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Review

Role of Ventilation and Spatial Designs in Airborne Disease Transmission Within Residential Aged-Care Facilities

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Abstract

The global aging population, particularly those aged 60 and above, is increasingly vulnerable to communicable diseases. Building ventilation (BV) plays a key role in residential aged-care (RAC) facilities, where COVID-19 has had a significant impact. This study systematically reviews the published literature to examine the influence of BV systems (BVSs) on airborne disease (COVID-19) transmission in RACs and recommends strategies to protect vulnerable residents. Using the PRISMA framework, articles published in the last decade were sourced from Scopus, Web of Science, and PubMed. Bibliometric analyses revealed key research clusters on risk factors, transmission, facilities and services, and gender-based and retrospective studies. Australia, the USA, Africa, and the UK have made the most scholarly contributions to this field. Three main research areas emerged: BVS functionality, ventilation's role in COVID-19 transmission, and spatial building design for effective airflow. Findings reveal that inadequate ventilation and poor indoor air quality are major contributors to disease spread, further influenced by ventilation rate, airflow, temperature, humidity, and air distribution. A hybrid ventilation design that integrates natural and mechanical systems with technologies such as HEPA filters, UVGI, and HVAC is recommended in the current study. In addition, building form and layout should incorporate spatial, engineering, administrative, and hierarchical controls in line with sustainable ventilation design guidelines. This study adds to the growing body of knowledge on the roles of ventilation and design in infection control. It offers practical recommendations for architects, RAC managers, government agencies, and policymakers involved in designing and managing RACs to reduce the risk of communicable disease transmission.

Keywords: airborne diseases; communicable diseases; COVID-19; residential aged-care facilities; spatial design; ventilation

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1. Introduction

Ventilation is an integral provision in buildings. Beyond enhancing buildings' aesthetic forms and functions, ventilation also facilitates occupants' comfort and good health [1]. From an aesthetic perspective, ventilation, particularly when guided by vernacular architecture and contemporary façade design, extends beyond the building envelope [2]. Architectural elements of ventilation, such as operable windows, perforated screens, and vegetated buffers, contribute to visual depth, surface articulation, and patterned compositions while enhancing the interplay of light and shade and fostering perceptions of transparency and spatial layering [3,4]. Furthermore, enabling greater occupant control over ventilation has been shown to improve not only thermal comfort but also perceptions of both the functional performance and the aesthetic value of buildings [5].

Evidence abounds in the normative literature regarding the significance of ventilation in construction science, including in relation to people's quality of life and the continued efficiency and sustainability of our planet [6]. However, despite the numerous reports on this, Sundell et al. [7] suggest that the health and spatial implications of building ventilation (BV) are often poorly understood and are seldom taken seriously. The centrality of Sundell's work is the relationship between BV and public health, in particular, how diseases are transmitted and spread through BV and related provisions. Evidence has emerged significantly on the role of BV in the control and management of airborne diseases such as coronavirus disease 2019 (COVID-19) [8]. A clear conclusion is that a poorly ventilated indoor space heightens occupants' vulnerability to airborne diseases. The risk of severity from this is significant. Despite this, previous studies are only heavy on energy efficiency, sustainability, and cost of comfort; they are amorphous on the role of ventilation in ensuring residential aged-care (RAC) buildings achieve their ultimate functional requirements regarding health outcomes of building users, including protection from environmental aggressions seen or unseen.

This study reviews BV parameters relating to specific outcomes of the COVID-19 pandemic amongst vulnerable users of RAC buildings. According to a report by the World Health Organization [9], over 660 million cases of COVID-19 have been documented across the world, with a death toll exceeding 6.7 million. Residents of RACs have been particularly affected. According to Levin et al. [10], RAC facilities account for 7% of all global cases, which led to a startling 75% of fatalities worldwide. The Australian Institute of Health and Welfare [11] estimated that 16.4% of Australians will exceed 65 years of age by the end of 2023. This is expected to exceed 21% by 2070. These numbers are significant as the RAC sector receives substantial public investment yearly. Thus, it is important that RAC facilities are safe and that the needs of the vulnerable residents are catered to. Some studies have investigated this. For example, Hashan et al. [12] reviewed 49 studies that examined the COVID-19 outbreak across 14 countries. They found that about 45% of COVID-19 cases were linked to outbreaks within a single RAC facility, with 23% fatality. Other studies also report how the impacts of the COVID-19 pandemic can be attributed to certain factors within the RAC. One key element of this is the building design and spatial layout, whilst others include indoor environmental conditions and BV issues [13].

This study systematically retrieves and reviews articles on BV in RACs in relation to COVID-19 spread with the following objectives:

1. To examine the role of built forms and functions in the transmission of COVID-19 in RAC facilities.
2. To investigate various BVSs and techniques, building forms and designs, and how they impact the transmission of COVID-19 in RACs.
3. To review the appropriateness of government policies in these facilities.

The additionality of these objectives is to enhance the understanding of stakeholders involved in RAC facilities—in particular, care receivers and their families, care providers and their staff, regulators and their agents, and the community.

The rest of the paper is organized as follows. Section 2 presents the methods adopted in this study. It lists the literature retrieval and analysis protocols, as well as the systematic literature review process. Section 3 presents the results and discussion on the retrieved literature, including the citation and publication analysis, the emergent research hotspots, including the RAC ventilation systems, the BV role in COVID-19 spread, and building design and spatial layouts for effective BV in RACs. Section 4 presents the regulations, guidelines, and recommendations for BVSs in RACs. Finally, Section 5 concludes the study and presents the key takeaways, limitations, and future direction.

2. Materials and Methods

In this study, the systematic literature review technique was adopted to review articles on the role of BV in RACs as an instigator of COVID-19 spread. This section explains the steps and methods of literature retrieval and the systematic literature review process, including the bibliometric analysis used in the current study.

2.1. Literature Retrieval

This study reviewed articles published in the last decade, i.e., from 1 January 2014 to 31 December 2024, to examine pre- and post-pandemic scenarios of pandemics, especially COVID-19 spread in RACs. The search criteria were focused on the last decade. The aim was to see if there were significant articles before COVID-19 (pre-2019), observe the trend during the period of COVID-19 (2019–2020), and a few years after the pandemic was over (2021–2024). Hence, a review of articles published between 2014 and 2024 was conducted. Pre-2019 articles were included to check if airborne diseases were focused on before the COVID pandemic. In this regard, three literature repositories, including Scopus, Web of Science (WoS), and PubMed (MEDLINE), were used to retrieve the relevant literature. Various combinations of keywords were carefully devised. These include combining ventilation, spatial design, building design, building layout, aged care, residential care, old age home, senior living, pandemic, virus, coronavirus, COVID-19, and communicable disease using Boolean operators "OR" and "AND." The detailed search strings utilized for literature retrieval are shown in Table 1.

A total of 70 articles were retrieved, including 27 articles from Scopus, 23 from WoS, and 20 from PubMed repositories when an unrestricted search was conducted. The article types were restricted to review papers and research articles due to the superior quality of the peer review process in such articles. The reference lists in the retrieved articles were also screened. All other types of articles were excluded. Additionally, the language of these articles was limited to English only. EndNote library and EXCEL sheets were used to maintain the records and remove duplicates prior to the detailed screening process. Furthermore, only those articles that exclusively incorporated the specified keywords in the search bar of all fields (title, abstract, topic, keywords, etc.) in the referred repositories were retrieved in this study.

After sorting and comparing the articles, 25 duplicate entries indexed in the repositories were identified and removed. Among the remaining 44 articles, 8 were found to be irrelevant to the focus of the study after in-depth analysis, leaving a total of 36 shortlisted articles used in the current research for a detailed systematic review. This study is in line with contemporary review studies such as Sajid et al. [14] and Ullah and Al-Turjman [15], who used 31 and 20 shortlisted articles in their review papers. A dearth of literature on the topic also reflects its nascency and the very refined focus of the current study.

2.2. Systematic Literature Review Process

Systematic literature review has been widely used to identify gaps and trends within various disciplines and topics of interest [16]. It encompasses a refined mix of bibliometric analysis and focused thematic investigations. For the bibliometric analyses, VOSviewer (Version 1.6.20) and Excel (Version 2508–Build 19127.20222) were used in this study. The systematic literature review process adopted in the current study summarizes the contemporary understanding of BV's role in COVID-19 transmission in RAC facilities. It also helps identify the knowledge gaps. The standards for conducting systematic literature review defined by the International Cochrane Organization are followed in the current study, with modifications by addressing the questions regarding etiology [17]. Further, Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocols and guidelines are followed in this study, as discussed below [14]. The PRISMA flow diagram for the current study is presented in Figure 1.

Table 1. The search string with restrictions and retrieved articles used in this systematic literature review.

