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An overview of solutions for airborne viral transmission reduction related to HVAC systems including liquid desiccant air-scrubbing

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A B S T R A C T

The spread of the coronavirus SARS-CoV-2 affects the health of people and the economy worldwide. As air transmits the virus, heating, ventilation and air-conditioning (HVAC) systems in buildings, enclosed spaces and public transport play a significant role in limiting the transmission of airborne pathogens at the expenses of increased energy consumption and possibly reduced thermal comfort. On the other hand, liquid desiccant technology could be adopted as an air scrubber to increase indoor air quality and inactivate pathogens through temperature and humidity control, making them less favourable to the growth, proliferation and infectivity of microorganisms. The objectives of this study are to review the role of HVAC in airborne viral transmission, estimate its energy penalty associated with the adoption of HVAC for transmission reduction and understand the potential of liquid desiccant technology. Factors affecting the inactivation of pathogens by liquid desiccant solutions and possible modifications to increase their heat and mass transfer and sanitising characteristics are also described, followed by an economic evaluation. It is concluded that the liquid desiccant technology could be beneficial in buildings (requiring humidity control or moisture removal in particular when viruses are likely to present) or in high-footfall enclosed spaces (during virus outbreaks).

1. Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a coronavirus of the β family with a diameter of 80−160 nm, responsible for causing the disease COVID-19 [1] and provokes the infection along the respiratory tract and pneumonia [2]. As of May 5, 2021, it killed over 3,200,000 people with over 155,000,000 reported infection cases [3]. Since the outbreak of the virus, different strategies have been implemented worldwide to limit its spread. These strategies, such as self-distancing (lockdown and quarantine) and frequent use of hand sanitisers, were initially drawn based on previous knowledge on transmission routes of influenza and coronaviruses [4]. Infection control strategies in buildings or enclosed spaces can be categorised as pathogen elimination, engineering control, administrative control and personal protection [5], as shown in Fig. 1, from the most to the least effective.

These strategies are not permanent measures. Whilst many countries imposed partial or full lockdown measures, there are examples across public transport, schools, hospitals and other public spaces where self-distancing measures may not be possible or effective, especially in high-footfall enclosed spaces. The engineering control strategies, such as increased ventilation rates and no use of air recirculation [1], increase energy consumption with negative environmental impact. Meanwhile, respiratory illnesses, such as flu, asthma, and tuberculosis (which may cause death [8] and are often associated with poor indoor air quality [9]), remain a global challenge. As such, identifying an engineering control strategy which can purify the air while ensuring high energy

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Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; $CaCl_2$, Calcium chloride; CIBSE, Chartered Institution of Building Services Engineers; COP, Coefficient of performance; COVID-19, Coronavirus disease 19; HCO_2K, Potassium formate; HEPA, High-efficiency particulate air filter; HVAC, Heating, ventilation and air-conditioning; IAQ, Indoor air quality; IBV, Infectious bronchitis virus; IL, Ionic liquid; LiBr, Lithium bromide; LiCl, Lithium chloride; MERS-CoV, Middle East respiratory syndrome coronavirus; MERV, Minimum efficiency reporting value; PRRSV, Porcine reproductive and respiratory syndrome virus; REHVA, Federation of European Heating, Ventilation and Air Conditioning Associations; SARS-CoV-1, Severe acute respiratory syndrome coronavirus 1; SARS-CoV-2, Severe acute respiratory syndrome coronavirus 2; TEG, Triethylene glycol; TGEV, Transmissible gastroenteritis virus; UVA, Long-wave ultraviolet light; UVB, Middle-wave ultraviolet light; UVC, Short-wave ultraviolet light; UVGI, Ultraviolet germicidal irradiation; WHO, World Health Organization.

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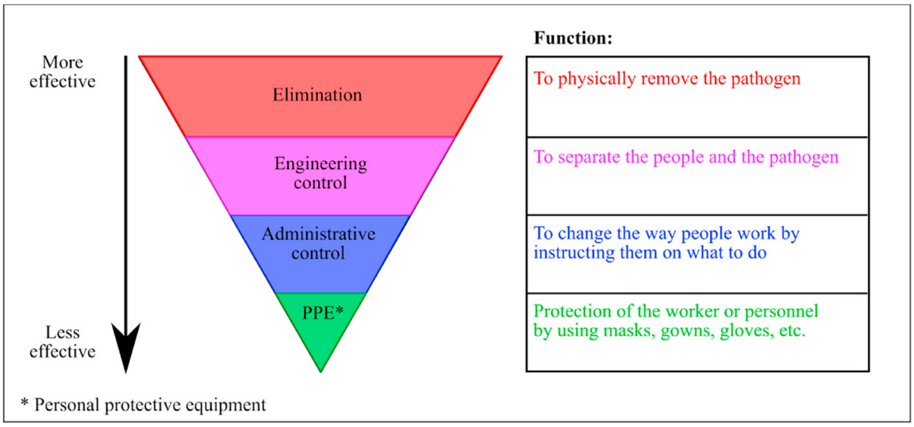

Fig. 1. Hierarchy of infection control strategies, adapted from Refs. [6,7].

performance in buildings and public transport has become a top priority [10]. Liquid desiccant technology could be an option because it offers the sanitising properties of desiccant solutions [11] with high energy efficiency in controlling the temperature and humidity of the air supplied [12].

This study focuses on factors affecting the transmission of SARS-CoV-2, common transmission patterns of other airborne viruses such as influenza, characteristics and drawbacks of HVAC strategies proposed for the reduction of airborne viral transmission in buildings, enclosed spaces and public transport. The energy and economic penalty imposed by these HVAC strategies was presented to highlight the potential benefits offered by the use of liquid desiccant technology. The article is structured as follows. **Section 2** describes the scope of the research, while **Sections 3** and **4** review the primary transmission routes of the virus and the effect of temperature and humidity on it. The HVAC strategies recommended by professional engineering associations to limit the transmission of airborne viruses are presented in **Section 5**. This is followed by **Section 6**, which describes the characteristics, sanitising properties, energy and economic impact of the liquid desiccant technology.

2. Scope

The scope of this study is shown in Fig. 2.

3. Transmission routes

SARS-CoV-2 is contagious with high secondary infection rates, large number of fatalities and rapid spread [13]. Its transmission might be similar to that of other coronaviruses (such as SARS-CoV-1 [14] and MERS-CoV [4]) through droplets, aerosols, and faecal-oral transmission. Appendix 1 explains these routes together with a summary of the previous research on the topic. Fig. 3 shows the production of droplets and aerosols, their main transmission routes, trajectories of transmission in the air, and the relationship between particle size and suspension time. The settling time of exhaled or expelled particles is affected by various factors, including size, time and evaporation [15]. The motion of the particles is the result of different forces acting on them, such as gravity, temperature and humidity, Brownian motion, electrical and electromagnetic forces, and turbulence [16]. For droplets larger than 20 μm, ballistic trajectories due to gravity are mainly observed [17]. Due to the characteristics of their movement in the air, engineering strategies for infection control based on the use of air ventilation and pressure differentials are not effective on such particles and do not affect their short-range transmission [18]. As the diameter of the exhaled or expelled particle decreases, the effect of the gravity on the particles becomes less important, increasing their suspension time and resulting in the potential to travel longer distances in buildings or enclosed spaces [17].

4. Effect of temperature and humidity

The effects of external factors on reducing the transmission of viruses is shown in Table 1 [22].

Different studies have tried to determine the behaviour of SARS-CoV-2 and investigate the effect of air conditions (covering parameters such as temperature, *T*, relative humidity, *RH*, and moisture content, ω) on its transmission to explore its potential seasonality [23] and understand the effectiveness of HVAC strategies in buildings and enclosed spaces [24]. Appendix 2 presents a summary of these studies.

