery, and make the housing sector less responsive to the changing demand and the evolving needs of society. Encouraging remote work, even in the aftermath of COVID-19, would disengage the attachment between the residence place and the work place and thus encourage the move to remote, affordable, and less densely populated areas. This reduces or even reverses the differences between urban and rural areas and thus reduces the demand for high-density urban areas. These shifts may bridge the disparities between housing prices and thus reduce segregation. Therefore, it is recommended to move from the rescue stage of measures to the recovery phase in order to develop sustainable, efficient and inclusive housing markets. This comes from investing in new affordable housing, provided that certain environmental standards are complied with to ensure that the supply of housing is commensurate with the demand of local society, in addition to improving existing neighborhoods [104,106,107]. The key is to pay investments accompanied by environmental sustainability, taking into account the local and national situation and the needs and recent desires of the local population.

In this context, it is important to highlight three considerable points: tenure type and housing security, the emerging housing preferences, and housing prices.

3.2.1. Tenure Type and Housing Security

It is worth noting that tenure type and housing security are important issues as well. The fears associated with job losses as a result of lockdowns, in addition to the actual loss of jobs, which reduced the ability of some residents to pay their rent and mortgage loans, leads to housing insecurity. Studies have indicated that housing insecurity is also one of the factors affecting the mental health of the population, as its symptoms are linked to chronic mental disorders, depression, psychological distress, anxiety and suicide, which appear among the most deprived social groups. Greater housing stability or housing ownership is related to the better mental health of the residents, so the type of tenure is one of the factors that modify the relationship between health and housing insecurity. But this does not mean that the health symptoms associated with housing insecurity do not also show up for property owners who cannot pay their mortgage payments [108,109]. Therefore, people affected by housing insecurity must be taken into consideration when developing current and future housing policies.

3.2.2. Emerging Housing Preferences

Identifying the factors affecting housing prices and the demand of the local housing real estate market after COVID-19 is very useful in real estate policy-making processes in order to avoid the risks of creating housing that is no longer suitable according to emerging demand preferences, as this leads to the deterioration of urban investments and goes against the direction of the 2030 SDGs. The long period of living at home during the COVID-19 quarantine has revealed the factors that have affected the housing real estate market during and in the aftermath of COVID-19. These criteria, based on users' preferences monitored in several studies, include adequate daylight access and natural ventilation combined with thermal comfort for all household spaces, so there will be a focus on the location and size of windows, the surrounding environment and landscape, as well as the larger home size provided with new emerging spaces such as workspaces, balconies, outdoor living spaces, and private gardens. That is in addition to the preferences for acoustic comfort as a result of the changing dynamics of work and social life [55,108,110].

In a survey conducted by the American Institute of Architects (AIA) to indicate whether there is a change in the demand for home space comparing the year 2020 with the year 2021, it was found that there is an increase in demand for new construction housing, such as luxury homes, condos and holiday homes, in addition to an increase on the overall size of the home, while the demand for affordable housing is declining. In terms of space types, the demand has increased for home offices, rooms with sunlight and landscape views, and mixed indoor or outdoor spaces (open-air kitchens, glass walls, and glass walls that open up). While the demand for outdoor living spaces such as decks and patios, and outbuildings such as barns, sheds, and pool houses is appeared [110]. Some studies conducted in Italy in October 2020 determined users' preferences regarding rooms in their homes; the results indicated a private garden, parking, kitchen or living space, balcony, living room, and two or more bathrooms, arranged from the top, with percentages ranging from 58% to 45%. These preferences reveal the advent of previously secondary spaces such as the balcony and the private garden [104]. Although the results of these surveys are likely to be generalized, there may be regional differences according to the standard of living and other considerations, but in general the emergence of spaces that were previously secondary, if not irrelevant, is observed, and that what we considered a luxury in the past is now a basic requirement. However, future research should examine the preferences of local residents across different urban areas to determine how the COVID-19 pandemic has affected the real estate markets.

