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COVID-19: Research Directions for Non-Clinical Aerosol-Generating Facilities in the Built Environment

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Abstract: Physical contact and respiratory droplet transmission have been widely regarded as the main routes of COVID-19 infection. However, mounting evidence has unveiled the risk of aerosol transmission of the virus. Whereas caution has been taken to avoid this risk in association with clinical facilities, facilities such as spa pools and Jacuzzis, which are characterized by bubble-aerosol generation, high bather loads, and limited turnover rates, may promote aerosol transmission. Focusing on these non-clinical facilities in the built environment, a review study was undertaken. First, the typical water disinfection and ventilation-aided operations for the facilities were illustrated. Second, cross comparisons were made between the applicable standards and guidelines of the World Health Organization and countries including Australia, Canada, China, the United Kingdom, and the United States. The similarities and differences in their water quality specifications, ventilation requirements, and air quality enhancement measures were identified; there were no specific regulations for preventing aerosol transmission at those aerosol-generating facilities. Third, a qualitative review of research publications revealed the emergence of studies on potential air-borne transmission of COVID-19, but research on built facilities posing high risks of aerosol transmission remains scant. This study's results inform key directions for future research on abating aerosol transmission of COVID-19: the development of bespoke personal protective equipment and engineering and management controls on water quality, ventilation, and air quality.

Keywords: aerosol; air quality; COVID-19; SARS-CoV-2; ventilation; water quality

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1. Introduction

Coronavirus disease 2019 (COVID-19) has triggered a world-wide pandemic, causing over 2.3 million deaths [1]. COVID-19 transmissibility, as reflected by its reproductive number, 2.87 [2], is much higher than influenza and other, similar types of human coronavirus [3,4]. Moreover, genetic mutations of the virus may further boost the infectious risk [5–8].

At the beginning of the COVID-19 outbreak, physical contact with pathogen carriers and droplet transmission were generally regarded as the dominant paths for transmitting COVID-19. However, mounting evidence suggests that other transmission paths have become apparent. In a hospital in Wuhan, China, researchers found that the concentration of SARS-CoV-2-RNA-laden aerosol was exceptionally high in crowded gathering places and poorly ventilated areas used by infected persons (e.g., toilet areas: 19 copies/m^3, main entrance: 11 copies/m^3), although negligible concentrations were found in most patient areas that are designed with negative pressurization and high air exchange rates [9]. Another study in Singapore found a much higher concentration of SARS-CoV-2 RNA in the airborne infection isolation rooms (AIIRs), which ranged from 1.84×10^3 to 3.38×10^3 copies/m^3 air sampled with particle sizes larger than 1 μm [10].

In mid-2020, around 240 scientists from 32 countries wrote an open letter to the World Health Organization (WHO) arguing that there was growing evidence for the spread of COVID-19 through opportunistic airborne transmission, especially in indoor environments with certain special uses (e.g., otorhinolaryngologic procedures) [11,12]. Around the same time, the National Health Commission, the State Administration of Traditional Chinese Medicine, and the WHO acknowledged the possibility of aerosol transmission in some indoor environments (e.g., due to insufficient ventilation, high aerosol concentrations) [13,14].

In the healthcare sector, the risk of COVID-19 transmission associated with aerosols generated from clinical facilities has been well-recognized. Therefore, caution has been taken to address this risk. In non-clinical areas of the built environment, facilities such as spa pools and Jacuzzis, which are characterized by bubble-aerosol generation, high bather loads, and limited turnover rates, may also promote aerosol-borne COVID-19 transmission. However, studies on such facilities are limited.

To contribute to the understanding of information or research outcomes that are conducive to mitigating the risk of COVID-19 transmission via non-clinical aerosol-generating facilities, this present study conducted a literature review of relevant national/international standards, leading professional guidelines, and top-notch research publications. Based upon the review findings, directions for future research were identified.

2. Methods and Materials

To facilitate a contemporary review of information on both the practice and research sides of this dynamic and critical public health issue, a series of search and review processes were implemented: namely, (i) Stage I—general search, (ii) Stage II—refined search, (iii) Stage III—screening, and (iv) Stage IV—snowball review. In Stage I, keywords including "COVID-19", "SARS-CoV-2", "aerosol", and "pool" were used in multi-combinations for sourcing the relevant literature (between 2000 and 2020) in Scopus, ScienceDirect, and Web of Science. This resulted in a total of 4750 publications, of which 77.4 percent were from Scopus, 19.2 percent from ScienceDirect, and 3.4 percent from Web of Science. Considering the abundance of such literature, a refined search was conducted in Stage II. In this stage, keywords including "COVID-19", "aerosol", and "pool" were used in combination and, because COVID-19 emerged in 2019, the articles covered were from 2019 up to the moment when the search process was implemented. Because the severe acute respiratory syndrome (SARS) was also due to coronavirus, a further series of searches were performed using the keywords "SARS", "aerosol", and "pool". Hence, approximately 1000 articles were identified. In Stage III, these articles were screened manually for their relevance by scrutinizing their titles, abstracts, and content. In Stage IV, articles accordingly found to be relevant were used to snowball the initial sample frame using the reference list within each publication to identify other relevant publications for inclusion in the review process. As some limitations existed in the review process—for example, some guidelines and standards may not have been considered as literature in the above-mentioned databases—a complementary search was conducted to fill the search gap for aerosol-rich facilities and virus spread containment measures and acquire relevant publications from the WHO and renowned professional institutions in countries including Australia, Canada, China, the United Kingdom, and the United States.