The control of the temperature and humidity in the air supplied to buildings is key for thermal comfort, air quality and building conservation [25]. Whilst high temperature inactivates viruses as a result of denaturation of the surface proteins and nucleic acids of viruses [26], the correlation with humidity is more complex. Particularly, any environment with extremely high or low values of RH would stimulate the growth of viruses, bacteria, moulds, *etc.* [27], as shown in Fig. 4 where the height of the blue bars is related to the effect presented by the organisms on the health of occupants. It is clear from Fig. 4 how no level of relative humidity is capable of fully suppressing the risks presented for human health by viruses, bacteria and biological organisms and the optimum RH range shown there is considered as a good compromise between adverse health effects occurring at both low and high levels of RH. For viruses responsible for respiratory infections, the RH of the air supplied should be controlled between 40% and 60% to limit the infectivity and mobility of lipid and non-lipid membrane viruses [5] and improve the defence mechanisms of the human respiratory system. In current practice, RH in buildings is also kept below 60% to avoid the growth of mould, harmful for building occupants and potentially responsible for structural damage to the building.

Whilst low temperature and humidity have been associated with higher infection rates for COVID-19 [23], outbreaks in conditions of high temperature and humidity were also observed, as evidenced by the outbreak in a bath centre [28]. Time of contact could play a remarkable role in the transmission of the virus [29]. The realisation of an environment that is less likely to favour the spread of the disease by controlling the temperature and humidity of the air supplied within the optimal range, as recommended by

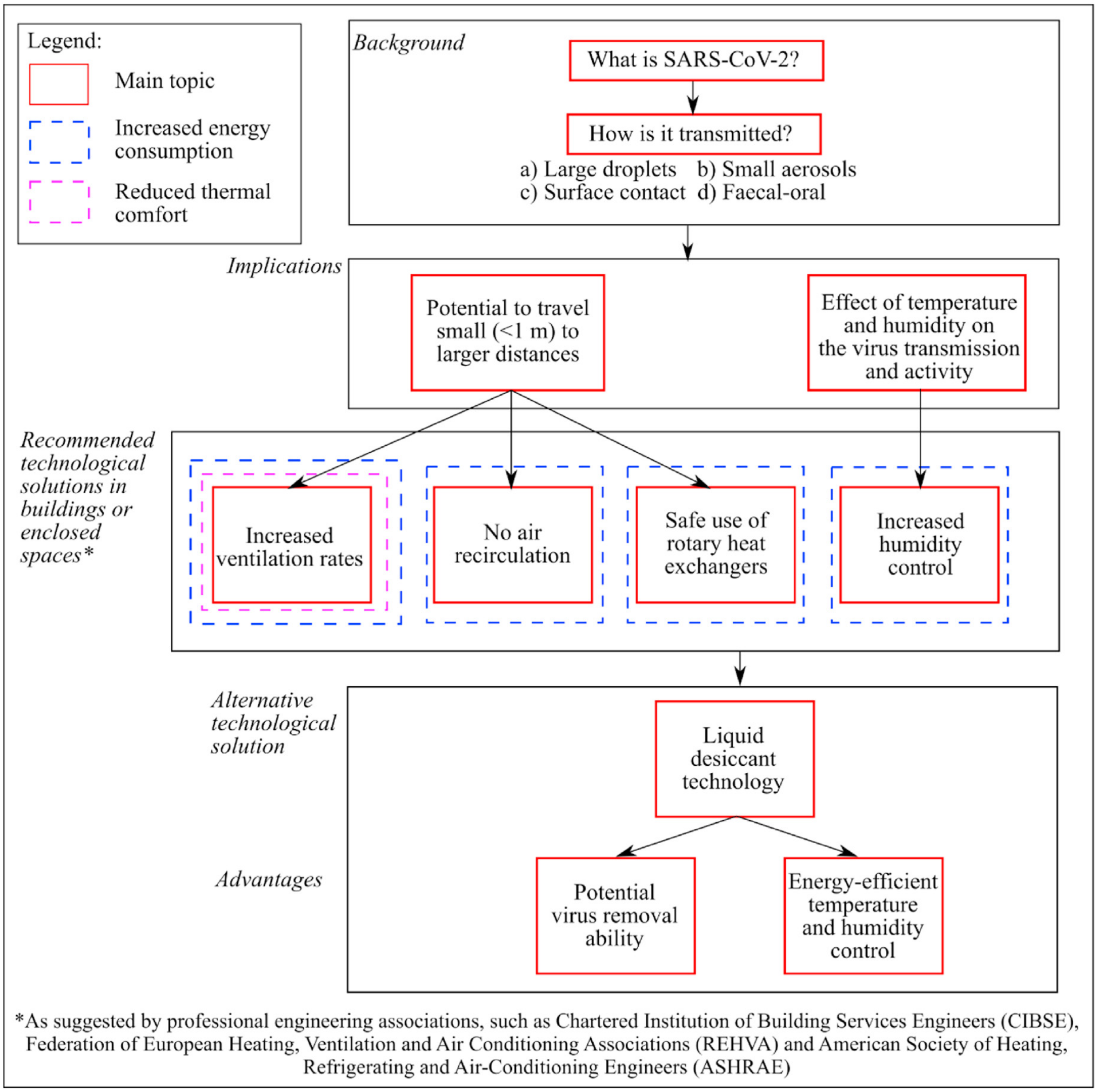

Fig. 2. Scope of the research.

ASHRAE [18], is believed to have a positive effect on indoor air quality and minimisation of the transmission and infectivity of viruses. More laboratory-based research on the subject is required to explore this. Besides, factors relevant to the air conditions in outdoor settings (such as wind [30] and sunlight [31]) may also play an important role in the transmission of the virus. The presence of particulate matter (PM) in the air has also been suggested as a potential factor [32] as PM may increase the suspension and accumulation of virus-laden aerosol in the air [19]. Additional factors, such as international travel, implemented mitigation strategies (*i.e.* lockdown, quarantine, social distancing and contact tracing), and rate of urbanisation may play a key role in the large spread of the virus in different climates [33,34].

5. Limitation strategies: characteristics, drawbacks and energy impact

Various air purification strategies have been suggested by professional engineering associations [1,35–37] for airborne viral transmission reduction in buildings and enclosed spaces. The strategies include dilution, filtration, adsorption, use of light, photocatalytic oxidation, and non-thermal plasma and air ionisation. Table 2 summarises the characteristics and drawbacks of these. The effective use of air ventilation, filters and light are the most commonly used engineering strategies for indoor air purification. As such, they are further described in the following sections. Other technologies, *i.e.* photocatalytic oxidation, non-thermal plasma and bipolar ionisation, have been identified as promising interventions but they are still undergoing research and development for further advancement.

5.1. Ventilation

Diluting the air where SARS-CoV-2 or other viruses might exist is a practical solution to minimise the risk of airborne transmission. Fig. 5 shows the guidelines recommended by REHVA for HVAC practices in buildings [1].

The strategies involve an increased supply of ventilated air by

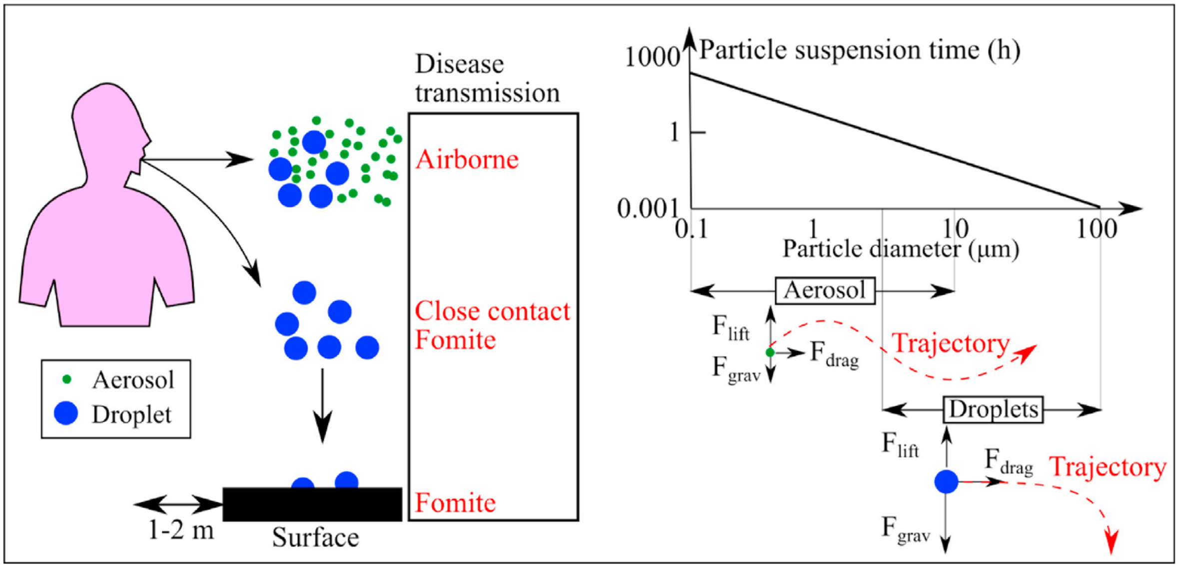

Fig. 3. Droplet and aerosol production and transmission, adapted from Refs. [19–21].