3.2.3. Housing Prices

Studies indicated that there is a correlation between the COVID-19 pandemic and the prices of housing real estate in light of the recent desires of users. In a study conducted in Italy, there was a significant decrease in the prices of existing residential properties that did not meet the new requirements expressed by buyers. The buyers preferred to invest their money in real estate that meets the new features, which increased the prices of real estate with new preferences. One study indicated that COVID-19 has caused house prices to fall by 2.47%, while in the long term the impact could become larger. It was found that the impact of the COVID-19 pandemic on housing prices is greater than the effect of SARS lesser than that of the plague and cholera. The same study indicated that the negative impact of COVID-19 on residential real estate prices appears only in areas with high infection rates and low levels of medical treatment [104].It can be concluded from this indicator that higher infection rates have been linked to lower housing conditions. In another study conducted to examine the effects of the lockdown on housing market prices in the United States, a decrease in the price of housing has been observed in highly populated locations while an increase was seen in less densely populated areas. Moreover, in densely populated areas, an increase was observed for homes with larger sizes and homes with an extra bedroom [111].

In sum, since the real estate industry plays an important role in the national economy, decision makers should set the real estate policies according to demand preferences discovered from the impact of the COVID-19 pandemic by defining intervention strategies for existing housing assets and developing new design and planning initiatives that are compatible with the current needs of the local communities. Therefore, it is useful to conduct surveys on the impact of COVID-19 on the real estate market in different urban areas around the world and interact with each region according to its living and economic conditions, with a focus on areas with higher rates of COVID-19 infection and worse medical treatment conditions.

3.3. Pandemic-Resilient Homes and Sustainable Assessment Tools

Sustainable assessment tools are one of the methods driving building design in a more sustainable direction. Looking at global assessment systems (BREEAM, GSAS, Estidama, and LEED), and on the basis that the residential building assessment tools include energy, water, site, indoor, and outdoor environments, and materials categories, it is found that the main priority is given to the energy category by the BREEAM, GSAS, and Estidama tools, while LEED places the environmental quality category first. Looking at the four tools, the environmental pillar receives the most attention, and the least attention goes to the social pillar. The set of problems resulting from COVID-19 pandemic are related to energy, waste, water, food supplies, and domestic violence, which the current capabilities of residential buildings have not been able to address [12]. In their subsequent study, Tleuken et al., 2021 [106] assessed the role of the pandemic resistance indicators in the sustainability rating tools (BREEAM, CASBEE, LEED, and WELL) to clarify the role of green building certification tools in ensuring better sustainability of residential buildings during and after epidemics in terms of the environmental and social aspects. They found that there is no single tool to address all indicators of pandemic resistance. Through their analysis, the authors found that WELL was the most responsive to the "health and safety" category but the least responsive to "environmental resource consumption," LEED sufficiently covered environmental efficiency but did not fully cover "occupants' comfort," while BREEAM and CASBEE dealt better with "occupants' comfort" as they were more generic. They also found that all four tools lacked a response to waste and wastewater management subcategories. Their study offered a general framework for improving other existing assessment tools or designing new ones [106]. To adapt the sustainability requirements of residential buildings to the new reality of COVID-19-like epidemics, in their other subsequent related study, Tokazhanov et al., 2021 [107] reviewed the current standards for the global assessment tools (BREEAM, CASBEE, LEED, and WELL) in order to determine their gaps in pandemic resilience, and subsequently put a set of assessment indicators for residential buildings during epidemics, allocating scores to these indicators based on practices that would affect sustainability during epidemics. The proposed criteria include three main categories: health and safety, consumption of environmental resources, and comfort. They consist of 10 sub-categories and 33 indicators that can assess the resilience of residential buildings in the face of epidemics.

3.4. Pandemic-Resilient Homes and Biophilic Design

The design framework for pandemic-resilient homes embraces a group of elements including air, sunlight/daylight, plants, water, weather, and landscape. These elements happen to represent the biophilic design elements that fall under nature incorporation. In addition, it is noted, through the result of this investigation, that the design of pandemic-resilient homes meets the challenges of sustainability such as combating climate change, improving biodiversity, reducing air pollution and improving its quality, enhancing thermal comfort, and food production, in addition to promoting physical, mental and psychological health and well-being. It can be concluded that the design principles of pandemic-resilient homes can help achieve sustainable architecture and biophilic design goals.