3. Aerosol Transmission and Aerosol-Rich Facilities

3.1. Mechanism of Aerosol Transmission

Aerosol transmission is a key factor in severe epidemics [15]. Aerosols can be considered as tiny droplets (also referred to as "droplet nuclei" or "respirable droplets") that may reach the susceptible lower respiratory tract without being trapped by mucus or cilia. Compared to aerosols, droplets are large particles that can be generated by close expiratory events and may eventually deposit onto mucous membranes [16]. Any human expiratory events (i.e., coughing, sneezing, laughing, talking, breathing, etc.) may generate both droplets and aerosols, whereas the latter is more prevalent [17]. Droplet transmission is a short-range path with gravitational settlement within a short duration, typically within seconds [16,18], whereas aerosols, due to their long suspension times (e.g., 8 to 10 min for droplet nuclei of 4 µm) in stagnant air environments [19], are transmitted over long-range paths.

Aerosols can contain traces of SARS-CoV-2, which survive longer than other respiratory viruses and remain viable and infectious for 3 h [20,21]. The medical industry has been alerted to aerosol-generating procedures (e.g., the use of 3-way syringes in dental settings, intubation during surgeries and endoscopy) [22,23]. To effectively reduce infection probability, scholars also considered the importance of ventilation rate and air distribution pattern on top of social distancing to reduce human exposure to aerosols [24,25]. Mathematical models indicated that quintupling the standard ventilation could gradually reduce the infection rate while doubling the ventilation rate could delay the infection peak to more than two times the original period [26].

3.2. Aerosol-Rich Facilities

Although some researchers had highlighted the importance of building engineering controls to reduce indoor aerosol transmission in public buildings and public transport facilities [27], strategic aerosol control measures for indoor aerosol-generating facilities have received limited attention. In fact, spa pools and similar facilities (such as hot tubs and whirlpools) for recreational, wellness, or therapeutic purposes are not only found on private premises (e.g., club houses) but also are prevalent in venues of the health, tourism, and leisure sector, which is a USD 100 billion market [28]. Facility users are exposed to high concentrations of the aerosols generated.

A spa pool involves an air injection system that generates air and water bubbles to produce a relaxing sensation against human skin. Due to the difference in density, bubble films (i.e., air bubbles) originating from water turbulence will rise to the water surface and then burst into film droplets and jet droplets above the water surface (see Figure 1). Jet droplets differed in size in the range of 100 µm, whereas bubbles with diameters of several millimeters could produce film droplets with diameters ranging mostly from 2 µm to 10 µm. These film droplets constitute aerosols that can be inhaled into the lung's alveolar region [29–31].

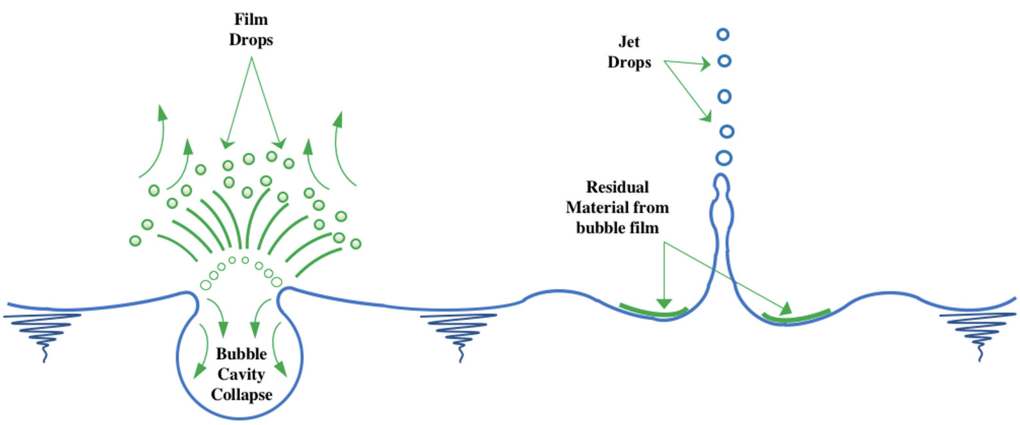

Figure 1. Formation of film droplets and jet droplets.