Table 1
Effect of external factors on the transmission of viruses, adapted from Ref. [22].

	Factor	Effect
Physical	Heat	Inactivation is directly proportional to temperature
	Light	Light, especially its UV component, is germicidal
	Desiccation or drying	Inactivation depends on the strain and type of virus
	Aggregation/adsorption	Protection from inactivation
	Pressure	High pressure induces activation
Chemical	pH	Worst stability at extreme pH values
	Salinity	Increased salt concentrations are virucidal
	Ammonia	Virucidal
	Inorganic ions	Some inorganic ions (e.g. platinum, palladium and rhodium ions) are virucidal
	Organic matter	Dissolved, colloidal and solid organic matters inactivate viruses
	Enzymes	Proteases and nucleases contribute to inactivation
Biological	Microbial activity	Inactivate viruses
	Protozoal predation	Remove or destroy viruses
	Biofilms	Adsorption to biofilms inactivates viruses while microbial activity in biofilms may be virucidal
	Type of virus	Stability varies according to the strain and type of virus

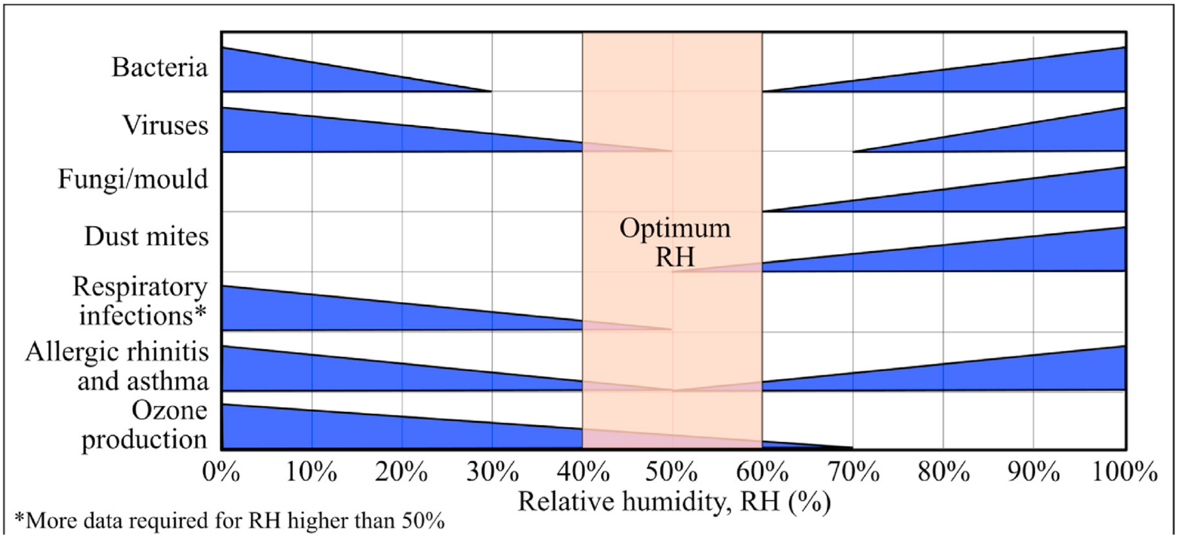

Fig. 4. Optimum relative humidity range for minimising adverse health effects, adapted from Ref. [27].

Table 2
Methods for indoor air purification, based on [38].

Strategy	Characteristics	Drawbacks
Use of air ventilation for dilution	• Increase of outdoor air and air change rates to increase the dilution of the pollutant or microorganisms in the air	• Energy consumption is associated with increased ventilation rates
Use of filters for filtration	• Filters are used to remove pollutants and microorganisms from the air with HEPA filters used for high-efficiency removal	• The filtering characteristics depends on the typology of filter • Filters responsible for an increase in pressure drop
Adsorption	• Main materials for removal of contaminants are activated carbon, zeolite, activated alumina, silica gel and molecular sieves	• Activated carbon loses removal efficiency over time with the reduction of efficiency after regeneration
Use of light	• Light reduces the viability of microorganisms. Ultraviolet light can deactivate viruses by disrupting their DNA or RNA chain	• Potential risk from the use of ultraviolet light • Absence of design standard
Photocatalytic oxidation	• Degradation of contaminants into products such as CO_2 and H_2O by use of photocatalysts operating at room temperature	• Low efficiency of the process • More research required to investigate the mechanism of the reaction
Non-thermal plasma and air ionisation	• By using negative and positive ions, the activity of the pathogen or contaminant is reduced • Different typologies available: negative air ionisation, bipolar ionisation, surface charging, *etc.*	• Unsteady operation with low efficiency • More research required on the impact of the uptake of negative ions on the respiratory system

increasing the outside air fraction, the rate of air change, and the use of natural ventilation with windows to prolong the hours of operation of the system [1,35,36,39]. The effect of the increase in the ventilation rate on the dilution of the air and the transmission of the virus can be expressed by the Wells-Riley equation [40]:

$$P = 1 - \exp\left(-\frac{I \cdot q \cdot p \cdot t}{Q}\right) \tag{1}$$

where P is the risk of cross-infection, I is the number of infectors, p is the pulmonary ventilation rate of each susceptible (m^3/h), Q is the ventilation rate (m^3/h), q is the quanta produced by one infector (quanta/h) and t is the duration of the exposure (h). Currently, q for COVID-19 has not been determined yet but is estimated as 14–48 quanta/h [41]. Nevertheless, Eq. (1) implies that an increase in the air ventilation could exponentially reduce the risk of cross-infection in buildings, enclosed spaces or public transport, with an effect correlated to the exposure time, respiratory activity and the number of infectors.