Search Engines	String/Conditions	Articles Retrieved
Scopus, Elsevier	TITLE-ABS-KEY ("Ventilation" OR "Spatial Design" OR "Building Design" OR "Building Layout") AND TITLE-ABS-KEY ("Aged Care" OR "Residential Care" OR "Old age Home" OR "Senior Living") AND TITLE-ABS-KEY ("Pandemic" OR "Virus" OR "Coronavirus" OR "COVID19" OR "Communicable Disease") AND (LIMIT-TO (DOCTYPE, "article")) AND (LIMIT-TO (DOCTYPE, "review")) AND (LIMIT-TO (LANGUAGE, "English")) Time span: 2014–2024	27
Web of Science (WoS)	All Fields ("Ventilation" OR "Spatial Design" OR "Building Design" OR "Building Layout") AND All Fields ("Aged Care" OR "Residential Care" OR "Old age Home" OR "Senior Living") AND All Fields ("Pandemic" OR "Virus" OR "Coronavirus" OR "COVID19" OR "Communicable Disease") and Article or Review Article (Document Types) and English (Languages) Time span: 2014–2024	23
PubMed (MEDLINE)	All Fields ("Ventilation" OR "Spatial Design" OR "Building Design" OR "Building Layout") AND All Fields ("Aged Care" OR "Residential Care" OR "Old age Home" OR "Senior Living") AND All Fields ("Pandemic" OR "Virus" OR "Coronavirus" OR "COVID19" OR "Communicable Disease") and Article or Review Article (Document Types) and English (Languages) Time span: 2014–2024	20
Sum of Papers		70
Duplicates		25
Remaining		44
Irrelevant Focus		8
Final Shortlisted Relevant Articles		36

1. The literature review was based on articles with pre-set keywords published in the last 10 years and retrieved from Scopus, WoS, and PubMed (MEDLINE).
2. The keywords must appear in the abstract, title, and keywords sections of the records to be eligible for inclusion in the current study.
3. The Scopus, WoS, and PubMed repositories were used as information sources, which can be accessed at (1) scopus.com/search/form.uri?display=basic (last accessed on 1 January 2025) (2) webofknowledge.com (last accessed on 1 January 2025) and (3) pubmed.ncbi.nlm.nih.gov/advanced (last accessed on 1 January 2025).
4. The search process comprises a search string with restrictions (inclusions and exclusions), as listed in Table 1.
5. This study's selection process consisted of keyword searching, screening at the title level, removing duplicates, and qualitative analysis of the abstracts and keywords.
6. The retrieved articles were analyzed in detail using bibliometric measures such as citation, country of origin, and publication trend analysis.

7. The considered data items included authors' names, titles, sources, study remarks, keywords, setting type, variables such as BVSs and techniques, spatial designs, and research outcomes.
8. The risk of bias for individual research studies did not affect the systematic literature review process, as the retrieved papers were individually reviewed by all authors and later collated and compared through a triangulation process to eliminate any potential bias.
9. The narrative analysis covered key environmental factors such as building forms, spatial designs, ventilation in aged-care buildings, BV's role in COVID-19 transmission, and related data.
10. The research findings were ultimately compared with the other research studies to check for consistency.
11. Additional analysis was performed by linking the factors of BV's role in disease spread associated with building forms and ventilation strategies in RAC buildings.

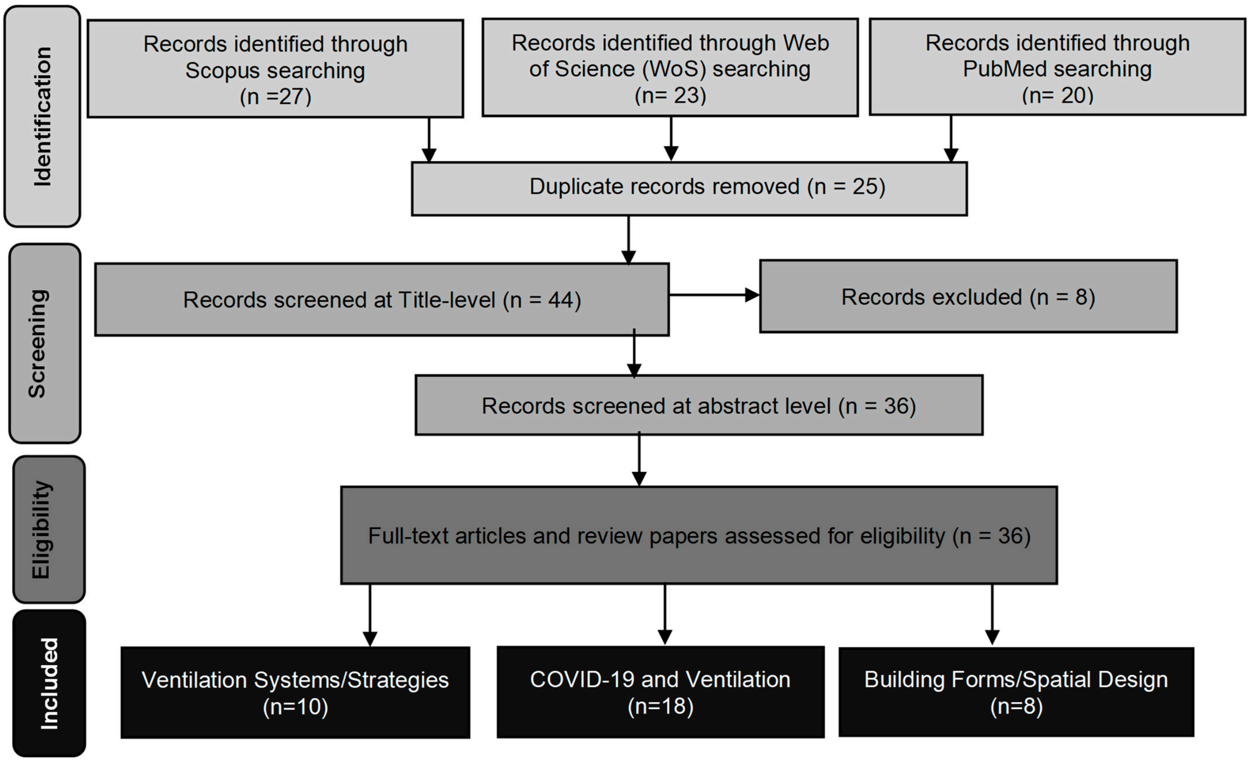

Figure 1. PRISMA flow diagram. Note, "n" = number of publications.

A screening at the abstract level was conducted to assess the 36 shortlisted articles. Among these articles, 10 focused on BVSs and relevant strategies, 18 delved into the relationship between COVID-19 and BV, and 8 studies explored building forms and spatial designs related to RACs.

2.3. Data Analysis

To conduct the data analysis, it was ensured that the selected articles were related to the spread or transmission of COVID-19 concerning ventilation in various indoor environments in RACs. Microsoft Excel was utilized to compile and organize the articles, as well as to generate tables and figures for both tabular and graphical representation. Moreover, the VOSviewer was employed to perform fundamental bibliometric analyses on the retrieved articles. BV-related factors and systems, such as natural or mechanical ventilation in buildings, were thoroughly studied. Bibliometric analyses, including citation and publication trends, were observed and reported to highlight key research hotspots and researchers' attention toward BVSs and techniques, particularly those influencing the spread of viral infections such as COVID-19 within RAC buildings.

3. Results and Discussions

3.1. Bibliometric Analyses

VOSviewer was used to conduct fundamental bibliometric analyses of the retrieved articles. Figure 2 shows the keyword analyses of the articles retrieved from each repository.

The articles retrieved from Scopus displayed three main clusters: gender-based studies (red cluster), risk factors (blue cluster), and retrospective studies based on the age of residents (green cluster). The WoS retrieved articles displayed the clusters of transmission (red cluster), facilities (blue cluster), and services (green cluster). Lastly, the PubMed articles displayed two clusters: retrospective risks (green cluster) and aged-care services (red cluster). The appearance of the term "ventilation" in limited clusters, even when used as the main search keyword, highlights the dearth of literature on this area and hence signifies the importance of the current study. Table 2 lists the pertinent numbers for co-occurrence and co-citation analyses conducted as part of bibliometric analyses in the current study. A total of 508, 66, and 61 keywords co-occurred in the articles retrieved from Scopus, WoS, and PubMed, respectively.

Table 2. Co-occurrence and co-citation analyses.

Analysis Type	Assessment	Considerations	Scopus Results	WoS Results	PubMed
Co-occurrence	Counting method	Full counting			
	Units of analysis	All keywords	508	66	61
	Minimum occurrence	Scopus, 5; WoS, 2; PubMed, 2	27	9	14
Co-authorship	Counting method	Full counting			
	Units of analysis	Authors	108	70	61
	Minimum citations	Scopus, 5; WoS, 5; PubMed, 0	43	29	61
	Counting method	Full counting			
	Units of analysis	Organizations	79	26	29
	Minimum occurrence	Scopus, 5; WoS, 2; PubMed, 0	23	20	29
	Counting method	Full counting			
	Units of analysis	Countries	19	8	NA
	Minimum occurrence	Scopus, 1; WoS, 1; PubMed, 0 Minimum citations, 1	15	5	NA

Similarly, a total of 108, 70, and 61 authors contributed to the articles retrieved from Scopus, WoS, and PubMed, respectively. In terms of organizations, a total of 79, 26, and 29 organizations were involved in the articles retrieved from Scopus, WoS, and PubMed, respectively. Lastly, in terms of countries, researchers from 19 and 8 countries were involved in the articles retrieved from Scopus and WoS. Country data could not be analyzed using VoSviewer for PubMed articles. However, this was included later in the manual Excel-based analyses.

Figure 3a illustrates the overall publication and citation trends related to the impact of BV on COVID-19 transmission in RAC facilities. The results reflect that less attention was given to viral prevalence concerning BV in RACs pre-2019 when COVID-19 took the world by surprise. However, after the global COVID-19 pandemic (in 2019 and onwards), researchers redirected their focus to highlight the primary cause of viral transmission within the vulnerable population residing in RACs. Hence, the number of articles on the topic grew substantially. Not only did the number of articles on the topic grow, but the number of pertinent citations (as on Google Scholar, 12 July 2025) from researchers working in connecting fields also increased exponentially. In 2020, a mere 12 research studies acquired a notable 5593 citations, signaling a heightened emphasis on viral infections and the urgent demand for effective mitigation strategies. This surge is evident in the increase in both publication and citation counts in recent years.