Finally, despite the short-term interventions that have been adopted in existing homes, the real challenges posed by COVID-19 remain. In spite of the adoption of spatial re-organization and measures such as using multi-purpose furniture, upgrading sanitary equipment in kitchens and bathrooms to eco-facilities, upgrading energy systems to smart management systems, taking advantage of available windows and balconies to bring nature inside, upgrading HVAC systems and equipping them with filtering and purification techniques, and planting, but the dilemma of pre-pandemic homes, including the rapid spreading of infectious diseases, self-inadequacy, residents' mental, psychological, and physical health problems (see Figure 9), still poses a challenge, especially for housing with unfavorable conditions. Pandemic-resilient home design includes urban design (urban spatial organization and site selection so as to provide sunlight, daylight, and ventilation and bring nature indoors, and adopting passive design strategies), architectural design (obtaining the optimal home size to achieve flexibility, privacy, and safety for each member of the family, optimal balcony size, flexible floor plan design to accommodate different functions, providing storage spaces), interior design (open layout that allows adaptive configurations, use of modular, collapsible, and multi-purpose furniture), as well as equipping the home infrastructure with the necessary information and communication technology to facilitate the equality, flexibility, and efficiency we need in the new lifestyle during the pandemic and its aftermath. To counter the increasing costs of adopting such changes, affordable and environmentally friendly strategies must be adopted. Therefore, it can be said that epidemic-resilient homes use more energy-efficient alternatives, reduce the use of resources, use lower cost and environmentally friendly materials, and focus more on health, equity, and climate change considerations.

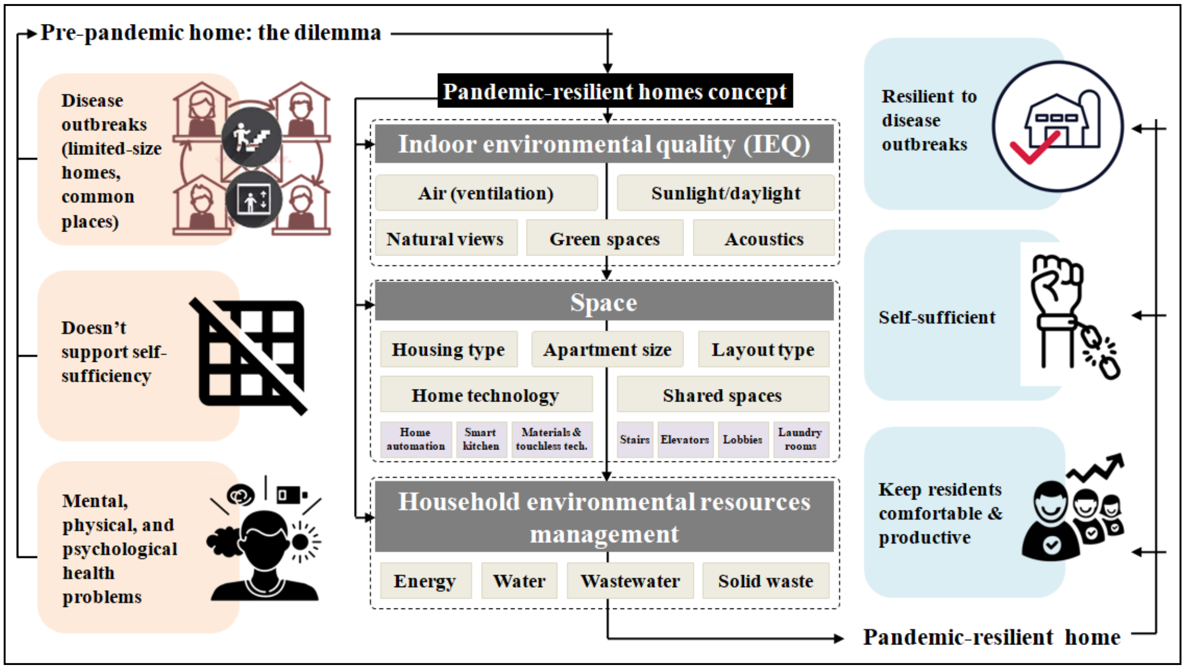

Figure 9. The concept of pandemic-resilient home.