For mechanically ventilated buildings, increasing the opening of

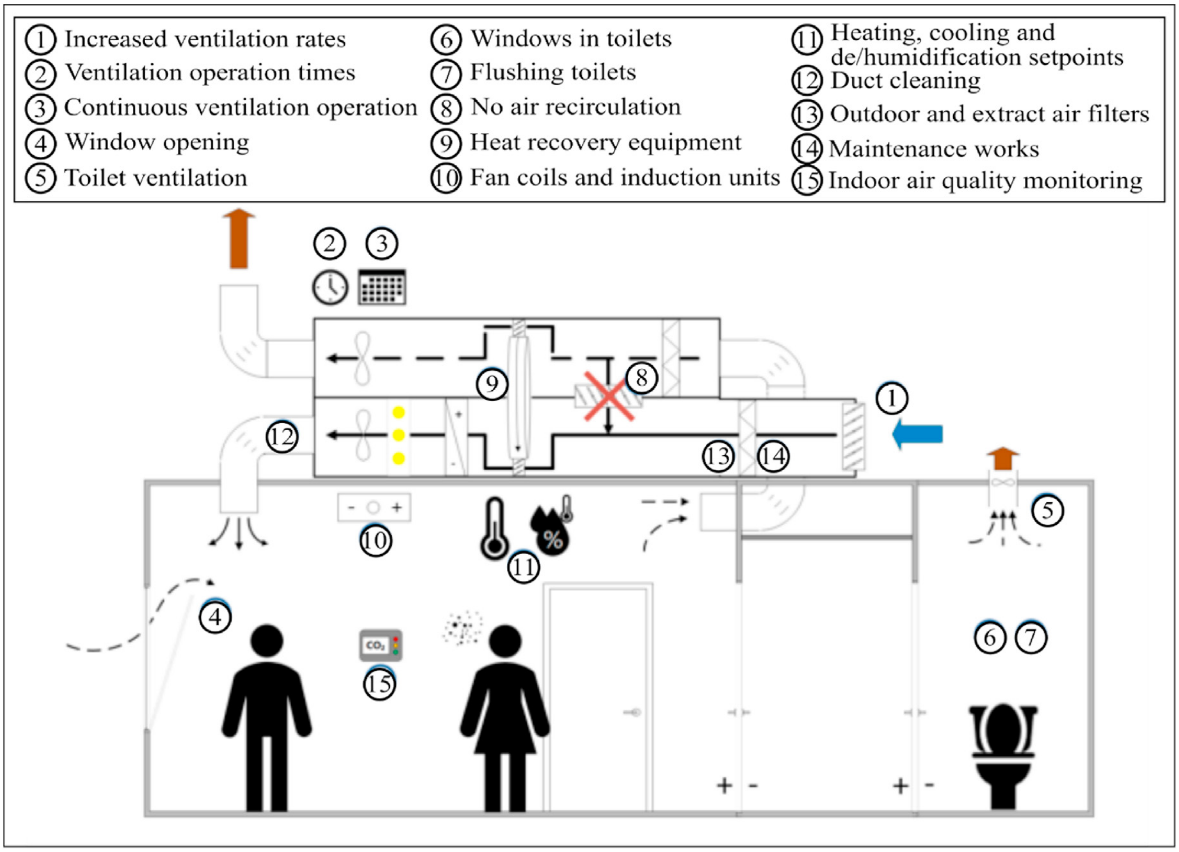

Fig. 5. HVAC building practices recommended by REHVA, adapted from Ref. [1].

the air damper in the air handling unit can boost the air flow rate [39]. Although it is effective in diluting the contaminants present in the air, this strategy is complicated and responsible for a significant increase in energy consumption. The ventilation rate, Q (L/s), *i.e.* the amount of intake air supplied to buildings, is defined as in Eq. (2) [42]:

$$Q = \frac{ACH \cdot V \cdot 1000}{3600} \tag{2}$$

where ACH is the air change rate (number of air changes per hour), defined as the ratio between the ventilation rate and the volume of the conditioned space, V (m^3). The minimum value of outdoor ventilation rate that is recommended to be supplied to mechanically-ventilated buildings or enclosed spaces ranges 8–10 L/s per person [43], whilst a ventilation rate of 1–3 L/s per person is associated with superspreading events of SARS-CoV-2 [44].

ACH is an index for the evaluation of ventilation performance and one of the biggest determinants for air dilution in buildings [45]. For instance, ACH in commercial buildings and isolation rooms are defined as 1 and 12 respectively [40]. A detailed list of ACHs for different typologies of buildings is reported in Ref. [46]. ACH impacts on the time required to clear a space, *i.e.* the higher the ACH, the lower the time required to remove the contaminants present [4]. Although able to dilute the contaminants potentially present in the air, the effectiveness of the ventilation might not be increased by an increase of the ventilation air due to the poor design of the ventilation system [47]. In hot and humid climates, the increase in the ACH is responsible for higher latent loads, resulting in an energy inefficiency of the air handling unit [48]. The required ventilation air increase would be significant and responsible for an increase in energy consumption and a decrease in indoor thermal comfort, depending on the outdoor air conditions. It was reported that an increase in the ACH of only 1% is responsible for an increase in the energy costs for heating and cooling ranging between £75 and £110 per year [47].

The relationship between the ventilation air and the energy requirement for air-conditioning, $E_{A/C}$ (kWh), is expressed in Eq. (3) [49]:

$$E_{A/C} = \frac{\rho_a \cdot Q \cdot \left[\left(c_{pa} + \omega_a c_{pw} \right) \cdot \Delta T + h_{fg} \cdot \Delta \omega \right] \cdot \Delta t}{1000} \tag{3}$$

where ρ_a, c_{pa} and ω_a are the density (kg/m^3), specific heat capacity (kJ/kg) and moisture content (kg_{H2O}/kg_{da}) of the moist air, respectively; c_{pw} is the specific heat capacity of water moisture (kJ/kg); h_{fg} is the latent heat of vaporisation (kJ/kg); Q is the ventilation rate (L/s); ΔT and $\Delta\omega$ represent the variation in temperature and moisture content, respectively, between the inlet and outlet air; and Δt is the operation time of the ventilation system (h). It was also recommended to prolong the operation of the HVAC system, for example for 2 h before and after occupying a building or continuously at lower ventilation rates [1], to further dilute the potential airborne viruses at the expense of a negative impact on energy consumption.

An increase in natural ventilation (*i.e.* maintaining windows widely open for prolonged hours) is also recommended to increase the dilution of the air in buildings and enclosed spaces [1]. In the case of a virus outbreak, natural ventilation is an easy to implement strategy able to provide high ventilation rates at low energy cost [40]. However, this strategy results in poor thermal comfort for the occupants (in terms of indoor temperature and humidity variation) and the absence of the filtering function provided by the air handling unit, which results in higher importance of the outdoor air quality (potential presence of allergens, pollutants and insects) [18]. In addition, larger use of natural ventilation may result in an increase in the energy consumption for heating in the cold months and cooling in the hot months [35]. As such, it cannot be considered as a long-term procedure for ventilation management in buildings or public transport.

It is fundamental that the ventilation systems are effective in diluting the air and are well-maintained, with air properly distributed in the building with the delivery of fresh air to breathing zones, avoidance of cross-contamination between zones and efficient removal of pollutants [40,50]. The direction of the air is hence a primary factor that should be optimised to limit the transmission of viruses in buildings or enclosed spaces, by (i) reducing the cross-contamination between zones and rooms and (ii) limiting the risk of contaminant build-up in stale air. In studies related to the airborne transmission of viruses, such as tuberculosis [51] and measles [52], it was identified that poorly designed and maintained HVAC systems are potentially responsible for the spread of diseases, presenting a negative effect on the dispersion of infective particles [21]. The choice of the ventilation strategy in buildings (recirculation, mixing or displacement) has hence an impact on virus transmission, as reviewed by Lipinski et al. [53]. Displacement ventilation strategies supply the air at floor level and exhaust it at ceiling level, being therefore able to reduce the risk of contamination of airborne pathogens by avoiding air mixing due to thermal stratification [50]. On the contrary, recirculation ventilation strategies, such as split air-conditioning, ceiling fans and hybrid systems, are potentially responsible for virus transmission due to the recirculation of the air and the velocity of the turbulent airflow produced [53]. In particular, systems not supplying any outdoor air, such as split air-conditioning and passive chilled beams (100% recirculated air), are considered as potentially responsible for the transmission of pathogens if additional outdoor air is not supplied [35]. Similarly, mixing ventilation strategies, such as air handling units and ventilation systems with heat recovery, can be responsible for the long-distance movement of pathogens (by means of turbulent airflows), which can accumulate on filters if adequate maintenance is not performed [53].

Conventional centralised HVAC systems employ recirculation of air to reduce the energy consumption to heat or cool the air within the temperature range required for indoor comfort and limit the capacity of the heating and cooling system, resulting in reduced capital costs for the system [54]. As an example, it was reported a typical ratio of 80% of recirculated air and 20% of outdoor air in the USA for mechanically ventilated buildings (classrooms and offices) [50]. In the event of an outbreak of COVID-19, the recirculation of air could be responsible for reintroducing the virus in the building, spreading it to different floors or zones of the building where it was not present previously [21]. It was therefore recommended to not recirculate the air in buildings in such circumstances [1,35,36]. This can be obtained by closing the damper of air recirculation and sealing it for the time of the virus outbreak to minimise the leaks [36]. However, the total elimination of air recirculation may not be possible in buildings, enclosed spaces or public transports, due to the limited capacity of the HVAC system to treat outdoor air. In these cases, the use of recirculation should be limited as much as possible [54]. When HVAC systems recirculate air at room level rather than at building level, such as in local fan coil units, split units, and induction systems, the effect of the recirculation of air on the virus transmission is less important [54].