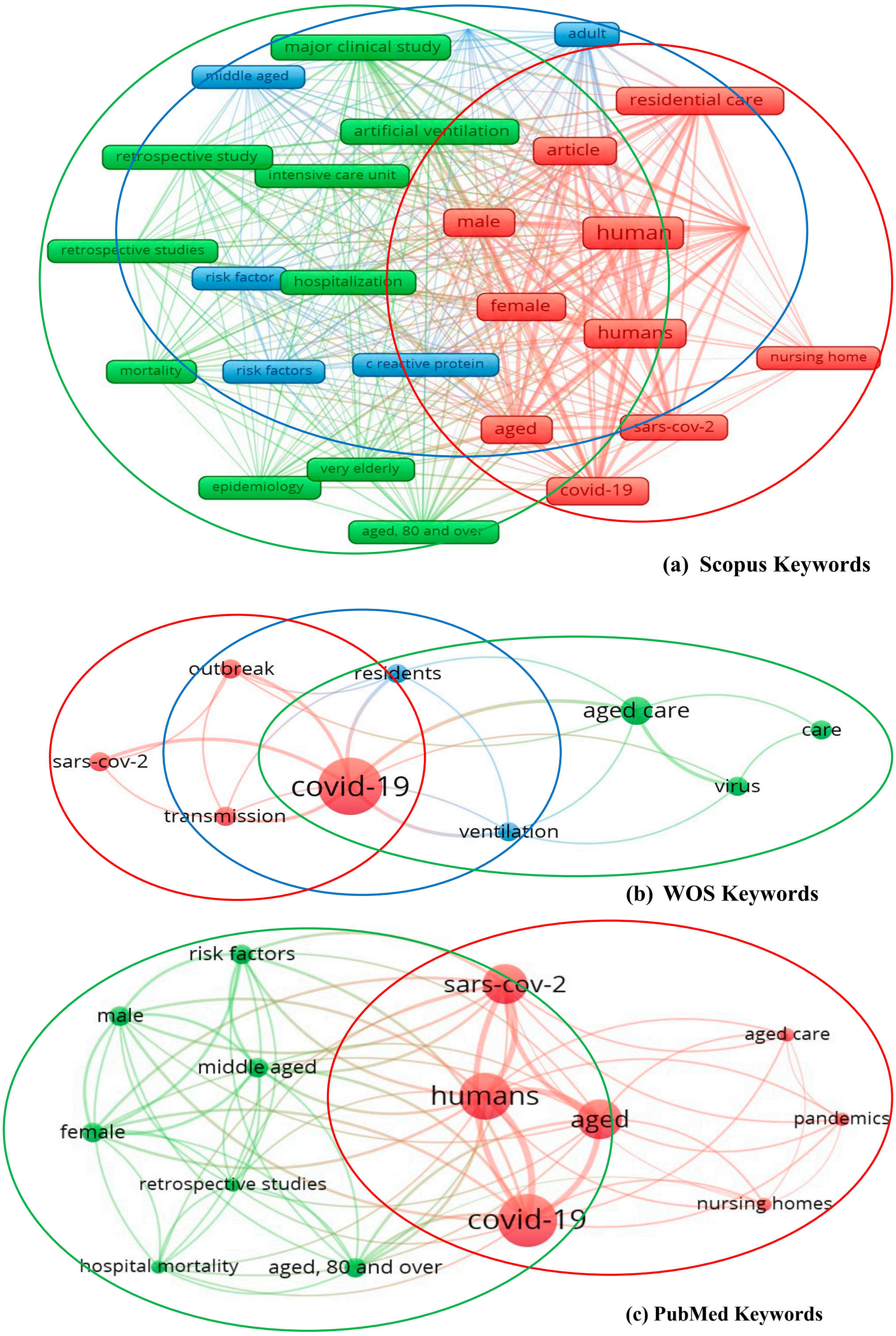

Figure 2. Keyword clustering of the retrieved articles based on repositories.

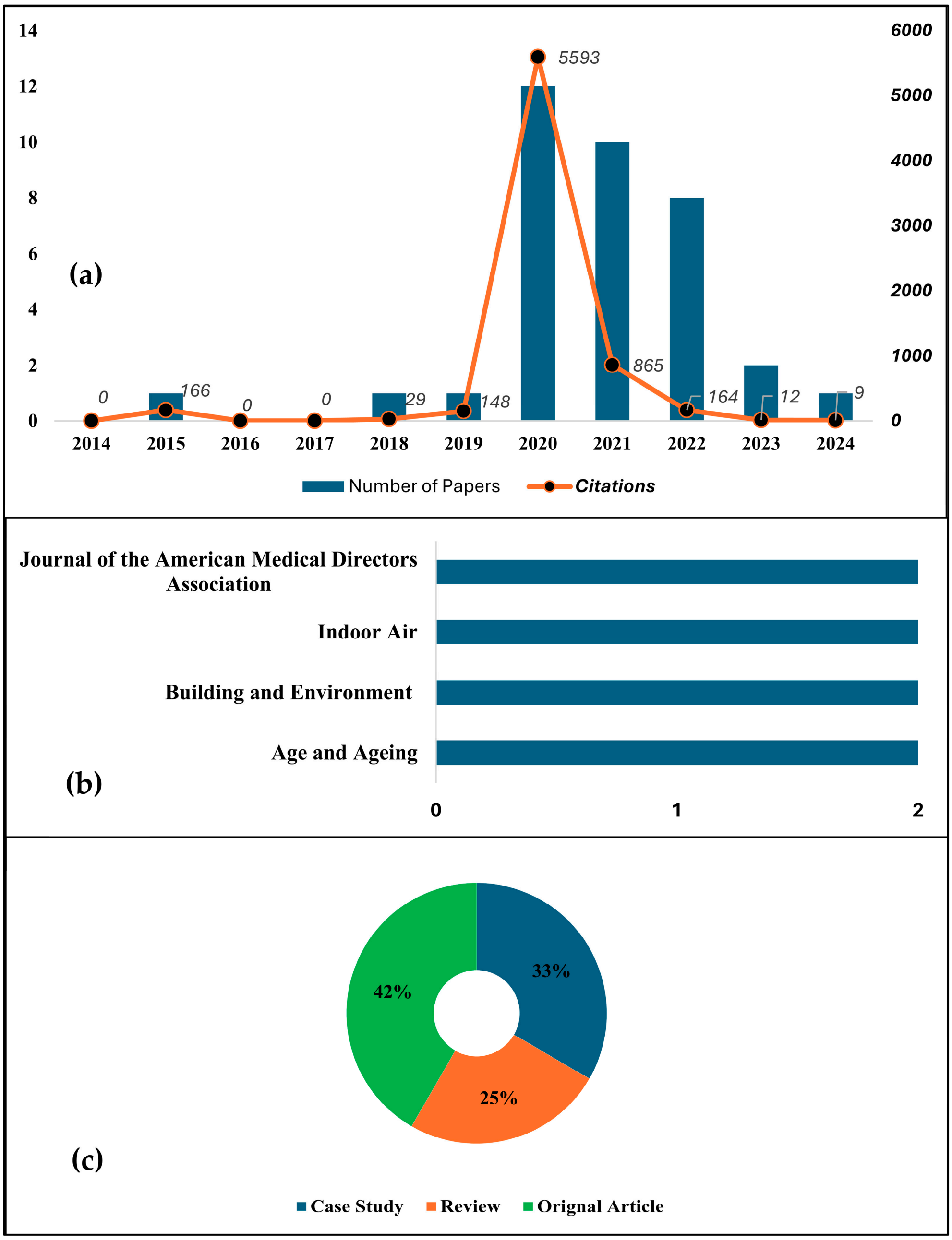

Figure 3. (**a**) Temporal publications and citations trend of research about the impact of ventilation on COVID-19 spread within RAC buildings, (**b**) top contributing journals, (**c**) distribution of article types.

While the number of articles has reduced from 2022 to 2024 as the world is moving out of the pandemic, there remains a gap in the literature concerning BVSs that considers advancing factors like room geometry, types of pathogens, ventilation rate, thermal comfort, spatial designs, building layout characteristics, and sources of contaminants in RACs. Future research endeavors should concentrate on exploring and evaluating optimal BV strategies adaptable to various pandemic scenarios. Such strategies aim to ensure optimal air quality and infection control in RAC facilities. In the absence of high-quality, concentrated studies on BV and its role in curbing diseases and pandemics in RACs, such facilities will remain vulnerable and victim to forthcoming pandemics or viral diseases. Given the vulnerability of the aging population and the projected increase in RAC users in countries like Australia [10], mitigation strategies must be devised and implemented beforehand rather than catching up when tragedies and pandemics like COVID-19 strike.

Figure 3b presents the top journals contributing to the current study's focus area. Four journals, *Age and Ageing*, *Building and Environment*, *Indoor Air*, and *Journal of the American Medical Directors Association*, each contributed two papers. Figure 3c presents the distribution of article types into three categories: case study, review, and original article. A total of 15 out of 36 (42%) reviewed articles were classified as original articles, followed by 12 (33%) case studies and 9 (25%) as review articles.

Figure 4 represents the country or region, indicating the location where the trend of current research outputs has been reported. According to the extracted data, 20 countries have contributed to BV studies in RACs. Australia leads this research with a percentage share of 13.51% (n = 5) among the retrieved articles. The United States of America (USA) and Africa follow Australia with a 10.81% share. These countries have predominantly engaged in collaborations with various organizations related to BV and air quality. For instance, researchers from the USA have partnered with the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the National Science Foundation for pertinent studies. These collaborations have resulted in the development of comprehensive guidelines for effective BVSs in RACs.