Although standard maintenance and operation (e.g., adequate free chlorine level and frequent cleaning) may prevent water contamination, virus-containing aerosols generated by any expiratory events of carriers or infected persons may trigger cross-contamination of the aerosols in the confined space. During the use of spa pools, general precautions (e.g., wearing a mask, social distancing, and pre-bath hygiene) cannot be taken to avoid direct exposure to high aerosol-related microbiological risk. Unlike general pool facilities, spa pools are characterized by high temperatures, large surface area to volume ratios, high bather density, more biofilms, and long usage periods; a confined setting may further increase the concentration of contaminated aerosols, against which standard water treatment is not a panacea [32].

An outbreak of COVID-19 in a public bath center in Huai'an, China infected at least eight individuals and may have been related to aerosol transmission [33,34]. Another outbreak, occurring on the Diamond Princess cruise ship, indicated a high possibility of passenger-to-passenger-dominated transmission in a confined setting. Note that the first infected person in this outbreak had used spa pools. Studies also found that the overall mean reproduction number (R0) reached up to 11 before any enhanced quarantine controls were implemented in this case [34]; preliminary findings showed that airborne transmission was the main route to the outbreak on the cruise ship [35,36].

3.3. Virus Spread Containment Measures

3.3.1. Water Disinfection

A proper water treatment system safeguards users against contaminated water. It is a robust process involving multiple stages of treatment (see Figure 2): (1) filtration—removal of suspended impurities and small particles by filters; (2) ozone disinfection—a secondary treatment to alter the chemical structure of water contaminants such as impurities and disinfect by-products (e.g., chloramines, trihalomethane [THM] precursors) through oxidation effects; (3) ultraviolet (UV) radiation—another secondary treatment to induce mutagenic deoxyribonucleic acid (DNA) lesions to inactivate various types of pathogens (e.g., CoV, MRSA) [37,38]; and (4) chemical dosing—using chemicals (e.g., chlorine) to provide further instant disinfection and ongoing disinfection.

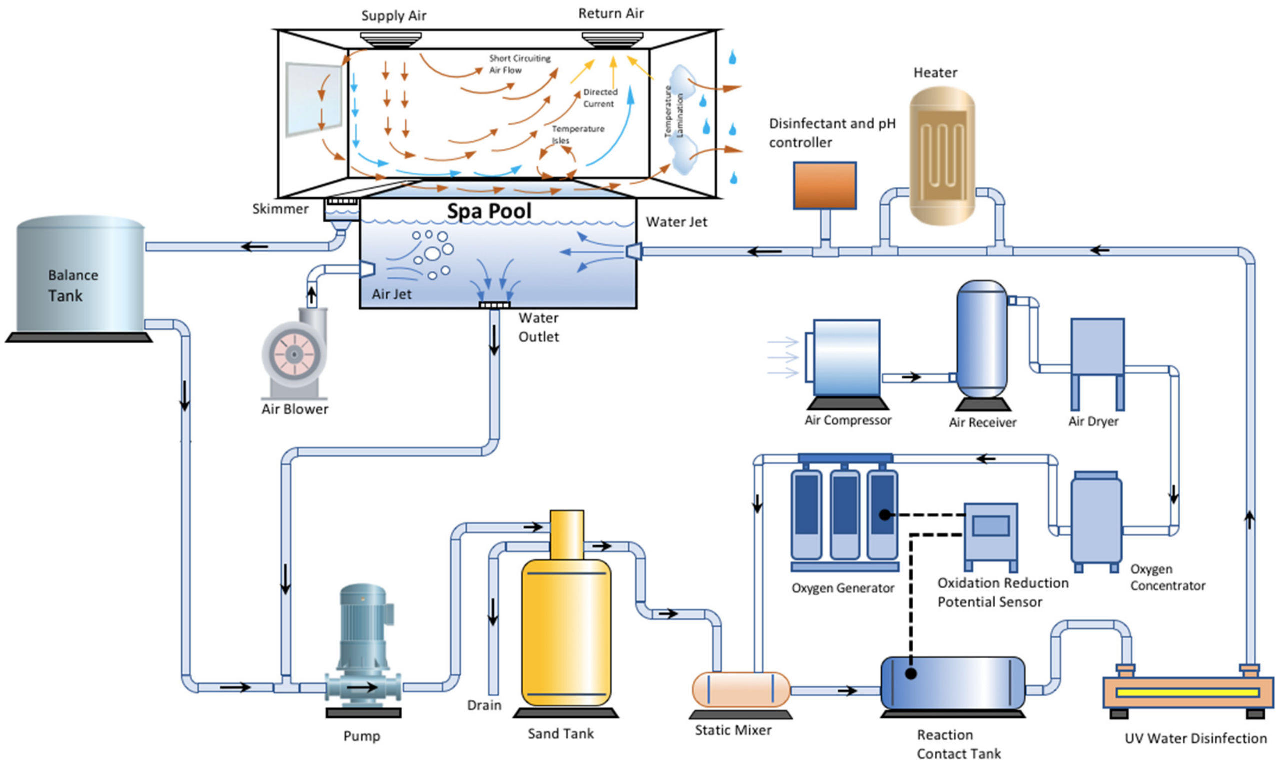

Figure 2. Typical spa pool water treatment system.