As described in **Section 4**, the humidity affects the survival and activity of viruses together with the self-defence mechanisms of the human body and the movement of the airborne particles. Although not currently considered a priority, the effective control of humidity in buildings, enclosed spaces and public transports (between 40% and 60% RH) would be beneficial in terms of increased

Table 3
Efficiency of various filters of HVAC systems for different particle sizes and related application, adapted from Refs. [59–61].

MERV[a]	Filter efficiency dependent on particle size (μm)			Particle size range (μm)	Typical contaminant	Typical application
	0.3–1	1–3	3–10			
1	–	–	<20%	>10	Pollen, carpet fibers, dust mites, lint	Light residential, split air-condtioning
2	–	–	<20%			
3	–	–	<20%			
4	1%	9%	15%			
5	–	–	20–35%	3–10	Some mould spores, cooking dust, pollen	Typical residential, typical commercial, paint or finishing booths
6	–	–	35–50%			
7	17%	46%	50–70%			
8	–	–	>70%			
9	–	<50%	>85%	1–3	Mould spores, fine dust, welding fumes	Industrial, better residential, better commercial
10	–	50–65%	>85%			
11	–	65–80%	>85%			
12	–	>80%	90%			
13	<75%	>90%	90%	0.3–1	Bacteria, smoke and other microscopic particles	Hospitals, smoking lounges
14	75–85%	>90%	90%			
15	85–95%	>90%	90%			
16	>95%	>95%	>95%			
17[b]	>99.97%	–	–	<0.3	Viruses	Cleanrooms, surgery, aeroplanes
18[b]	>99.99%	–	–			
19[b]	>99.999%	–	–			
20[b]	>99.9999%	–	–			

[a] Minimum efficiency rating value.
[b] High-efficiency particle air (HEPA) filters.

air control quality and providing a negative environment for virus proliferation. In cold winter weather, it was recommended the use of humidifiers to increase the RH of the air (that otherwise would be too low with conventional air handling unit practices based on direct heating) [18]. However, the implementation of this technological solution is complicated for retrofitting because of the need for the addition of water storage [55] and requires proper selection, operation and maintenance [18]. In addition, conventional humidifiers (evaporative, spray and steam) are potential sites of accumulation and amplification of microorganisms and odours [11].

The use of heat exchangers in buildings, such as rotary heat exchangers and enthalpy wheels, has been also considered as potentially responsible for the increase of the transmission of the virus. In the case of poor design and limited maintenance, a leakage might be present and responsible for re-entering the virus-laden air into the building [1]. As such, it was recommended to only use heat recovery systems able to effectively separate return and supply air (as in twin coil systems) and not in presence of leaks.

For public transports, it was identified how the design of the air management systems method together with the arrangement of the seats played a key role in the transmission of airborne viruses, such as influenza [56]. As such, the use of natural ventilation (by keeping windows opened and increasing the opening of doors) in combination with increased ACH was suggested in public transport [57], together with a reduction of the occupants. If possible, no use of recirculation air was also recommended [57,58].

5.2. Filtration

Filters are an economical and easy to implement strategy used to efficiently remove contaminants and improve air quality in buildings. Table 3 shows the classification of filters used in the HVAC systems depending on their minimum efficiency rating value (MERV) and the efficiency of particle removal and potential application for various particle sizes.

Table 3 shows that the majority of commercial and residential buildings are equipped with filters characterised by a MERV lower than 13. Although effective in filtering dust or spores, these filters do not remove fungi, bacteria and viruses [62]. It was recognised the beneficial effect of filters with high MERV to reduce the possibility of airborne transmission by the SARS-CoV-2 virus [39]. CIBSE recommends the use of filters to limit the spread of viruses but also declares that this technological solution must not be thought of as able to eliminate the risk of transmission of the virus [35].

Although able to limit the transmission of small-sized particles, such as airborne viruses, due to their higher filtering characteristics, the use of high-efficiency particle air (HEPA) filters may not be a feasible strategy in HVAC units of most buildings due to their increased resistance to airflow and the resulting increase in pressure drop [63], which imposes an energy penalty for the operation of the fans that blow the air through the filters, as shown in Eq. (4) [49]:

$$E_{\text{fan}} = \frac{Q \cdot \Delta P_{\text{fan}} \cdot \Delta t}{\eta_e \cdot 1000} \tag{4}$$

where E_{fan} is the energy consumption for the operation of the fan (kWh), Q is the air volume flow rate through the fan (m^3/s), $\varDelta P_{\text{fan}}$ is the total pressure rise from the fan inlet to the outlet (Pa), $\varDelta t$ is the operation time of the fan (h) and η_e is the overall efficiency of the fan and motor system.

It was reported that the replacement of conventional filters with HEPA filters would result in an increase of $\varDelta P_{\text{fan}}$ between 3 and 5 times [64], resulting in significant energy consumption. The increase in $\varDelta P_{\text{fan}}$ may not be accommodated by the majority of the HVAC systems, resulting in being complex for retrofitting [1], and is not recommended for use in public transports, because it would be detrimental for the HVAC equipment. In addition, filters also represent a site of accumulation and amplification of microorganisms [11,59], which results in a decrease in the efficiency of the filter and in its deterioration [38], requiring high maintenance costs [65]. As such, HEPA filters are not commonly used in commercial or residential buildings but only for specific applications, such as in healthcare facilities or airplanes [21], and are not further considered in the case study of **Section 6.2**.

5.3. Use of light

The use of light has also been identified as a potential engineering control strategy for air cleaning due to its characteristics to inactivate microorganisms, such as bacteria, viruses and fungi [39,66]. Schuit et al. investigated the potential of using sunlight to inactivate the influenza virus [67] and SARS-CoV-2 [31], identifying an inverse correlation between the level of sunlight and virus transmission. Although potentially interesting considering the large availability of sunlight, further research is required to fully understand the characteristics of sunlight to inactivate coronaviruses [39].

On the other hand, the use of ultraviolet light (UV) to kill or inactivate microorganisms has been largely reported, particularly for short-wave UVC light (characterised by photons with wavelength ranging between 220 and 280 nm) [18]. Ultraviolet germicidal irradiation (UVGI) technique employs UVC light for the inactivation of microorganisms based on the disruption of their DNA at the molecular level, affecting their reproduction characteristics [68]. It was reported the characteristics of a 222 nm UVC light to inactivate human coronaviruses and that to achieve a 90% viral inactivation it would require exposures of 8–25 min [69]. Most of the commercial UVGI systems employ low-pressure mercury lamps emitting UVC light at 253.7 nm (close to the peak value of effectiveness at about 265 nm) [68]. Fig. 6 presents the germicidal efficiency of UV treatment at different wavelengths (top) and the species-dependent effect on various microorganisms (bottom).

Main configurations of UVGI systems used in buildings (healthcare facilities, laboratories, *etc.*) are upper-room (for the disinfection of the whole room surface and of the air) and in-duct (in HVAC units for surface disinfection of cooling coils and for air disinfection) [61], with a dose of UV light specific to the application (low UV dose for coil disinfection and high UV dose for air disinfection) [70]. In-duct UVGI systems for air disinfection should be located on the exhaust air duct of the HVAC unit to reduce the transmission of microorganisms before recirculating or exhausting the air [71], although more research is required to evaluate the effectiveness of air velocity and UVC light intensity on the virus inactivation characteristics of in-duct UVGI, particularly for coronaviruses [72].