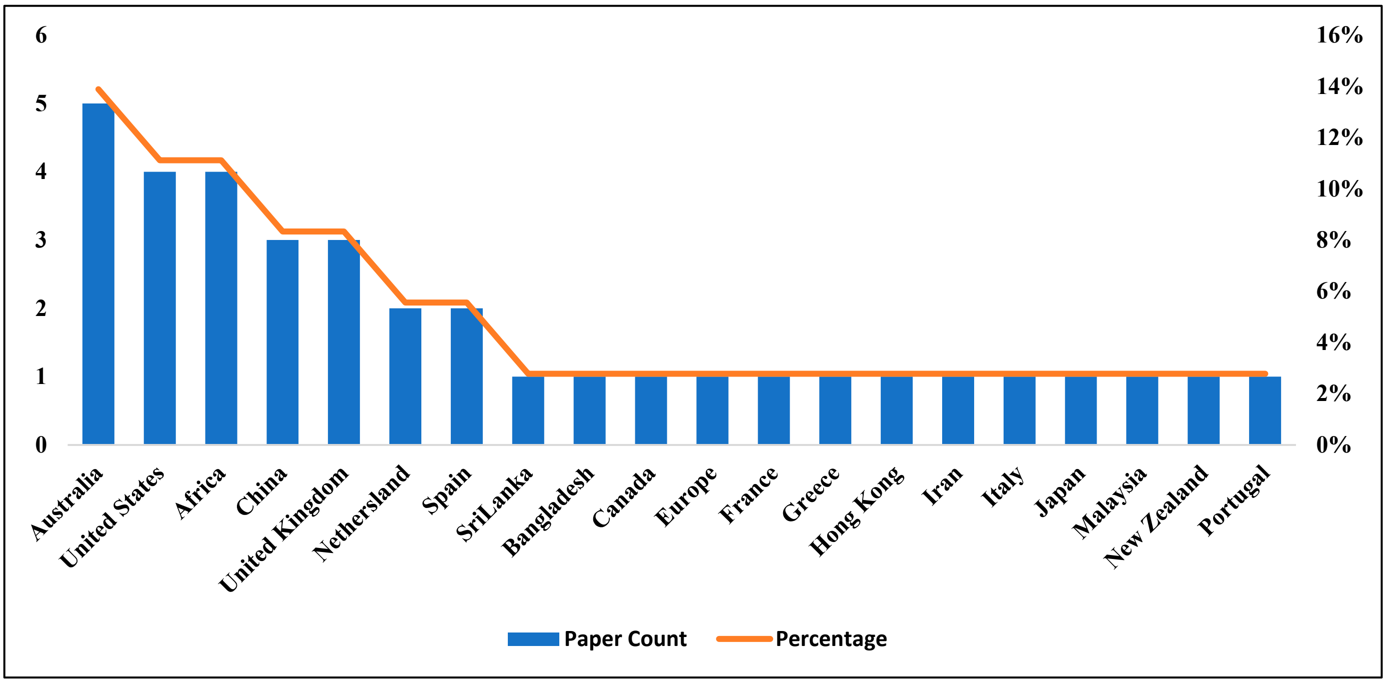

Figure 4. Publications count per country/region (bar graph) and the percentage share.

Similarly, the United Kingdom (UK) has witnessed relevant research progress driven by investments from the UK Research and Innovation (UKRI) and the National Health Service (NHS). These entities have actively invested in research and development of guidelines for infection prevention and control. Japan, the Netherlands, Greece, New Zealand, and Spain have directed their efforts toward advancing BV technologies and infectious disease management, leading to notable research advancements in BV strategies and building forms or spatial layouts in RACs. Countries like France, Europe, Sri Lanka, Canada, Bangladesh, and Italy have also developed guidelines for BV design and operation, highlighting the crucial role of proper airflow management and filtration in minimizing infection transmission in buildings such as RACs. The supportive funding agencies and policies, encompassing technological innovation, public health priorities, regulatory frameworks, and considerations of building characteristics and spatial designs, collectively contribute to the development of effective BVSs for mitigating airborne infections in these countries.

Figure 5 shows the top keywords appearing in the article title. The term "COVID" appeared in 17 articles, followed by "transmission" in 13 articles, and "ventilation and ventilation systems" in 10 articles, constituting the top 3 keywords. The word "review" appeared in eight articles, "SARS-CoV" in six, "effect" in five, "nursing home" and "virus" in four, and "outbreak", "pandemic", and "spread" in three articles each. Authorship analyses were not performed as no author contributed more than one paper to the study area.

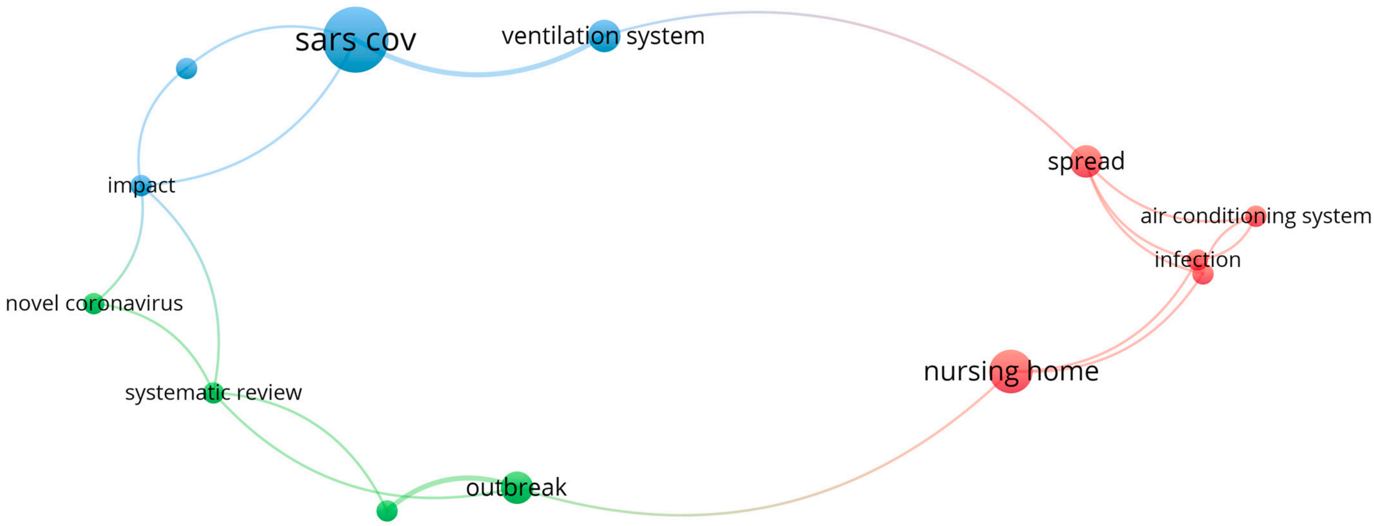

Figure 5. Prominent keywords appearing in the reviewed articles.

3.2. Emergent Research Hotspots

Throughout the review, a lack of focus on BVSs was observed, which was reflected in the low number of retrieved articles. Regardless of the number of papers, three research hotspots emerged as a result of the review: types of BVS, the role of ventilation in COVID-19 spread, and adequate ventilation through building design and spatial layouts. These hotspots are areas of research interest where a multitude of retrieved studies and collaborative efforts converge or seem to be pointing. These hotspots signify a dynamic domain of scientific exploration and advancement and are subsequently discussed.

3.2.1. Types of Building Ventilation Systems

Ten articles (28%) among the retrieved studies specifically focused on types of BVSs in RACs. BV ensures optimal air quality in RACs and is a key determinant influencing microbial composition in indoor environments.

In many multi-occupancy buildings, the air is brought in through windows along the building perimeter from the surrounding environment, building leakage, and some form of mechanical ventilation to ventilate the entire structure without relying on comprehensive filtration efficiency. This can lead to the widespread distribution of microbial communities throughout the building [18]. Directly circulating air through an open window without filtration has been observed to enhance the phylogenetic diversity of microbes within indoor environments, yielding communities similar to those found outdoors. In the service industry, centralized heating, ventilation, and air-conditioning (HVAC) systems are generally utilized for BV purposes. HVAC units, such as packaged terminal air conditioners (PTACs), are commonly found in aged-care facilities, hotels, condominium units, motels, and apartments. Perimeter passive BVS, exemplified by perimeter damper vents, is also used in certain buildings.

The features of HVAC design, such as filtration, ventilation, humidity, and ultraviolet radiation, have been linked to virus spread in RACs [19]. Efficient BVSs offer a means to mitigate viral transmission, particularly through inline filtration media. Therefore, RACs should employ high-efficiency particulate air (HEPA) filters and ultraviolet (UV) disinfection to improve BVS. Several studies reinforce this deduction. For example, Miller et al. [20] investigated the COVID-19 spread in RACs in Pennsylvania and recommended controlling the spread by modifying HVAC systems using advanced filters, vents, and blowers. Schoen [21] suggested using modified HVAC systems to enhance air ventilation and filtration to curb COVID-19 transmission within RACs.

BVSs can be categorized into three groups based on the dynamics of aerosol and droplet transmission in indoor environments [22]. These categories consist of

1. Hybrid/recirculating BVS;
2. Mechanical BVS;
3. Displacement BVS.

The hybrid or recirculating air-conditioning (AC) system circulates indoor air using a ceiling fan or split AC system, blending it with outdoor air before entering the room. This process, known as heat recycling or hybrid BV, is commonly used in many RACs [8]. The problem with such a system is that it generates turbulent air flows, recirculating stale air within the affected rooms and spreading it from one corner to another. This has been associated with many cases of COVID-19 in RACs across the globe.

Mechanical BVS, such as the HVAC system, is typically employed to distribute fresh air evenly throughout all occupied spaces, ensuring a uniform supply of air quality to all individuals. Ventilation diffusers and outlets are utilized for this purpose. The mechanical BVS encompasses both localized, smaller mechanical BV units with heat recovery (MVHR) and centralized, larger air handling units (AHU). These systems generate turbulent and well-mixed air flows within building rooms [22]. In the absence of proper filtration systems, the HVAC system can spread the virus throughout the building. This was particularly observed in the case of hotel quarantines, where the HVAC systems were never designed for isolating patients [23]. Such systems ended up spreading the virus to connected ducted rooms. Another similar instance was observed in the case of the Diamond Princess Cruise Ship, where almost all passengers and crew on board were impacted due to the HVAC-related spread of COVID-19 [24].