With the disinfection afforded by a water treatment system, inevitably formed aerosols (i.e., film droplets) above the water surface have no pathogens to attach to. However, biofilms and contaminated materials arising from facility users (e.g., hair, fat, fecal release, urine, sweat, nasal secretions, saliva, mucus, and skin flakes) are resistant to the disinfection effectiveness. Moreover, spa pools are usually designed with complicated and concealed small pipe systems, which facilitates the formation of biofilms [39]. Reportedly, germs under the protection of biofilms cannot be killed under standard chlorine levels [32]. COVID-19 might also potentially spread through fecal-oral transmission in recreational water as COVID-19 fragments detected in fecal matter could survive in water for up to 10 days [40,41]. Until now, there has been limited evidence that COVID-19 can spread through water sources [42]; water subject to robust water treatment does not appear favorable for the survival of COVID-19.

To monitor both the effectiveness of the disinfection facilities and water quality of pool facilities, different parameters such as free residual chlorine, pH value, total bacteria count, *Escherichia coli* level, and turbidity have been established. Public health authorities, including the WHO and those in Australia, Canada, Hong Kong, the U.K., and the U.S., have published guidelines on health protection for use of spa pools (Table 1). These guidelines cover three key issues, namely, water quality, sampling frequency, and operation and maintenance.

Pool water quality significantly depends on the level of free chlorine and pH value. While almost all the above guidelines follow the WHO's recommendations (i.e., minimum of 2 ppm for free chlorine and a pH value between 7.2 and 7.8), some regions (e.g., Hong Kong, the U.K., the U.S.) have their own guidelines, allowing up to 5 ppm free chlorine for better disinfection against high bather load. Other water-balancing parameters (for those specified), such as total alkalinity used to prevent pH fluctuation and calcium hardness used to avoid corrosion or scaling, fall within the ranges of 60–200 mg/mL and 75–800 mg/mL, respectively. Most of the guidelines cover parameters of microbiological quality, such as total bacteria count and level of *E. coli*. In contrast, only some specific guidelines provide recommended limits on bacteria including *Pseudomonas Aeruginosa*, *Legionella*, and *Staphylococcus Aureus*. In addition to the above parameters, requirements on pertaining to operation and maintenance activities (e.g., regular draining and routine backwashing) are also given.

Table 1. Water quality specifications for spa pools.

		WHO: Guidelines For Safe Recreational Water Environments Volume 2 Swimming Pools and Similar Environments	Centre for Health Protection, HKSARG: Guidelines on Infection Control of Commercial Spa Pools	Queensland Health: Water Quality Guidelines for Public Aquatic Facilities	ANSI/APSP/ICC-11-2019: American National Standard for Water Quality in Public Pools and Spas	HSE, U.K.: The Control of Legionella and Other Infectious Agents in Spa-Pool Systems	Newfoundland and Labrador: Public Pool Standards and Guidelines
System Disinfection	Turnover Rate (min)	5–20	Not Specified	20–30	Not Specified	6–15	Not Specified
	Free chlorine (ppm)	2–3 (Twice daily)	3–5 (Twice daily)	≥3 (Five times daily [(i)])	2–5 (Hourly)	3–5 (Daily at opening and every two hours thereafter)	1.5 (Class A Pool); 2–3 (Class B Pool) [(iii)]; (1/2 h before opening and every four hours thereafter)
	Combined chlorine (ppm)	ideally <0.2	≤1 (Twice daily)	≤1, ideally <0.2 (Five times daily)	≤0.4 (Hourly)	≤1 (Ditto)	≤0.5 (Ditto)
Water balance	pH value	7.2–7.8 (Several times a day)	7.2–7.8 (Twice daily)	7.2–7.8 (Five times daily)	7.2–7.8 (Twice daily)	7.0–7.6 (Ditto)	7.2–7.8 (Ditto)
	Total alkalinity (mg/L)	Not specified	80–200 (Not specified)	80–120 (Weekly)	60–180 (Once daily)	Not specified	80–120 (Weekly, Class A; Daily, Class B)
Microbiological quality	Calcium hardness (mg/L)	Not specified	75–150 (Not specified)	Not specified (Weekly)	100–800 (Once daily)	Not specified	200–300 (Weekly)
	Total bacteria count (CFU/mL)	Not specified	≤200 (Monthly)	≤100 (Monthly)	≤200 (Not specified)	<100 (Monthly)	<250 (Not specified)
	Escherichia coli (CFU/100 mL)	<1 (Monthly)	0 (Monthly)	<1 (Monthly)	<2 (Not specified)	<1 (Monthly)	0 (Not specified)
	Pseudomonas aeruginosa (CFU/100 mL)	<1 (Weekly)	Not specified	<1 (Monthly)	Not specified	<10 (Monthly)	<10 (Not specified)