Although considered beneficial to reduce the viability of microorganisms and increase the indoor air quality, the use of UVGI technology for air disinfection presents drawbacks, such as the absence of design standards, the risk to occupants and objects (degradation of the materials which are exposed to UVC light) and the capital and operating costs [61] and its implementation should be evaluated case by case, depending on the occupancy and geometry of the space, the type of ventilation system, *etc.* [72]. In particular, UVGI technology is not recommended for use in public transport, as the vehicle should be redesigned to account for the safety of the occupants [58]. As such, the use of UVGI as a stand-alone technology for air disinfection is limited, whilst it is beneficial as a supplement to HEPA or high MERV filters [71]. For this reason, the use of UVGI in HVAC systems is not considered in the case study

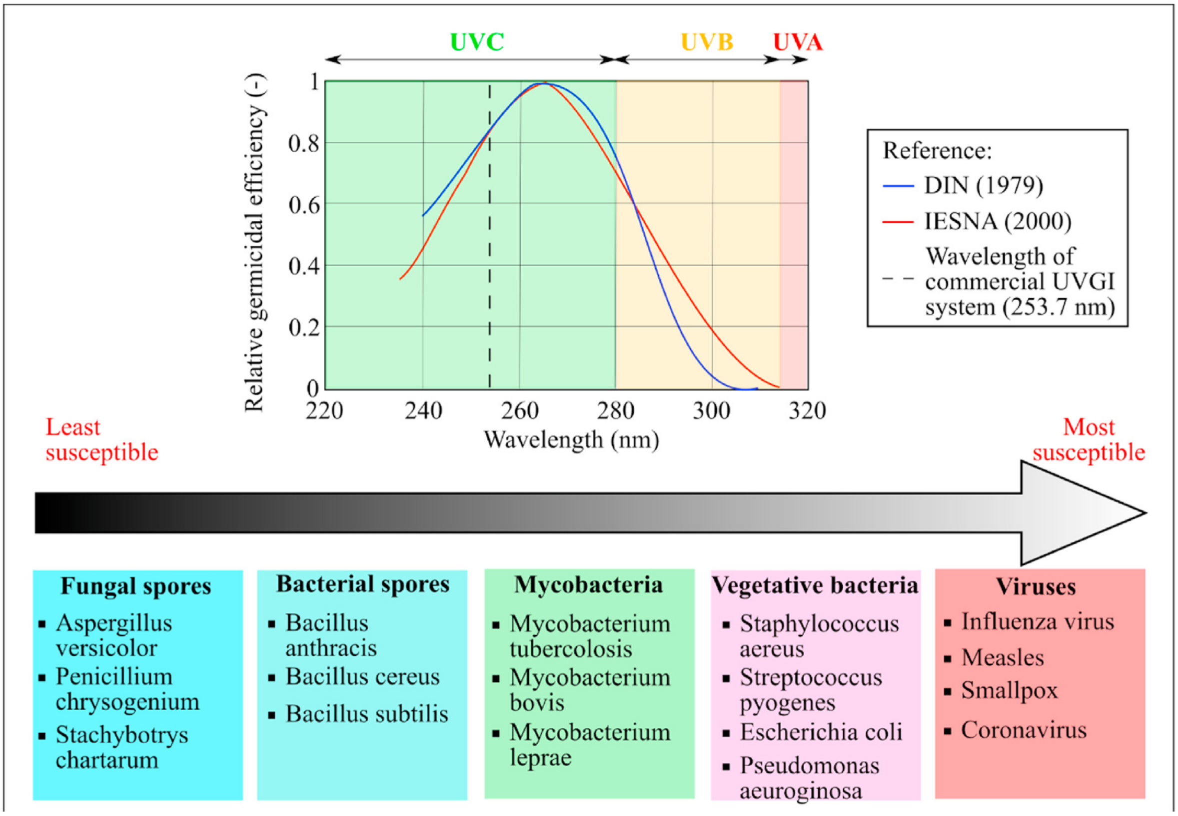

Fig. 6. Effect of UV light on germicidal characteristics (top) and susceptibility to UVC inactivation of microorganisms, adapted from Ref. [68].

of **Section 6.2**, although its application in combination with liquid desiccant technology for air sterilisation is promising and further described in **Section 6.1**.

6. Potential scrubbing technology: liquid desiccant

6.1. Working principle and sanitising characteristics

Liquid desiccant solutions could be employed as a potential alternative strategy for the inactivation of SARS-CoV-2 or other airborne pathogens in buildings, enclosed spaces or public transports. Liquid desiccant is a technology that uses hygroscopic solutions, usually LiCl, LiBr, $CaCl_2$, HCO_2K, TEG, *etc.*, to dehumidify the air [12]. A schematic diagram of a liquid desiccant system in its conventional configuration is shown in Fig. 7, where the desiccant solution depending on its temperature and concentration is able to produce dry and hot/humid (usually as scavenging air) in the dehumidifier and regenerator, respectively.

The liquid desiccant technology is usually driven by low-grade heat sources, such as industrial waste heat [73], solar [74] and geothermal energy [75], to energy-efficiently control moisture and temperature, particularly for processes where moisture control and moisture removal are required. It has therefore found application in buildings with high latent loads (such as gyms and swimming pools [76]), in buildings where moisture control is essential for the conservation of goods (such as art galleries, libraries, museums and archives [77]), in hospitals and healthcare facilities [78], in refrigeration and cold rooms [79], in greenhouses [80], *etc.*

Desiccant solutions have been identified as a potential tool to increase the indoor air quality (IAQ) in buildings or enclosed spaces due to their bacteriostatic, bactericidal and antiviral characteristics, in addition to the capacity to remove volatile organic compounds (VOCs) and capture particulate matter (PM) [11]. In addition, their moisture control capacity makes of the liquid desiccant a very appealing technology in the case of an airborne viral outbreak, being able to provide to the building's occupants thermal comfort, indoor air quality and safety without resulting responsible for an increase in energy consumption. Compared to conventional technologies for humidity control (*i.e.* cooling-based dehumidification and humidifiers), the liquid desiccant technology does not use water storage systems, resulting in limited breeding sites for microorganisms [11]. As an example of application, Liu et al. [81] developed an air-conditioning system able to independently control the temperature and humidity of the air supplied to a residential building, which is able to provide both dehumidification in summer and heating/humidification in winter. It was recognised how liquid desiccant technology could significantly increase the IAQ in buildings or enclosed spaces by supplying 100% outdoor air with no significant difference in electricity consumption compared to the operation with recirculated air [82]. In hybrid HVAC systems, the decoupling of sensible heat removal (usually performed by vapour-compression cooling) and latent heat removal (performed by liquid desiccant) result in higher energy and economic performance in terms of increased coefficient of performance (COP), reduced size and capital cost, *etc.* [83]. It was also investigated the potential use of desiccant systems (solid or liquid) to condition the temperature and humidity of the air supplied to buses [84]. In combination with an evaporative cooling system, the technology is able to supply the air within the temperature and humidity range required and be driven by the heat available from the engine.

A literature review of the sanitising properties of liquid desiccants showed that different studies focused on the analysis of the bacteria, fungi and virus deactivation characteristics of the conventional desiccant solutions (such as LiCl and TEG), as shown in Table 4 for experiments conducted in air-conditioning systems, while Appendix 3 reviews in vitro experiments of cell culture on the virus inhibition capacity of commonly used liquid desiccant solutions. Slayzak et al. [85] studied the capacity of a low-flow liquid desiccant system to inactivate the *Bacillus subtilis* and *Bacillus cereus spores*. In the context of the development of technological solutions against chemical and biological weapons for increased security in buildings, a liquid desiccant solution, such as LiCl, has the capacity to capture and inactivate spores used as surrogates for anthrax. After capturing the contaminants from the supply air (dehumidifying it), the liquid desiccant solution is heated and then sent to the regenerator where it desorbs the moisture, becoming concentrated. As reported in the patent by Slayzak et al. [86], the technology would represent an example of a regenerable filter that is able to provide continuous removal of gaseous, aerosols and particulate microorganisms, including bacteria, fungi and viruses. Compared to conventional filters, such as HEPA, electrostatic precipitator, photocatalytic oxidation, *etc.*, the liquid desiccant technology could inactivate different types of contaminants while providing an energy-efficient technological solution [86]. It was

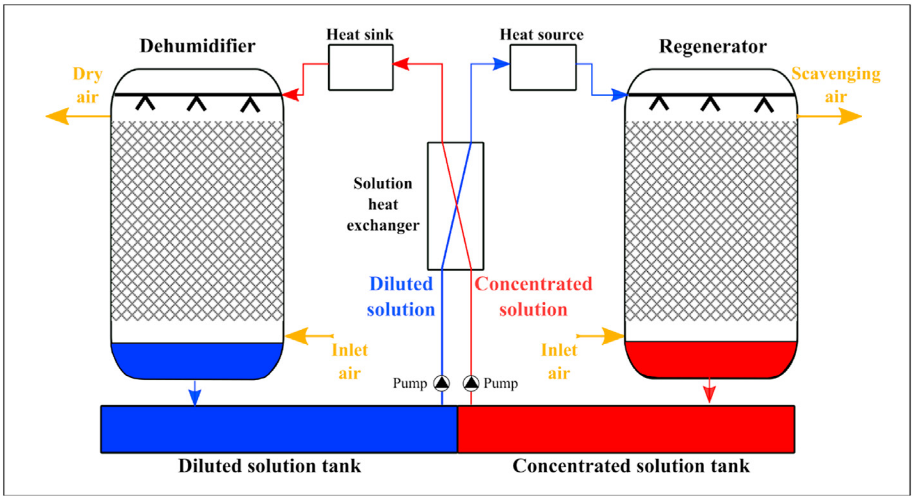

Fig. 7. Conventional schematics of liquid desiccant technology.