4. Conclusions

This investigation indicates that epidemics pose a future risk, which requires adaptation of housing to face such situations. The noticeable change in lifestyle during the lockdown has affected the use of homes. It is therefore necessary to develop solutions to meet these changing needs. The changes include hygiene practices, work, education, shopping, health, and almost all areas of life. Therefore, to counter this changing pattern, new designs must be flexible so as to accommodate quick changes in lifestyle, enrich quality of life, and improve residents' physical, psychological, and mental health. The COVID-19 pandemic has radically changed the perception of the home space, thus new preferences have emerged in terms of housing demand in the real estate market. These new preferences include flexible, multi-functional spaces, comfortable private domestic workspaces, and physical household areas connected to green areas. Homes now need to adapt quickly to the shocks of pandemics, and this will only come with the resilience that our homes must characterize. The most demanded housing market in the new scene is housing that offers the desired amenities in terms of size, luxury and openness to nature, far from dense urban centers, especially in light of the wide adoption of telework. In sum, the pandemic may have highlighted the shortcomings of cities in general, but it has provided a new opportunity for re-planning and acceleration of sustainability-oriented design.

This paper provided a basis for the development of pandemic-resilient homes in a post-pandemic world by setting up a general and comprehensive framework for such constructions, which can encourage innovation and enhance the quality of homes in the pursuit for and drive of sustainable architecture. This investigation also provides an appropriate approach and insight into contextual policy options taking into account all social groups. Figure 9 and Table 1 show the general structure. This framework represents the future requirements of homes to guide architects, governments, and stakeholders in increasing resilience in residential spaces, as COVID-19 has highlighted the important role of architects and planners in the architectural and urban transformation toward healthier, resilient housing so as to enhance residents' health and support their social, mental, and physical well-being. There is also an important role for local governments and policy makers as key players in crisis response and recovery, as they must support key methods and procedures and adjust regulations and building codes in line with the developed framework.

Table 1. Health-oriented design indicators and guiding principles of pandemic-resilient homes.

Feature	Element	Design Principles	Homes	
			Existing	New
Space	Housing type	(1) Low-rise and mid-rise residences of up to five floors are ideal. (2) Balconies and green roofs are mandatory for high-rise residential buildings. (3) Gated communities could provide more safety via access control, home design, and urban design.	-	√
	Size	Larger sizes to accommodate the new lifestyles and guarantee privacy (personal space)for each family member. Larger home size to accommodate a quarantine room with an extra bathroom, private workspace, and a sanitized home entry. Open-plan layout could be appropriate for limited sized-homes.	-	√
	Layout type	Open-plan layouts (adaptable, modular) include multi-purpose areas with movable walls, modular, collapsible, and multi-purpose furniture to conserve more space in limited-sized homes.	-	√
	Home advanced technology and IOTs	(1) Home automation/smart home j Provision of ICTs, advanced computer systems equipped with sensors (temperature and motion), intelligent home remote control (lighting, curtains, and IAQ through smart phones). j Contactless technology (automated doors with facial recognition systems and motion sensors, touch-free solar-powered faucets, j Smart detection systems to adjust IAQ.	√	√
		(2) Smart kitchen design - Increase storage space. - Improving natural lighting as one of the healthy kitchen-related design elements. - Using contactless technologies such as voice activation technology and remote control of lights, appliances and faucets.	√	√
		(3) Fomite transmission and touchless technologies - Germ-resistant materials (copper and copper alloys) and antimicrobial polymer surfaces. - Contactless technology (to operate elevators, doors, faucets). - Hands-free door openings (foot-, voice-, or wave-activated doors, foot/elbow pedal-operated door openers). - Self-cleaning mechanism for toilets. - Frequent cleaning and disinfection of surfaces. - Steam sterilization of non-washable surfaces (carpets,	√	√