Displacement BVSs effectively eliminate polluted air from buildings while introducing fresh air from the external environment. This displacement occurs in a buoyancy-driven convention without disrupting the air supply to the building. A displacement BVS primarily operates passively, involving natural BV methods such as opening windows and façade louvers, creating a laminar airflow within the building rooms [25]. Table 3 provides details of various BV systems used in various buildings, their associated measures, and descriptions.

There are three primary categories of ventilation systems: natural, mechanical, and hybrid (or mixed-mode) BVSs [26]. Natural ventilation relies on airflow achieved without mechanical assistance [18], typically through the use of open windows and vents. Mechanical ventilation systems, on the other hand, rely on equipment such as fans and air-handling units, which can significantly increase energy consumption. They can also use heat or energy recovery units to temper incoming supply air using the energy in exhaust air. Hybrid ventilation combines both approaches, utilizing mechanical devices such as blowers and fans alongside natural ventilation methods, making it a more adaptable and energy-efficient solution [6].

Five key indices are used to evaluate ventilation system efficiency in buildings: pollution removal, air exchange rate, heat removal, air distribution index, and airborne particle exposure [27]. Another parameter for assessing the effectiveness of BVSs in indoor spaces is the response coefficient. Airborne particles are removed and diluted through the upgradation of BVSs in RACs [28]. An inadequate BVS can contribute to the transmission of viral infections in buildings [29]. Indoor air quality (IAQ) poses a significant impact on human health within indoor spaces, making it imperative to design efficient BVSs in RACs to ensure optimal air quality [30]. For mechanical BVSs in RACs, the recommended ventilation rate ranges from 6 to 12 air changes per hour (ACH). Contemporary RAC constructions use a ventilation rate of about 12 ACH. In natural BVS, the average rate is approximately 160 L of air per second (L/s) [31]. To ensure efficient ventilation between rooms and corridors, a permissible pressure difference of $\geq$2.5 Pascal (Pa) is recommended [32]. Maintaining an optimal ventilation rate (>6 ACH) is crucial to meet airflow variation (>60 L/s) and achieve a negative pressure difference (>2.5 Pa) [33].

Table 3. Details of BVSs used in various buildings.

BV Systems	Ventilation Measures	Brief Description
Recirculating BV	Split AC system	The ceiling-mounted fan unit and wall-mounted unit work together to recirculate room air at high speeds, ensuring a consistent distribution of the air throughout the rooms.
	Hybrid ventilation	External air is blended with room air and dispersed throughout the spaces via a fan, guaranteeing swift and thorough mixing of air.
	Ceiling fans	Fans are used to circulate room air at a high velocity, ensuring effective wind chill cooling and uniform distribution throughout the space.
Mixing BV	Mechanical ventilation with heat recovery (MVHR)	These systems, such as HVAC systems, are localized and known as balanced supply and extract systems. They incorporate heat recovery methods to mitigate heat loss associated with ventilation.
	Air handling units	Fresh outdoor air is delivered and conditioned in occupied spaces through ceiling ducts or floor diffusers. The fresh air is blended with stale air and distributed through various outlets into the occupied space.
	Positive input ventilation	These localized fanned systems deliver fresh air through façade openings, utilizing positive pressure to facilitate exhaust and mirroring the airflow dynamics of air handling units.
Displacement BV	Natural ventilation measures	Such building-related measures are devised to replace stale air with fresh air through buoyancy, utilizing various elements such as windows, solar chimneys, or passive stacks.
	Continuous extract ventilation	Centralized or localized fan-driven systems are linked to the extraction of stale air and the introduction of fresh air based on the building fabric openings, such as louvers or windows, which enable the inflow of fresh air through negative pressure.

HVAC systems are employed to regulate humidity and temperature while addressing air quality in various types of buildings, including commercial, residential, healthcare, industrial, and aged-care facilities [18]. In RACs, these systems must be designed with a pressure gradient potential, creating negative or positive pressure to help prevent the spread of airborne viruses. The existing ventilation systems in RACs are primarily designed to eliminate heat and pollution under normal conditions. However, during the COVID-19 pandemic, these systems proved inadequate due to their insufficient efficiency in providing the required low supply flow rates and their high initial costs associated with large air-handling ducts and exhaust systems. To mitigate the transmission of diseases in buildings, it is recommended to increase the ventilation rate [34]. Although the ducting, air supply, exhausts, and air-handling systems are designed to be economical and energy-efficient, their limitations necessitated alternative measures during the pandemic. Portable units, such as windows equipped with fans (window fans or box fans), air cleaners, and ultraviolet germicidal irradiation (UVGI) systems, were installed to enhance ventilation. These measures effectively provided cleaner air and maintained high ventilation rates in buildings [34].

Additionally, HVAC systems in RACs should incorporate recyclable air filters made of fiberglass. Cost-effective alternatives like HEPA and UV filters can be used to remove airborne particles, with HEPA filters capturing particles as small as $\geq$0.3 μm and UV filters eradicating microbes [22]. Notably, the particle size of COVID-19 ranges from 0.25 to 4 μm, making HEPA filters effective in trapping these particles. Therefore, it is recommended that HEPA and UV filters be used to eliminate viral particles in RACs.

Establishing a sustainable and efficient indoor environment involves implementing practical strategies such as enhancing the effectiveness of BVS, employing air purification techniques, and implementing pollution source control [35]. Ventilation and thermal comfort are provided in buildings through air-conditioning systems like HVAC and AHU. These systems in RACs comprise air pumps, heat exchangers, mixing chambers for indoor and outdoor air, airflow ducts, vents, and filters [36]. In the context of RACs, adhering to two fundamental principles is essential for minimizing the risk of infectious disease spread among elderly residents and staff: (1) utilizing fresh air through an effective BVS, and (2) recirculating filtered air using efficient air filters [37]. However, in some instances, such as wildfires, traffic, and outdoor pollution, air filtration might be required. Currently, BVSs play a crucial role in providing both thermal comfort and maintaining good IAQ for residents of RACs. Advanced technologies in ventilation, including HEPA filters, mechanical air filters, ion generators, and UV irradiation for microbial eradication [37], along with engineering controls, are required to mitigate the infection risk of COVID-19 and similar communicable diseases in RACs.

3.2.2. Role of Ventilation in COVID-19 Spread

Half of the retrieved shortlisted articles (18, i.e., 50%) focused on the role of ventilation in the spread of COVID-19 in buildings and RACs. COVID-19 transmission is not limited to droplets and physical contact; viral particles can spread through various dissemination patterns and trajectories [38]. BV, particularly HVAC systems, is recognized as a crucial element in controlling COVID-19 in various settings such as RACs, hospitals, healthcare facilities, long-term care facilities, nursing homes, hotels, and residential buildings [39]. HVAC increases indoor air dilution, effectively reducing the concentration of infectious viruses. Several factors related to installed HVAC systems in RACs, including air filtration systems, ventilation methods, ventilation rates, and pressure control gradients, play a significant role in influencing the spread of pathogens [38]. It is worth noting that the absence of filters in ducts significantly contributes to the spread of diseases [29]. Therefore, proper installation and maintenance of HVAC systems and effective filtration strategies are essential elements in controlling the transmission of infectious diseases within indoor environments.

BVSs play a significant role in the transmission of viral particles associated with infectious diseases, including measles, smallpox, coronavirus, tuberculosis, and others [29]. The Federation of European Heating, Ventilation, and Air-Conditioning Associations (REHVA) has compiled guidelines on utilizing building services to mitigate the transmission of COVID-19 in workplaces and residential buildings. These guidelines outline operational rules for installing effective HVAC systems to prevent the spread of infectious diseases such as COVID-19. The key recommendations to address viral spread include controlling air recirculation and increasing the inflow of outside air [40]. The primary factors contributing to the spread of COVID-19 are airborne virus/droplet transmission and inadequate BV in RACs. The diameter of the coronavirus ranges from 60 to 140 nm in its pleomorphic form [41]. Notably, currently used BVSs with filters typically have a diameter greater than 1 µm.

Researchers have investigated inadequate BV as a potential cause of the transmission of airborne diseases [30]. Pertinent studies have revealed an association between higher ventilation rates and a reduced risk of airborne infection transmission, including but not limited to viral agents. Studies have precisely pinpointed the spread of COVID-19 in RACs due to poor BV [42,43]. Jayaweera et al. [33] indicated BVS as a significant contributing factor to the expansion of COVID-19 in RACs. Sanglier-Contreras et al. [44] conducted a multivariate analysis to explore the association between poor BV and the global pandemic (coronavirus) in RACs in Spain. The authors had a similar opinion about poor BVSs and the increased risk of viral transmission. Domínguez-Amarillo et al. [45] investigated air quality, BV, and the risk of COVID-19 exposure during the lockdown and concurred with the increased chances of viral spread in RACs with poor ventilation. Other studies have emphasized the role of BV, mainly through HVAC systems, in preventing the spread of COVID-19 [28]. However, in contrast to the popular option, the findings regarding the spread of coronavirus through HVAC systems lacked strong evidence, as reported in a narrative review by Chirico et al. [46] in Italy. Nevertheless, most published articles reinforce the concept of HVAC playing a key role in the spread or control of viral infections.

HVAC systems can contribute to the spread of viral infections through air circulation in enclosed spaces with infected individuals. The recirculation of unfiltered air within an indoor environment is a key reason for the spread of the virus in closed spaces such as RACs. Airborne particles have the potential to disperse through the air circulation system, facilitated by BVSs in RACs [29]. de Man et al. [47] discussed that there is an elevated spread rate of COVID-19 among elderly residents and staff within RACs, irrespective of implemented preventive measures and established standards. An ineffective HVAC or ventilation system was identified as the key contributing factor, which circulated unfiltered indoor air, thereby facilitating the spread of COVID-19. Chow [43] investigated the environmental contamination and the primary route cause of the COVID-19 outbreak in RACs in Hong Kong. The authors argued that airborne viruses are spread due to the recirculation of unfiltered air in indoor spaces. Brass et al. [48] assessed the risk of viral transmission by measuring CO_2 level and ventilation rate (ACH) in RACs in South Australia. The authors highlighted staff-access rooms and common rooms as super-spreader zones in RACs. They recommended using optimized BV strategies such as HVAC systems to address such risks.