Table 1. *Cont.*

		WHO: Guidelines For Safe Recreational Water Environments Volume 2 Swimming Pools and Similar Environments	Centre for Health Protection, HKSARG: Guidelines on Infection Control of Commercial Spa Pools	Queensland Health: Water Quality Guidelines for Public Aquatic Facilities	ANSI/APSP/ICC-11-2019: American National Standard for Water Quality in Public Pools and Spas	HSE, U.K.: The Control of Legionella and Other Infectious Agents in Spa-Pool Systems	Newfoundland and Labrador: Public Pool Standards and Guidelines
	Legionella (CFU/100 mL)	<1 (Monthly)	Not specified	Not specified	Not specified	<100 (Quarterly)	Not specified
	Staphylococcus aureus (CFU/100 mL)	<100 (Not specified)	Not specified	Not specified	Not specified	Not specified	<50 (Not specified)
Clarity	Turbidity (NTU)	≤0.5 (Not specified)	≤0.5 (Once daily)	≤0.5 (Once daily)	Visible	Total dissolved solids (TDS) ≤1000 ppm (Daily)	(Not specified)
Notes		-	Drain the pool weekly; backwash filters weekly; cleanse pool, equipment, and pool surrounding daily	Highly recommended to use secondary disinfectant (e.g., UV and ozone)	Recommend complete draining instead of gradual water replacement based on given formula (ii)	Backwashing should be done after the last user of the day; total volume should be drained weekly	-

Notes: (i) Queensland Government allows "once-daily" sampling for pool facilities with automated monitoring; (ii) Water replacement interval (WRI) = (0.33) × (Spa volume in gallons)/(Number of bathers per day since last change); (iii) "Class A Pool" and "Class B Pool" are defined in R.R.O. 1990, REGULATION 565, Health Protection and Promotion Act.

3.3.2. Ventilation-Aided Operation

In indoor venues with spa pools or similar facilities, generated aerosols could accumulate, although mechanical ventilation could help remove such aerosols. Recommended ventilation requirements for spa pools or similar facilities in Australia, China, Hong Kong, the U.K., and the U.S. are summarized in Table 2.

Table 2. Ventilation requirements for spa pools or similar facilities.

	Australia	China	Hong Kong	U.K.	U.S.	U.S.
Guideline/ Codes	Code of Practice for the Design, Construction, Operation, Management & Maintenance of Aquatic Facilities	GB 37488-2012: Hygienic indicators and limits for public places	Guidelines on Infection Control of Commercial Spa Pools	HSG 282—The control of legionella and other infectious agents in spa-pool systems	ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality	California Mechanical Code 2016
Ventilation requirement	10 L/s (per person), or 10 $L/s/m^2$ (of wet area)	Min. outdoor air: 20 m^3/h per person (i.e., 5.56 L/s/p), $CO_2 \leq$ 1500 ppm, bacterial concentrations $\leq$ 4000 CFU/m^3	N.A. (ventilation should be of 6 to 12 air changes per hour)	10–15 $L/s/m^2$ (of wet area)	3.2 $L/s/m^2$ (of wet area) (akin to general swimming pool)	Negative pressure, min. outdoor air change: 2 (min.); 6 (for hospital hydrotherapy setting)

The standard published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) requires the same ventilation requirement for swimming pools to be applicable to spa pools, while the standards of the U.K. and Australia impose a higher ventilation requirement (i.e., 10 $L/s/m^2$) on spa pools. Comparatively, the California Mechanical Code 2016 provides more ventilation requirements, namely: negative pressure, minimum outdoor air provision, and total indoor air change, but these are mainly for hospital hydrotherapy settings. Hong Kong's Guidelines stipulate a high air exchange rate for spa pools but a minimum for outdoor air exchange is not specified. In China, the GB standard sets limits on indoor CO_2 concentration and microbiological indoor air quality as ventilation controls for public facilities, which cover public bath centers.

A universal standard of ventilation requirements for spa pools was not found from the above review. In places where the recommended ventilation rates are set with a range of values, facility owners or operators may select a low ventilation rate or even the lowest limit to minimize energy consumption. By virtue of technological advancement, some engineering systems such as regenerative energy conservation and demand control ventilation have been developed to further reduce energy consumption [43]. However, the resultant decrease in ventilation may weaken the effectiveness of infection control during the COVID-19 pandemic.

Professional institutions including the ASHRAE, the Indian Society of Heating, Refrigerating & Air Conditioning Engineers (ISHRAE), the Chartered Institution of Building Services Engineers (CIBSE), the International Facility Management Association (IFMA), and the China Property Management Institute (CPMI) have published guidelines for guarding against COVID-19. To minimize the growth of germs or accumulation of virus-carrying aerosols, the measures recommended for strengthening indoor air quality or ventilation are summarized in Table 3.

Table 3. Measures for strengthening indoor air quality or ventilation.