		mattresses, and upholstery).		
	Conveys (shared areas)	Encourage the use of stairs (good lit). Elevators (limit the number of passengers, contactless buttons, foot-activated call buttons (Toe-To-Go (T2G) hands-free elevator system), and air purification systems). Lobbies and corridors (air purification systems, widening or unidirectional travel).	√	√
Indoor environmental quality (IEQ)	Air (ventilation)	Natural ventilation: generate pressure differentials by layout design, promote cross and stack ventilation by vent design: operable windows, clerestories, courtyards, balconies, terraces, porches, solar chimneys, light wells, wind catchers, airshafts, etc.	-	√
		Mechanical ventilation: (generate pressure differentials by positioning of the supply and exhaust vents: (1) supply ventilation system (SVS), (2) exhaust ventilation system (EVS), and (3) energy recovery ventilation system (ERVS)).	-	√
		-Ceiling fans and table/floor fans.	√	√
		-Exhaust fans in bathrooms, kitchens (above stovetop), and closets.	√	√
		HVAC systems(not recommended in residential buildings, if used, use more efficient filtration techniques such as the HEPA filters.	√	√
		Air purification systems(air ionization systems standalone or integrated into the HVAC system, non-thermal plasma technology like airPHX, germicidal ultraviolet (GUV), UVGI (Upper-room Ultraviolet Germicidal Irradiation) technology.	√	√
		An ample supply of houseplants.	√	√
	Access to: sunlight/daylight, green areas, natural views	Site selection;	-	√
		Urban design (building arrangement, streets design and orientation, facade design and orientation, etc.);	-	√
		No obstructions (Street width to building heights ratio) Using wide windows, window solutions to keep daylight in (clerestories, light wells, courtyards, and daylight transport systems), and walls with reflective colors, all subjected to climatic design requirements.	-	√
		Exposure to green spaces (Indoor plants (pots and green walls), windows gardens, balconies gardens, roof gardens, private gardens, and neighborhood gardens).	-	√
		Bringing nature indoor: Windows with views;	-	√
		Balconies and terraces (considering balconies' shading, depth, and area, and the spacing between balconies to provide privacy);	-	√
		Construct landscapes (wetlands, grasslands, prairies, and forests);	-	√
		Construct waterscapes (fountains, water walls, ponds and water basins) in outdoor gardens (roof gardens, private gardens, neighborhood gardens).	-	√
		Construct animal habitats (nest boxes, aquariums, and	-	√

		ponds).		
	Acoustics	Urban design and building configurations (geometric shapes of residential clusters, distance from noise sources, using fences and solid walls to reflect the noise outside);	-	√
		Preference goes to single-story houses and courtyard houses.	-	√
		Architectural design: Keep the most sensitive rooms away from external noise sources;	-	√
		Reducing apertures;	-	√
		Using active noise cancellation (ANC);	√	√
		Inserting acoustic louvers;	√	√
		Soundproofing windows;	√	√
		Using thicker, densely woven and heavy curtains;	√	√
		Placing balconies in protected areas.	-	√
Household environmental resources management	Energy	Solar chargers (to charge cell phones). LED bulbs (green lighting). Smart energy strips (to save energy). Home energy monitoring devices (smart energy management). Thermostats (to adjust temperature).	√	√
	Water	Providing household water storage tanks if possible. Treating gray water for reuse. Faucets and sprayers with backflow valves. Eco-showerheads and motion-activated washroom fixtures Decreasing water consumption through well-maintained plumbing work (sealed bathroom catchments, sprayers and faucets with backflow valves).	√	√
	Liquid Waste	Observe permanent hygiene (washing hands, use of sanitizers). Not throwing toilet paper and face masks into toilets. At municipality level, special treatment of wastewater.	√	√
	Solid waste	Wise consumption of canned food products. Encouraging the consumption of fresh food. At municipality level: provision of additional separation bins and treating of new waste category in a manner similar to that of hazardous medical waste.	√	√

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