Researchers have investigated the transfer of aerosols and coronavirus through BVSs in RACs and general indoor environments. Various measures have been proposed to curb the spread in such indoor environments. Sun and Zhai [49] screened the efficacy of BVSs and implemented social distancing measures to control viral spread. The combination of social distancing and high ventilation efficiency has been shown to significantly reduce the transmission risk of COVID-19, particularly among older populations. The findings indicate that implementing these measures in indoor settings, such as RACs, can have a substantial impact. Specifically, reducing occupancy rates by 50% was found to lower the transmission risk by 20% to 40%. Other studies have highlighted environmental factors, including ventilation rate, air distribution systems, temperature, humidity, and others, as contributors to the increased spread of COVID-19 in indoor environments [50,51].

Controlled outdoor airflow has been proposed to isolate viral particles and increase the ventilation rate in RACs to reduce the risk of COVID-19 spread [18]. Similarly, open-building design has been highlighted as being more vulnerable to COVID-19 spread than closed-building plans [22]. Table 4 lists the main findings of the reviewed articles related to COVID-19 transmission through ventilation systems.

Table 4. Findings of reviewed articles concerning ventilation and COVID-19 spread in RACs.

References	Country	Study Design	Build Type	Aim	Assessment Tool/Method	Findings
de Man et al. [47]	The Netherlands	Experimental	Single Dutch nursing home	Poor ventilation results in COVID-19 spread	Retrospective cohort study, environmental pollution measures, differential transmission rate between aged people and staff	COVID-19 spreads due to inadequate BV systems and recirculated contaminated air
Brass et al. [48]	Australia	Experimental	RAC facilities	Assessment of CO_2-based ventilation in RACs to eliminate viral transmission	CO_2 sensor for monitoring in RACs, assessed the ventilation rate, and ACH determined by non-linear regression	High-risk viral transmission zones were identified by measuring the level of CO_2. Ventilation strategies proposed to curb viral spread.
Bentayeb et al. [52]	Europe	Experimental	Elderly Care Facilities; Nursing homes	Assessing the link between BV, air quality parameters, and COVID-19 spread	Questionnaires and medical examinations are used to assess air pollutants and ventilation measures	BV spreads infectious diseases and affects the IAQ in RACs
Chow [43]	Hong Kong	Narrative Review	Nursing home	Review care homes for COVID-19 spread	Source control approach, early intervention	RACs are more vulnerable to COVID-19 due to poor BV
Mouchtouri et al. [42]	Greece	Experimental	Nursing home; long-term care facility	Transmission of COVID due to BV and Environmental Contamination	Reverse transcriptase–polymerase chain reaction (RT-PCR)	COVID was spread due to inadequate mechanical BVS
Wang [50]	China	Narrative Review	Senior-living facility	Environmental factors' role in disease spread (COVID-19)	Quantitative and qualitative content analysis of guidelines for senior living facilities	Environmental, mechanical, design, and BVSs can control the COVID-19 spread
Sanglier-Contreras et al. [44]	Spain	Experimental	Nursing homes	Investigation of the link between BV and COVID-19 spread	Multivariate statistical analysis was used to report the relationship between total deaths and the number of residents.	Outcome status in terms of the number of deaths due to poor BV
Fadaei [53]	Iran	Systematic Review	RAC facilities	COVID-19 prevention through effective BVS	Systematic analysis to determine the BVS role in COVID-19 transmission	BV and AC systems, temperature, and humidity help prevent COVID-19
Morawska et al. [54]	Australia	Narrative Review	RAC facilities	Protecting workers, patients, and staff in RACs	Observational study of ventilation rate, air filtration, and disinfection factors in terms of COVID-19 transmission	Engineering controls for BVS, such as HVAC systems, eliminate COVID-19
Fadaei [51]	Iran	Systematic Review	Residential; indoor environment	Importance of ventilation in COVID-19 spread	Systematic review of 20 articles on the role of ventilation in preventing the spread of COVID-19	Effective BV, social distancing, disinfection, and decontamination control are proposed

Table 4. *Cont.*

References	Country	Study Design	Build Type	Aim	Assessment Tool/Method	Findings
Sopeyin et al. [22]	Africa	Narrative Review	RAC facilities	Evaluation of COVID-19 transmission in mechanical and natural BV environments	Interconnection between BVS (natural/mechanical) and COVID-19 spread was reviewed	Mechanical BV is more effective than natural ventilation in eliminating COVID-19 transmission
Jafri et al. [55]	Malaysia	Experimental	RAC facilities	Spread risk assessment of COVID-19 in RACs	Environmental and Epidemiological data were collected, and swab samples were gathered for lab investigation	Lack of natural BV causes COVID-19 to spread. 66.67% and 55.5% attack rate for residents and staff of RACs
Jayaweera et al. [33]	Sri Lanka	Narrative Review	RAC buildings	Investigation of airborne COVID-19 spread in indoor buildings	Literature on the transmission of COVID-19 due to aerosol, droplets, and ventilation was reviewed	Poor BV, droplets, and aerosols are responsible for COVID-19 transmission in RACs
Khaliq et al. [56]	UK	Experimental (Modelling)	Aged-care homes	Monitoring of environmental data and infection risk from COVID-19	CONTAM airflow model used for ventilation rate and CO_2 level measurement	Effective BVS is needed to increase the ventilation rate and reduce the COVID-19 spread
Somsen et al. [28]	The Netherlands	Experimental	Nursing homes; elderly care facilities	Droplet measurement and BVS to curb COVID-19 spread	Spray Scan laser sheet used for tracking droplets, comparison of mechanical and natural ventilation	Both droplets and BV are significant factors in COVID-19 transmission in poorly ventilated spaces
Chirico et al. [46]	Italy	Narrative Review	RACs; nursing homes	Evaluation of COVID-19 risk related to HVAC systems	Snowball strategy applied to highlight the risk of coronavirus spread due to AC and BV systems	Evidence is not established; more research and safety consultants are needed
Guo et al. [39]	China	Narrative Review	Indoor environment	The linkage between HVAC systems and COVID-19 spread	Observation and descriptive strategies used to determine BVS strategies in indoor environments	BV is of paramount importance in curbing coronavirus

3.2.3. Building Design and Spatial Layouts for Effective Ventilation

The influence of building forms and spatial designs of RACs on the spread of diseases was observed in eight (22%) reviewed articles. Building forms and spatial design affect the ease of movement and overall quality of life of building occupants. Orientation, window sizing, vents, and window openings are essential components of building forms and architectural designs in RACs [57]. Factors such as construction and building forms and layouts, building design, BV, and the number of residents and their routine activities are responsible for the likelihood of viral particle exposure [36]. Ventilation acts as a practical engineering approach to manage the transmission and diffusion of airborne natural BV, which was found to be more effective than mechanical and energy-driven BVSs in RACs in relevant studies [58].

An effective ventilation rate can decrease the risk of cross-infection from viral infections in RACs and indoor spaces. Mata et al. [36] highlighted the effect of BV on the indoor environment of RACs. Adequate BV and thermal comfort must be ensured to enhance IAQ within RACs, consequently helping to mitigate the spread or transfer of COVID-19 within RACs. Also, an effective BV rate per individual must be mandated in buildings, especially

RACs, where occupants such as elders, disabled people, staff, and workers spend most of their time in an indoor environment.

Designers and architects planning RACs need to consider implementing efficient BV strategies within rooms, incorporating green walls for shading, addressing safety concerns, and optimizing sunlight exposure [52]. The source control strategy has been shown to effectively minimize the indoor airborne spread of infectious diseases by incorporating intermittent gaps in building occupancy. This approach involves implementing periodic short intervals during which all occupants vacate the space, reducing the potential accumulation and transmission of airborne pathogens [34]. Recognizing the significance of green infrastructure is vital in establishing a connection between environmental factors, indoor design, and spatial distribution in RAC buildings. This approach aims to create an optimal experience for elderly individuals in terms of thermal comfort and visual perceptions through thoughtful designs of thermal-scape and air-scape spaces [59]. Thus, while such green spaces provide residents with a feeling of freshness, they also help limit the spread of airborne particles.

Built forms play a pivotal role in curbing the transmission of infectious diseases like COVID-19. The impact of the built forms, especially BV and spatial layouts, on COVID-19 spread in RACs remains an understudied area. The global pandemic has particularly exposed the vulnerabilities of elderly residents and staff members in RACs, emphasizing the urgent need for building re-designs or modifications that safeguard these community members from pandemics. Chow [43] argued that RACs with an open-plan layout were notably more vulnerable to the airborne transmission of the COVID-19 virus compared to buildings with a closed design. In these open-plan buildings, a significant number of elderly individuals could easily be exposed to asymptomatic carriers. Li [60] conducted a study evaluating the impact of layout and building design on RACs, revealing a substantial influence of the COVID-19 pandemic in three private aged-care facilities characterized by an open-plan structure. The viruses demonstrated a rapid spread in rooms with larger spaces and inadequate BVS. As a result, 71% of the cumulative COVID cases in Hong Kong occurred in RACs with an open-plan layout. In comparison, only 20 individuals were affected in buildings featuring separate bedrooms.

A poor BVS leads to the spread of diseases within indoor spaces. Buildings and BVS should be designed in a way that effectively expels most, if not all, pollutants generated within the catchment area. The efficiency of BVSs in RACs can be assessed by considering environmental factors such as IAQ, ventilation rate, aerosols, indoor viral particles, and thermal comfort conditions [61]. Substandard construction considerations, including inadequate natural BV and breaches in window frames and doorcases, are deemed unacceptable for RACs. These poor-quality construction works hinder effective air purification, particularly in the winter season, and pose a risk to the health of elders and staff, making them more susceptible to infectious diseases such as COVID-19 [33]. Presently, mechanical BVSs play a crucial role in recirculating indoor air and mixing it with the outdoor environment. A sustainable building design with an effective BVS is essential for combating COVID-19 infections in RACs [62].