	Engineering Institutions				**Management Institutions**	
Measure	**ASHRAE: Guidance for Building Operations during the COVID-19 Pandemic; Position Document on Infectious Aerosols**	**ISHARE COVID-19 Guidance Document for Air Conditioning and Ventilation**	**REHVA COVID-19 Guidance**	**CIBSE COVID-19 Ventilation Guidance**	**IFMA Pandemic Manual**	**CPMI: Technical Guidelines for the Operation Management of Air-conditioning Ventilation System in Public Buildings During the COVID-19 Epidemic**
1. Increase outdoor air rate	✔	✔	✔	✔	✔	✔
2. Bypass energy recovery ventilation system with potential air leakage	✔	✔	✔	✔	-	✔
3. Provide full fresh air supply (No use of recirculated air)	✔	(For quarantine areas and COVID-19 patient area and industrial facilities)	✔	✔	✔	✔
4. Upgrade central air filtration to MERV-13 or higher	✔	✔	-	-	✔	✔
5. Extend operating hours of HVAC systems	✔ (24/7 if possible)	✔ (Fresh air and ventilation system should be kept on throughout the off cycle and on the weekend and holidays in air circulation mode)	✔ (Start ventilation at nominal speed at least 2 h before the building usage time and switch to lower speed 2 h after the building usage time; keep the ventilation on 24/7 with lower ventilation rates when people are absent)		✔	✔ (Start the AC system 1 or 2 h before the building usage time)
6. Consider the use of portable room air cleaners with HEPA filters	✔	-	✔	✔	-	-

Table 3. *Cont.*

Measure	Engineering Institutions				Management Institutions	
	ASHRAE: Guidance for Building Operations during the COVID-19 Pandemic; Position Document on Infectious Aerosols	ISHARE COVID-19 Guidance Document for Air Conditioning and Ventilation	REHVA COVID-19 Guidance	CIBSE COVID-19 Ventilation Guidance	IFMA Pandemic Manual	CPMI: Technical Guidelines for the Operation Management of Air-conditioning Ventilation System in Public Buildings During the COVID-19 Epidemic
7. Consider the use of ultraviolet germicidal irradiation (UVGI)	✔ (For high-density spaces such as waiting rooms, prisons, and shelters)	✔ (For larger ducted units and AHUs)	✔ (Normally a suitable solution for healthcare facilities)		-	-
8. Adopt temperature and humidity control	✔ (As applicable to the infectious aerosols of concern)	✔ (Humidity: 40–70%; Temperature: 24–30 °C)	-	✔ (Maintain relative humidity above 40% wherever possible)	-	Properly increase supply air temperature and indoor temperature setpoint in summer, etc.
9. Replace filters/clean and disinfect HVAC coils	-	✔	As usual		✔	✔
10. Disable demand-controlled ventilation	✔	-	Change CO_2 setpoint to lower, 400 ppm value, in order to maintain the operation at nominal speed		-	-

Remark: For details of the above recommendations, please refer to the respective guidelines.

While the focuses of concern of the aforementioned six institutions belong to two disciplines, namely, engineering and management, they share common recommendations on the following measures: increase outdoor air rate and extend operating hours of heating, ventilation, and air-conditioning (HVAC) systems. Other common measures recommended by most of the engineering institutions are to bypass the energy recovery ventilation system with potential air leakage; consider the use of ultraviolet germicidal irradiation (UVGI); consider the use of portable room air cleaners with high-efficiency particulate air (HEPA) filters; and disable/adjust demand-control ventilation. On the management side, the IFMA and the CPMI both offer the following two recommendations: upgrade central air filtration to MERV-13 or higher; and replace filters/clean and disinfect HVAC coils.

The six institutions vary in their specific recommendations regarding extended hours of HVAC system operation and the adoption of temperature and humidity controls. For the former measure, for instance, the ASHRAE and the ISHRAE recommend operating the HVAC system on a 24/7 basis; the REHVA and the CIBSE recommend, *inter alia*, full-speed operation at least 2 h before building usage time and low-speed operation 2 h after building usage time; and the CPMI recommends starting the AC system 1 or 2 h before building usage time.

The above professional institutions' guidelines, which are specific for tackling COVID-19, may serve as reference in operating aerosol-rich facilities such as spa pools and installations. Because experience in applying these guidelines to indoor venues should be of reference value, it is worth investigating whether there are difficulties in implementing the recommended measures, and whether the measures are effective [44]. Consider the first recommended measure in Table 3 as an example—is it practicable to increase the outdoor air rate of an existing ventilation system? Caution should be exercised because the air duct size and fan capacity of such existing systems, which were fixed when the systems were installed, might not be fit for delivering extra amounts of outdoor air. Even if this is made possible by modifying the existing system, how much in additional system operating costs will be incurred? To what level can the inhalational exposure to airborne coronavirus be reduced? Such measures could have a ripple effect, leading to many more technical questions, not to mention environmental, financial and management issues (e.g., an increase in energy consumption stemming from the increase in the outdoor air rate). In addition, not all of the recommendations of the six institutions are identical; the reasons for their differences as well as any scientific grounds for the recommended settings also warrant future investigations.