Table 4
Literature review of the use of desiccant solutions for bacteria, fungi and virus removal in air-conditioning systems.

Ref.	Year	LD[a]	Research/experiment	Conclusion
[85]	2003	LiCl	Tests conducted on the reduction capacity of a 40% wt. LiCl solution on spores of *Bacillus subtilis* and *cereus*, as surrogates for anthrax spores	The spores were reduced of about 99.99% after treatment at 60 °C for 4–6 h, while no effect was identified after treatment with deionised water
[121] [b]	2004	LiCl LiBr	Development of direct contact liquid desiccant dehumidification system able to increase IAQ by removing bacteria and viruses	It was reported the capacity of a mixture LiBr–LiCl to deactivate the SARS-CoV-1 virus
[91] [b]	2005	LiBr	Development of immune air-conditioning system based on the combination of liquid desiccant technology with evaporative or refrigeration cooling	It was reported a significant reduction (−90%) of the bacteria after direct contact with the liquid desiccant solution
[86]	2007	LiCl	Patent on the development of a regenerable filter for capture and inactivation of contaminants, such as surrogates of anthrax (*Bacillus cereus* and *Bacillus subtilis*)	It was reported the capacity of the LiCl solution to inactivate the spores with a direct correlation between the temperature and concentration of the solution and the inactivation of the spores
[87]	2011	TEG LiCl	Tests on the capacity of LiCl (35.9–39.5% wt.) and TEG (79.9–89.5% vol.) aqueous solutions to inactivate airborne fungi in an air-conditioning system	It was proved the capacity of the solutions to inactivate the fungi. Higher capacity was observed for TEG in the operating range in most of the cases
[45]	2017	LiCl	Test conducted on the capacity of a 36% wt. LiCl solution to remove VOCs (toluene and formaldehyde) and microorganisms, such as bacteria and fungi	It was reported a fungi removal efficiency of 38.8–44.4%, whilst bacteria removal efficiency was 77.5–81.3%. Mechanisms involved in bacteria and fungi removal were also suggested
[122]	2018	LiCl	Test conducted on the capacity of a 36% wt. LiCl solution to remove bacteria and fungi by direct contact in cellulose structured packing	The fungi removal efficiency was low (7.4–8%), whilst higher removal capacity was detected for bacteria (61.9–82.8%)
[88]	2018	LiCl	Tests conducted on the capacity of the liquid desiccant solution combined with UVGI technology to reduce the concentration of surrogates for pathogens connected with healthcare-acquired infections	It was reported the capacity to reduce the concentration of all the microorganisms (*Staphylococcus epidermidis*, *Klebsiella aerogenes*, *E. coli*, *Enterobacter cloacae*, *Salmonella Typhimurium*, *Pseudomonas fluorescens*, *Listeria innocua*)
[90]	2020	LiCl	Tests conducted on the capacity of the liquid desiccant solution in combination with UVGI technology to inactivate bacteria and moulds from the air and on the packing of the direct evaporative cooler	It was reported the capacity of a LiCl solution to inactivate 78.3% of the airborne bacteria, whilst no effect was identified on moulds. A significant reduction was obtained in the packing

[a] Liquid desiccant.
[b] Paper reviewed in Ref. [11].

identified in the research a direct proportionality between the inactivation of the spores and the temperature and concentration of the desiccant solution.

Wang et al. [87] studied the effect of two desiccant solutions (TEG and LiCl) on the activity of fungi, such as *Cladosporium*, *Aspergillus* and *Penicillium*, identifying how the inactivation process is directly proportional to the concentration of the solution and inversely proportional to its temperature. Park et al. [45] investigated the capacity of a liquid desiccant system to remove microorganisms (bacteria and fungi) and VOCs (toluene and formaldehyde) from the air. It was reported that the solution can remove bacteria with an efficiency ranging between 77.5% and 81.3%, while the capacity to remove fungi was lower (ranging between 38.8% and 44%). Compared to the conventional variable air volume (VAV) system, it was reported that the liquid desiccant technology could increase the ACH up to 3.1 times, resulting in a beneficial effect for the dilution of contaminants in the air. The manufacturer of liquid desiccant systems Alfa Laval [88] investigated the operation of a liquid desiccant system combined with the UVGI process to reduce the activity of surrogates of seven bacteria commonly found in healthcare facilities, such as *Staphylococcus epidermidis*, *Klebsiella aerogenes*, *Escherichia coli*, *Enterobacter cloacae*, *Salmonella Typhimurium*, *Pseudomonas fluorescens* and *Listeria innocua*. By calculating the logarithmic reduction of the microorganisms at the outlet of the desiccant system, it was identified how the technology would be able to effectively control the analysed bacteria. It was reported how the technology could find application in the food processing industry where a higher risk of bacterial contamination is present [89]. The integration of the liquid desiccant technology with UVC light was also studied by Bang et al. [90], which evaluated the effectiveness of the technology to inactivate bacteria (*Legionella* and *Staphylococcus*) and fungi (*Penicillium*, *Aspergillus* and *Cladosporium*). Whilst bacteria were reduced by 78.3%, no effect was identified on fungi. As described by Slayzak et al. [86], the microbes inactivation characteristics of the liquid desiccant technology could be further enhanced by using additional purification systems, such as ionisation, electrostatic precipitators, inertial filters, *etc.*, depending on the typology of pathogen or contaminant considered.

Following the outbreak of SARS-CoV-1, different studies were conducted in China for the development of air-conditioning systems able not only to energy-efficiently control temperature and humidity of the air supplied to the building but also to sanitise it and remove viruses, bacteria or fungi [11]. Lu et al. [91] investigated the capacity of a combined liquid desiccant and UVC radiation system to purify and sterilise the air. It was reported by Fu et al. [11] that employing such technology would significantly reduce the bacteria present (reduction higher than 90%). In the review article by Fu et al. [11], it was also reported a study by the Chinese CDC Virus Institute on the effect of a LiBr–LiCl mixture to inactivate SARS-CoV-1. Since the genetic material of the SARS-CoV-1 virus after treatment with the desiccant solution was highly unstable, it was hypothesised that the solution could have an effect of direct chemical damage on the virus.

Different potential mechanisms have been suggested for the action of the desiccant solution on the contaminant, as reported in the technology patented by Slayzak et al. [86]. It is important to note that the technology was designed to be effective against spores, such as *Bacillus spores*. However, it was reported that since the spores, in general, are harder to deactivate microorganisms, the same conclusion could be applied to easier to deactivate microorganisms, such as viruses, bacteria, fungi, *etc.* Primarily, it was suggested that the desiccant solution is responsible for the reduction of water activity, a_W [12,86]. A 45% wt. LiCl desiccant solution at 40 °C has a_W equal to 0.1, whilst it was reported in literature how bacteria growth is limited for values of a_W lower than 0.9 [86]. It was identified the removal of water molecules from the capsid as responsible for the inactivation process of bacteria [92]. However, a different behaviour was identified for viruses, characterised by structural differences compared to bacteria [92] and able to survive in conditions of very low a_W [93].