Figure 6 presents a sustainable building design with respect to BV (natural/mechanical) systems for RAC facilities inspired by the study of Mata et al. [36]. As shown in Figure 6, a practical spatial layout of RACs involves multiple considerations. Firstly, it must have suitable living spaces for the residents, including communal lounges, canteens, and bedrooms. Secondly, attention must be given to the BVS and ensuring thermal comfort within these spaces. Thirdly, it is crucial to mitigate safety risks such as slips, falls, and scratches due to the restricted movement or general vulnerability of elderly residents. Also, incorporating indoor gardens is crucial to provide fresh air and facilitate natural BV. This can be complemented by mechanical HVAC systems (including demand control ventilation systems) as proposed by pertinent studies [57].

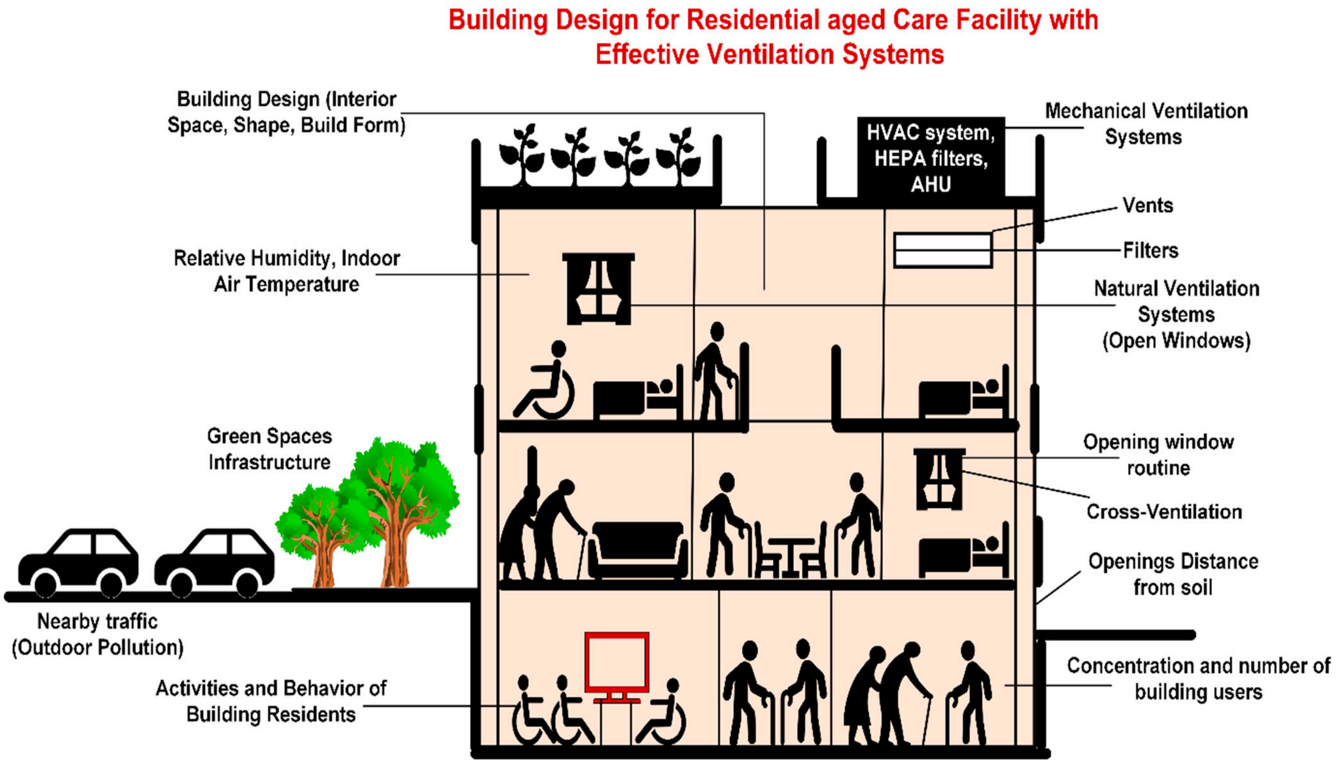

Figure 6. Proposed building design with effective ventilation systems for RACs. Developed by authors based on [36].

Emmanuel et al. [58] recommended the following design measures for ventilation in RACs:

1. Implementing cross-ventilation as an essential feature.
2. Ensuring open-ended corridors to guarantee an effective ventilation rate.
3. Use of hallways and closed-ended corridors must be avoided during a viral spread.
4. Installing ventilation louvers at doorsteps and placing upper ventilation windows on dividing walls of hallways to reduce hot air recirculation.
5. Rethinking the courtyard design to establish a cohesive ventilation route utilizing the courtyard area.

Figures 7 and 8 present the design considerations in light of Emmanuel et al.'s [58] recommendation, inspired by the study of Adly et al. [63]. As suggested, the design should follow an open corridor or courtyard ventilation structure, creating an integrated ventilation channel in RACs. This open-ended corridor or courtyard approach can enhance the ventilation rate and minimize the risk of COVID-19 exposure. As shown in Figure 7, an open corridor can help push clean air into the rooms and out of them through windows, hence reducing the recirculation of infected air in the building.

Similarly, Figure 8 shows a courtyard-based approach where all air from rooms is pushed outside into an open-ended courtyard that can be closed to the residents in case of viral infections. This way, infected air can be forced out of the building through natural BV without being recirculated in the building. In cases where natural BV is not feasible based on the building structure, adopting hybrid and mechanical BVSs is advisable.

The design considerations for hybrid and mechanical BVSs must be supplemented with other measures, including purifying the air to prevent the airborne spread of the virus and selecting and installing an efficient BVS for disinfecting and eradicating the coronavirus from RACs.

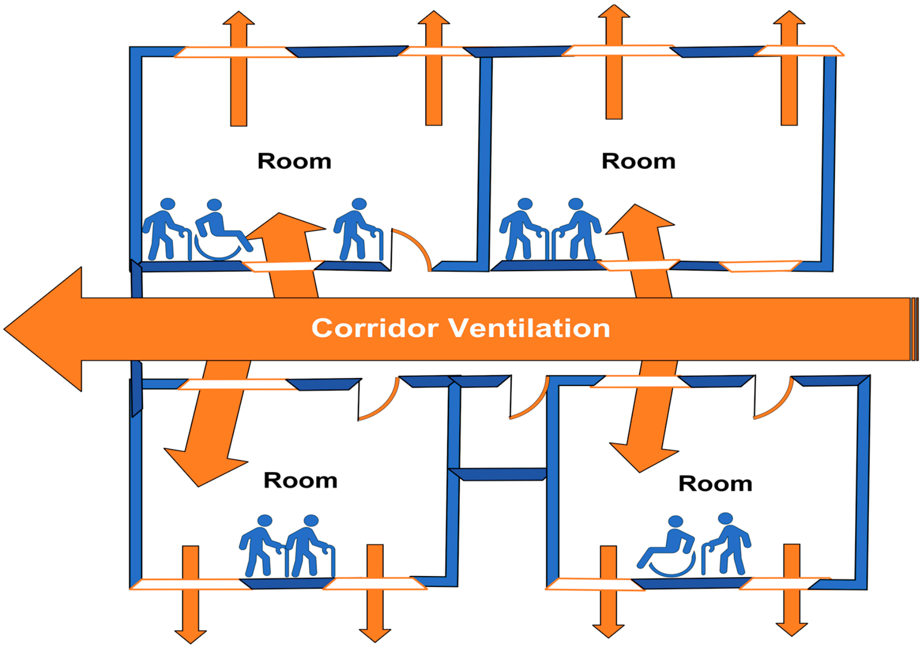

Figure 7. Open-ended corridor ventilation strategy in RACs. Developed by authors based on Adly et al. [63] and Emmanuel et al. [58].

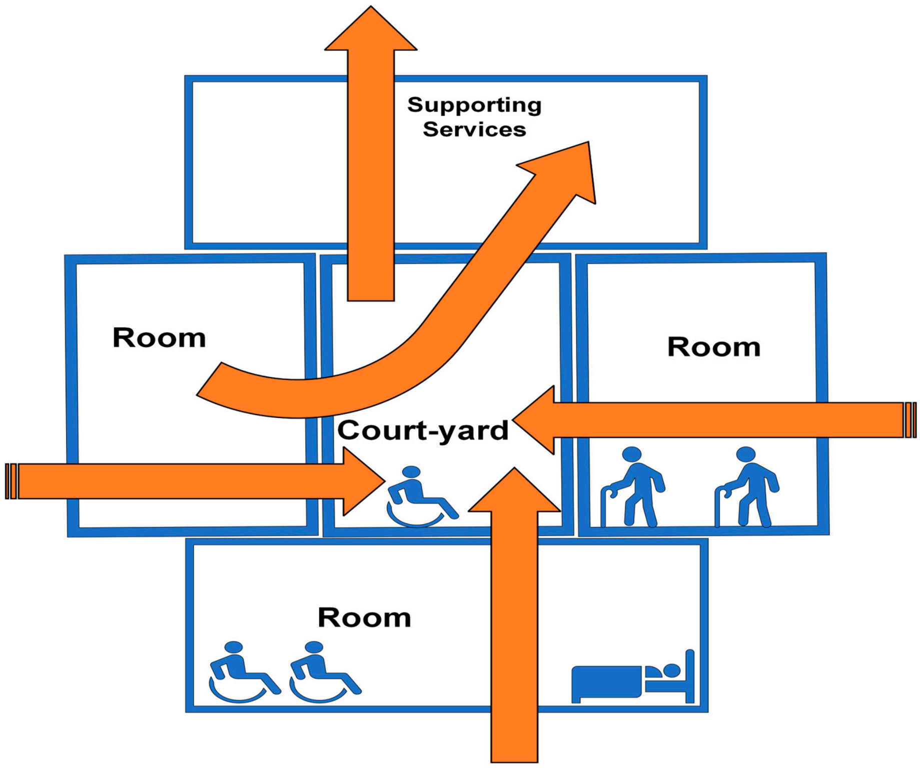

Figure 8. Courtyard-style ventilation strategy in RACs. Developed by authors based on Adly et al. [63] and Emmanuel et al. [58].