4. Recent Research Efforts

Since the emergence of COVID-19, the research community has made various efforts to obtain findings that are conducive to the prevention, suppression, and/or elimination of the disease. In addition to the drive to identify the ways in which the virus is spread and new variants evolve, as reported below, research has been actively undertaken to investigate the critical factors of COVID-19 transmission and control and certification measures while battling the virus.

4.1. Spread and New Variants

According to the review of Morawska et al. [27], air samples taken from hospitals in Singapore, the U.S., and China revealed that aerosols could contain traces of SARS-CoV-2. COVID-19 ribonucleic acid (RNA) copies per liter of air vary within a range between 0.02 and 4.1. Through literature searches in various publication databases, Amoah et al. [45] found that virus-bearing aerosols may be formed during the transport of wastewater, which is a hotbed for COVID-19. Nevertheless, the signature refrain among health protection agencies (e.g., WHO) has been to call for more in-depth research to investigate this phenomenon in greater detail [46].

Using tracer gas testing, computational fluid dynamics simulations, and quantitative reverse transcription PCR (RT-qPCR) for the surface and air samples collected from a high-rise apartment building in Guangzhou, China, Kang et al. [47] recognized the circumstantial evidence supporting the spread of virus-containing fecal aerosols along the vertical stack.

Through a mega-data analysis of viral genome sequences, various new variants (i.e., multiple spike protein mutations) were identified. N501Y mutations, which dominated the rapid surge of infection cases in the U.K., were preliminarily more transmissible than previously circulating strains, with an estimated potential to increase the reproduction number (R_0) by 0.4 or greater [48].

4.2. Critical Factors

Through a literature search, Morawska and Cao [49] identified that sampling challenges and knowledge gaps between microbiologists and building scientists are major obstacles to achieving a global consensus amid the inherently false "droplet-borne versus airborne" dichotomy. In addition, the review research of Megahed and Ghoneim [50] identified insights of post-coronavirus architecture and urbanism: decentralization, urban farming, multi-modal transport, modular construction, hygienic building materials, artificial intelligence, and touchless technologies. By analyzing the counter-measures suggested in ventilation and air-conditioning-related guidelines, Guo et al. [51] pinpointed that the maximization of outdoor air flow, extension of ventilation systems, and portable room air cleaners were the common strategies to mitigate COVID-19 transmission.

Using correlation and regression analysis, Anthony Aroul Raj et al. [52] studied the dependence of mortality and infection rates in various Indian states with respect to climatic data. Findings revealed strong correlations between infection rates, air-conditioning usage, dry conditions, etc., as droplets exhaled from the human body may undergo size reductions through heat and mass transfer to colder, drier surrounding air and linger in the air for longer periods.

Using statistical analysis with the Riley model, Sun and Zhai [24] found that stay/exposure time, occupant density, and ventilation rates are key factors for low infection probability. Using CFD simulation, Leng et al. [53] analyzed geometric design parameters for the development of courtyards to ensure airborne disease control. If courtyard width varied from 5.8 m to 11.8 m, the average air pollutant concentration decreased by 80%. Whereas person-to-person pollutant exposure was found infeasible, passive building designs may be an alternative.

4.3. Control and Certification

Using an agent-based SEIIR model, Zhang et al. [54] analyzed the efficiency of different intervention strategies to prevent infection by the SARS-CoV-2 virus in Shenzhen, China. Whereas the existing control measures (e.g., quarantining arrivals and work stoppages) could not be deemed a panacea, the risk of infection could have been reduced by 50% if all symptomatic individuals had immediately gone to hospital for isolation, and 35% if a 14-day quarantine for arrivals from Hubei Province had been introduced one week earlier.

Using a tracer gas measurement test, Xu et al. [55] analyzed the effectiveness of personalized ventilation in protecting against airborne disease transmission between occupants. Under high clean air volumes, this air delivery system may be effective in disease control within indoor environments.

As certification can help guarantee that facilities have high ventilation rates and adequate occupancy, Blocken et al. [56] suggested implementation of an aerosol exposure-related certificate for sports centers, settings where users are exposed to a high risk of infection due to intensive inhalation.

5. Future Research Directions

Amid the fight against COVID-19, researchers in the scientific community have been unfailingly devoted to studying how the disease can be avoided, including investigating its transmission mechanisms. However, the above illustrates that research on COVID-19 transmission associated with aerosol-rich facilities such as spa pools remains scant.

With reference to the hierarchy of controls of the Centers for Disease Control and Prevention (CDC), a multi-pronged strategy comprising six aspects of controls (Figure 3) could be adopted to combat COVID-19 [44]. Undoubtedly, prevention is better than cure, and elimination and substitution are effective means of control to remove or replace the hazard (i.e., the coronavirus). This reduces the risk of infection and contains the risk of community outbreak, thus alleviating the pressure exerted upon the public healthcare system.

Figure 3. Multi-pronged strategy of controls [44].