4. Regulations, Guidelines, and Recommendations for BVSs in RACs

Regulations, guidelines, standards, and policies have been proposed regarding building characteristics and design, particularly concerning BV and climatization equipment and operating systems for RACs. These policies were reviewed during the current study.

For example, the Building Code of Australia stipulates that RAC buildings must incorporate windows and allocate 10% of floor space for a natural BVS [64]. For ventilation systems in RACs, the Australasian Health Facility Guidelines, particularly AS1668.1-2015, and AC in buildings, Part 1: fire and smoke control in residential buildings for the use of ventilation, apply. The guidelines under AS:1668.2 apply to all mechanical BVSs in RACs. Similarly, AS:36661 applies to the installation of ventilation equipment in RACs. Other guidelines, such as the National Construction Code (NCC), Health and Safety (H&S) legislation, building design, ventilation system, and technical advice guidelines discussed in guidance material by the Australian Commission on Safety and Quality in Residential Care, also apply to RACs.

According to the Victorian Health and Human Services Building Authority [65], optimal BV strategies must be organized through a hierarchy of control strategies, and their consequences must be evaluated to prevent infectious disorders like COVID-19. Table 5 presents the strategies deemed essential for ensuring the well-being of elderly individuals, staff, visitors, contractors, and workers in RACs [51]. The key strategies include the provision of effective BVS, elimination of viral particles, replacement/mixing of air, engineering and administrative controls, and use of personal protective equipment [66]. Overall, the recommended interventions for enhancing the BVSs in RACs include the following:

1. Building design and construction must consider the specific requirements of the regional climate and optimize the temperatures for residents' routine activities.
2. Engineering controls such as dilution ventilation, HEPA filtration, UVGI systems, scavenging equipment, and physical barrier walls should be adopted.
3. A conventional infection control hierarchy, including elimination (a physical removal method for viral particles within spaces), replacement, engineering controls (segregating older people and infectious materials), and administrative controls (policies/practices to mitigate the risk of COVID-19 exposure), must be adopted.
4. Personal protective equipment (gloves, gowns, masks, etc.) must be put in place.
5. Specialized HVAC ventilation systems with appropriate interventions regarding humidity, airflow, ventilation rate, and temperature must be in place.
6. Effective BVSs and thermal comfort must be prioritized as primary solutions to enhance IAQ.
7. Smart BVSs should be used within indoor spaces that respond to emission events, such as opening windows during high-traffic hours and drawing activities.
8. A building evaluation or rating approach must be mandated for RACs, ensuring that building characteristics are sufficient for occupancy density to counter the spread of infectious diseases.
9. Automated air recirculation systems must be installed to maintain the ventilation rate and airflow in climatization systems based on real-time digital sensors and BVS.
10. Air cleaners must be a mandatory feature of RACs as a complementary approach to cleaning any residual viral particles from indoor air.
11. Awareness campaigns must be in place to inform all stakeholders, including managers and staff, about effective practices that can be implemented to enhance BVSs and IAQ.
12. Decision-makers, policymakers, and architects should emphasize the recognition of environmental factors within indoor spaces.
13. A detailed plan must be developed to address future pandemic scenarios, with a focus on environmental factors and BV.
14. Research should be conducted to continuously determine various conditions and optimal ranges of air quality and BV.

Table 5. Ventilation strategies and controls in RAC facilities.

Type of Controls	Examples of Ventilation Solutions
Elimination	Recirculating air within confined areas should be avoided. Reduce overcrowding and limit the usage of enclosed rooms. Avoid placing individuals infected with COVID-19 in rooms with positive airflow pressure. Use HEPA filters in all air supply systems.
Replacement Isolation	Replace existing split AC systems with smart HVAC systems and HEPA filters. Isolate infected individuals in suitably designed rooms that do not share air with other rooms.
Engineering Controls	Ensure that supply and exhaust systems comply with permissible air exchange standards (6 ACH for standard rooms; 12 ACH for rooms with infected individuals; 10 ACH for utility rooms to control odor). Modify HVAC controls to reduce the risk of COVID-19 exposure by introducing an adequate amount of outdoor air (ventilation rate), maintaining a temperature of 20–25 °C, achieving 40 to 60% relative humidity (using portable humidifiers), and controlling airflow direction. Enhance the air exchange rate in outdoor spaces and minimize the recirculation of unfiltered air. Use mechanical air filters (HEPA filters) or air cleaners to upgrade the existing BVS. Deploy portable air filtration units in corridors and rooms. Implement floor-to-ceiling filtration, such as physical barrier walls like ZipWalls, to inhibit airflow and separate clean areas (staff occupied) from infected spaces. Regularly disinfect the air using UV radiation in exhaust vents before the recirculation process. Ensure that BVSs along the air passage and ceiling are fully ducted to minimize leakage. Increase air exchange through exhaust air grills, variation in damper settings, and louvers for air supply.
Administrative Controls	A technician or engineer should properly monitor and clean filters, HVAC systems, purifiers, and humidifiers. Ensure regular testing and maintenance of BVS, including HEPA filters, and changing them according to the manufacturer’s specifications. Strictly adhere to relevant guidelines and standards. Monitor air quality, airflow, and air exchange per hour in all rooms and corridors regularly to prevent airborne viral infections. Minimize the usage of fans as they lead to an enhanced circulation of viral particles. Install smart BVSs to optimize energy consumption.
Personal Protective Equipment	All staff, workers, elderly people, and elderly people with disabilities should wear appropriate PPE during a transmission event. Use approved PPE during cleaning, maintenance, and installation of BVS.

Overall, effective BV strategies must be implemented to dilute indoor pollutants and regulate airflow patterns within indoor environments. Consequently, these measures can significantly reduce the transmission of airborne contaminants responsible for COVID-19 spread. The current study has both theoretical and practical implications. In terms of theoretical implications, the current study solicits pertinent research on the impacts of BV on infectious disease spread within RACs. Subsequent researchers can expand on each of the identified themes, particularly the design considerations presented in this study, and present guidelines and factors to be considered. Further, each control and strategy identified in the current study can be researched by future scientists to develop holistic policy frameworks. From a practical perspective, the current study provides valuable guidelines and aspects for architects, RAC managers and operators, government organizations, and policymakers to consider while designing, approving, or managing RACs and associated BVSs to help curb the spread of infectious diseases and save valuable lives.

5. Conclusions

The current review used a systematic literature review method to examine the impact of BV on the prevalence of COVID-19 in RACs. Three key themes were observed as emergent research hotspots in BV and its impact on infectious disease spread in RACs. These include types of building ventilation systems (reported by 28% of papers), the role of ventilation in COVID-19 spread (50%), and building design and spatial layouts for adequate ventilation (22%).

The primary findings of this review indicate that inadequate BV and poor air quality in RACs contribute to the proliferation of viral infections and pathogens in indoor environments. Environmental factors, including ventilation rate, air distribution, climatization systems, humidity, airflow, and temperature, are significantly responsible for the spread of COVID-19 and other infectious diseases in RACs. The current study further highlights that both mechanical and natural BVSs play a significant role in infection prevention and control of COVID-19 in RACs. While natural BV proves cost-effective, its efficacy may be affected by fluctuations in temperature and humidity. On the contrary, a mechanical BVS poses challenges due to high installation and maintenance costs, making them less viable in resource-limited buildings. Therefore, a hybrid approach is recommended for RAC facilities that use a mix of natural and mechanical BVSs for effective control of communicable diseases in RACs.

The current study also explored recommended building forms and spatial designs for RACs and presented guidelines emphasizing the necessity of installing appropriate BVS. It highlighted the critical importance of implementing hierarchical controls and adhering to policies and guidelines concerning the adoption of sustainable air purification and BVS. This includes the utilization of high-efficiency filters such as HEPA filters, UVGI, and HVAC systems. These measures are indispensable for effectively mitigating the transmission of infectious diseases such as COVID-19 within RACs. Further research is essential to guide RAC management, policymakers, and architects, ultimately aiding in the prevention of COVID-19 transmission in RACs.

The current study has certain limitations. First, a limited number of articles have been retrieved and reviewed, which can be expanded in the future. Second, the hotspots are limited to only three key areas due to the lower number of articles that future studies can expand on. Third, only three literary repositories, Scopus, WOS, and PubMed, are used in the current study. Fourth, the study does not consider non-governmental standards for review. Future researchers can consider papers from additional repositories and include non-governmental standards, such as ASHRAE Standard 241, which is a non-enforceable voluntary standard on infection control in housing. Similarly, the current study, due to its review nature, did not present a prototype design for RACs that future studies can target.

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Abbreviations

The following abbreviations are used in this manuscript:

BV	Building Ventilation
BVS	Building Ventilation System
RAC	Residential Aged Care
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
WoS	Web of Science
COVID-19	Coronavirus Disease 2019
HEPA	High-Efficiency Particulate Air
UVGI	Ultraviolet Germicidal Irradiation
UV	Ultraviolet
HVAC	Heating, Ventilation, and Air Conditioning
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers

UKRI	United Kingdom Research and Innovation
NHS	National Health Service
PTAC	Packaged Terminal Air Conditioners
MVHR	Mechanical BV units with Heat Recovery
AHU	Air Handling Units
IAQ	Indoor Air Quality
ACH	Air Changes per Hour
REHVA	Federation of European Heating, Ventilation, and Air-Conditioning Associations

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