Among the COVID-19 preventive measures are vaccines. Although vaccines have been developed for combating the coronavirus, a full picture of their effectiveness was unavailable at the time of this writing. Even if the vaccines are highly effective, vaccination does not always confer full immunity to virus infection. Further, because proven medicine for curing COVID-19 patients remains unavailable while elimination and substitution of the hazard are not guaranteed, continued effort should be made to pursue the remaining control strategies.

Social distancing, a notable example of administrative control, has been widely enforced by governments across the world since the COVID-19 outbreak. However, such control measures, which restrain personal freedom and undermine the economy, are often unwelcome. Therefore, further effort should be made to explore the control strategies in the remaining three aspects: (a) personal protective equipment (PPE); (b) engineering control; and (c) management control.

For PPE, facial masks have become a daily necessity for most people during the COVID-19 pandemic. However, special masks or respirators should be developed for users of facilities such as spa pools. Besides the effectiveness of shielding virus transmission and cost considerations, a prime objective for such devices should be that their use does not jeopardize users' enjoyment of spa pools.

For engineering control, research should be focused on the water treatment systems and mechanical ventilation systems for spa pools and similar facilities alike. Many questions need to be addressed by research studies on these issues. Consider the water treatment process as an example—can the typical water treatment mechanism effectively kill viruses before they attach to the aerosols generated from a burst of water bubbles? Are there any secondary treatment systems other than using ozone or UV? Are the water quality requirements in Table 1 sufficient for controlling COVID-19 transmission? Does the same question apply to the issues of ventilation and air quality (Tables 2 and 3)?

For research on management control, multiple questions again present themselves. For instance, are the existing preventive maintenance measures sufficient for assuring the hygiene of spa pools or similar facilities? Are the recommended measures on air quality (Table 3) sufficient for controlling COVID-19 transmission, especially for the prevention of aerosol exposure? In implementing such measures, are any challenges posed, for example, by building restrictions, cost constraints, or user requirements?

Applicable to the above three aspects (i.e., PPE, engineering control, and management control), development and application of innovative or smart technologies that enable automatic sensing, monitoring, and control functions for fighting against the spread of COVID-19 should also engender future research directions. Such technologies reside under the broad banner of Industry 4.0 and may include, for example, sensor-based networks to connect individual electronic sensors together to gather real-time data on a building's internal environment; the internet of things (IoT), to upload big data gathered from sensors to virtual servers that have greater and more-expedient computational power than local desktop computers; artificial intelligence to analyze and interpret data acquired to inform decision support and knowledge management within an organization; and augmented or virtual reality to visualize the internal environment, identify any problem areas, and communicate the results of analysis in a visually stimulating and accessible manner (cf. [57,58]). These technologies therefore have the innate capability to coalesce to provide automated systems that can continuously monitor and control an internal environment with precision (cf. [59]). As credible certification schemes for virus-free facilities can further give confidence to users of the facilities, research on the establishment and implementation of such schemes is also recommended.

6. Conclusions

Through a review of contemporary standards, guidelines, and research publications about COVID-19 and aerosol-rich facilities in the built environment, the findings of this study outlined aerosol transmission mechanisms and identified useful measures for containing the spread of the virus. Comparisons made between the standards and guidelines of the WHO and those applied within Australia, Canada, China, the United Kingdom, and the United States revealed similarities and differences in water quality specifications, ventilation requirements, and air quality enhancement measures. Such observations warrant that the differences be further investigated on scientific grounds.

A further significant observation from our review was that no specific regulations have been imposed to prevent aerosol transmission in facilities such as spa pools and Jacuzzis, which pose high risks of aerosol transmission. Studies on this topic remain limited, although research on potential air-borne transmission of COVID-19 has notably increased. Therefore, more research effort should be focused on investigating how the transmission of COVID-19 in such aerosol-rich facilities can be mitigated.

Combating COVID-19 entails a multi-pronged strategy that comprises hazard elimination, hazard substitution, the use of PPE, administrative control, engineering control, and management control. The results of this review suggest that apart from the administrative controls of governments and continuing efforts to develop medications for hazard elimination or substitution purposes, the remaining elements of the strategy require further in-depth study. Such future research will help to abate aerosol transmission of COVID-19 in our built environment and include (1) the development of bespoke PPE; (2) engineering control over water quality, ventilation, and air quality; and (3) management control (also over water quality, ventilation, and air quality).

Despite the above findings, our review study was not without limitations. First, the standards and guidelines reviewed were confined to those of the WHO and the countries we reviewed. In the future, similar review studies may be conducted with an extended scope of review, covering standards and guidelines in other countries internationally to gain a far broader perspective. Second, the reviewed journal articles were limited to those indexed in three major literature databases. Whereas these databases are renowned for their wide coverage of credentialed publications, efforts may be made in future studies to identify any useful literature that has not been included in the above review. In conclusion, this study reviewed and compared a disparate range of existing literature to foster wider debate and future "targeted" research investigations. The current pandemic has revealed weaknesses in current provisions to protect the health and well-being of the general public and national economies; such future investigations will be instrumental to the longer-term health and prosperity of the international community.

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