Slayzak et al. [86] suggested that the presence of lithium ions could be responsible for the inhibition of the viral activity, as also suggested by the research of Skinner et al. [94] and further illustrated in Table 4. In terms of the research on the capacity of LiCl to inactivate the replication of viruses on cell culture, Skinner et al. [94] investigated the effect of LiCl on various DNA and RNA viruses. It was observed the capacity of such solution to inhibit the replication of the analysed DNA viruses (pseudorabies and vaccinia virus) on baby hamster kidney cells with an effect directly proportional to the dose of LiCl. However, the same effect was not observed for RNA viruses (encephalomyocarditis, EMC, and influenza). In addition, it was suggested that the inhibition of the virus was specific to the presence of the Li ions since a similar effect was observed after treatment with lithium sulphate (Li_2SO_4) but not with potassium chloride (KCl) and sodium chloride (NaCl). In recent years, various in vitro studies on the capacity of LiCl to inactivate viruses in cell culture were conducted, such as avian coronavirus infectious bronchitis virus, IBV [95,96], porcine deltacoronavirus [97], TGEV [98], type II porcine reproductive and respiratory syndrome virus [99], porcine epidemic diarrhoea virus [100], foot-and-mouth virus [101], feline calicivirus [102] and mammalian orthoreoviruses [103]. The capacity of LiCl to inhibit different DNA and RNA viruses with an effect dependent on the dose was identified, particularly for coronaviruses [98]. Harrison et al. [95] studied the capacity of LiCl to inactivate IBV, an avian virus of the coronavirus family, identifying how the inhibition effect was correlated with the dose of LiCl in the replication stage, whilst no effect was detected in the attachment and entry stages. As such, the LiCl is thought to operate on a cellular level by affecting the production of viral proteins and inhibiting the reproduction ability of the virus, rather than killing it with direct virucidal characteristics. The temperature was also detected as a primary factor in the inactivation of the virus. Similarly, Ren et al. [98] studied the effect of LiCl on another family of coronaviruses, TGEV, identifying how the inhibition of coronaviruses could be a common feature for LiCl. The research was performed in vitro and/or on surrogate viruses, requiring more research to fully understand the mechanisms involved in the process of inactivation of the virus performed by LiCl and how these inactivation characteristics could be exploited in the realisation of a sanitising air scrubber.

As reported by Slayzak et al. [86] and detected by Harrison et al. [95], the action of the desiccant solution on the virus inactivation could be the result of the coactive effect of the antiviral characteristics of the LiCl solution and of the treatment at high temperature. After direct contact with the virus-laden air, the desiccant solution is sent to the regenerator where it desorbs moisture at a relatively high temperature (45–60 °C), stimulating the inactivation of the pathogen. In addition, the exposure time of the virus in the desiccant solution could also affect the inactivation [86], as detected for the treatment with LiCl of feline calicivirus [102]. Studies were also conducted on the capacity of TEG to inactivate the influenza virus [104,105], showing how, among the desiccant solutions, not only the LiCl could be able to inactivate viruses but other additional factors might be involved in process of inactivation performed by desiccant solutions, such as the dehumidification of the virus-laden air, the increase in the salt concentration, *etc.*

It was also suggested by Slayzak et al. [86] that the chemistry of the desiccant solution could be modified to enhance its capacity to inactivate the virus. Metal ions could be added to the liquid desiccant to further increase the sanitising characteristics of the solution without affecting the performance of the technology [86]. In recent years, metal nanoparticles, such as silver, gold, zinc oxide (ZnO), titanium oxide (TiO_2), copper oxide (CuO), aluminium oxide (Al_2O_3), magnesium oxide (MgO), *etc.* have been investigated because of their inhibitory activity against bacteria, fungi and virus [106]. The use of particles with antimicrobial characteristics, such as iodine, chlorine and metals, were also studied for application in filters and surgical masks [107]. These nanoparticles could be added in suspension to the liquid desiccant solution with a resulting increase in the mass transfer process, which could further enhance the removal of viruses or pathogens from the air. Various studies are reported in the literature on the addition of surfactants and nanoparticles to increase the heat and mass transfer performance of desiccant systems [108–112]. Abu-Hamdeh and Almitani studied the addition of ZnO, Fe_3O_4, and Al_2O_3 nanoparticles to water to increase the performance of an evaporative cooling system used in combination with liquid desiccant technology [113]. Langroudi et al. [111] studied the addition of γ-Al_2O_3 nanoparticles to a LiBr solution, identifying an increase in the heat and mass transfer coefficients higher than 20%. Shoaib et al. [112] added nanoparticles of CuO (0.35% vol.) to a $CaCl_2$ desiccant solution, showing an enhancement of the mass transfer process. As investigated by Dong et al. [114], nanoparticles of TiO_2 can also be used for the self-coating of the dehumidifier of a liquid desiccant system to increase the mass transfer of the process.

In addition, Slayzak et al. [86] suggested that Lewis acids, such as aluminium chloride ($AlCl_3$), zinc chloride ($ZnCl_2$), iron chlorides ($FeCl_2$ and $FeCl_3$) and other chlorides acids from the transition metal and lanthanide groups, could be added as homogeneous catalysts in the desiccant solution to increase the chemical reaction of virus inactivation. By increasing the acidity of the desiccant solution, the denaturation of the surface proteins of the virus and the hydrolysis of its viral genome might be stimulated, resulting in the inactivation of the virus [115]. Various studies identified how extreme pHs are responsible for the inactivation of viruses, such as influenza, herpes simplex virus type 1 (HSV-1) and type 2 (HSV-2) [116], virus bacteriophage Φ6 [115], SARS-CoV-1 [117], *etc.* Darnell et al. [117] described how alkaline (pH higher than 12) and acidic (pH lower than 3) conditions would enable inactivation of SARS-CoV-1 virus, together with treatment with heat (at a temperature higher than 65 °C) and UVC light (at a wavelength of 254 nm). In addition, the presence of chloride could be beneficial as antibacterial. SARS-CoV-2 has been tested highly sensitive to disinfectant products, such as chloride [118].

It was reported by Slayzak et al. [86] that negatively charged ions, such as sulphate ion (SO_4^{2-}), phosphate ion (PO_4^{3-}), pyrophosphate ion ($P_2O_7^{4-}$), *etc.*, and organic compounds as salts, such as HCO_2K, or in polar form could also be advantageous to inactivate the viruses. As such, innovative solutions, such as ionic liquids (ILs), could be studied in the future as liquid desiccants not only because of their higher dehumidification ability, lower corrosion, higher solubility, flexibility, *etc.* which could result in a higher performance of the liquid desiccant technology [12] but also because of their potential capacity to inactivate viruses, as demonstrated for the enveloped virus Φ6 by Sommer et al. [119]. Because of the flexibility of these solutions, namely the opportunity of changing cations and/or anions according to the process requirement, it would be possible to investigate a solution able to produce an energy-efficient temperature and humidity control process while ensuring high sanitising characteristics [12]. Recently, Maekawa et al. [82] screened various ILs to investigate the more appropriate fluid for use in air-conditioning systems, identifying the high potential of a quaternary ammonium type IL ([Ch][$DMPO_4$]), characterised by high dehumidification ability, no corrosion to metal and low cost. Quaternary ammonium compounds are also used as cationic surfactants because of their capacity to inactivate enveloped viruses by acting on their lipid surface [120].

Although various hypothesises on the forces acting on the process of inactivation of viruses were suggested, the mechanisms behind the virus scrubbing characteristics of liquid desiccant solutions and how to improve their effectiveness are still not completely clear. Further research must be conducted to evaluate the potential of using desiccant solutions as inactivators of airborne viruses, such as SARS-CoV-2 and influenza, by evaluating the main factors involved in the inhibition of viruses, including the influence of different salts, concentration and temperature of the solution, exposure time, *etc*.

6.2. Case study

To estimate the energy and economic penalty imposed by the recommended HVAC strategies and identify the potential of using the liquid desiccant as an alternative technological solution for airborne viral transmission reduction, an analysis of case studies for different typologies of buildings or public transports was conducted. The main assumptions for the calculations were:

- The operation of the HVAC unit was considered based on the main guidelines: (i) operation at maximum ACH (as reported for different types of buildings or public transports in Refs. [46,84,123]), (ii) 100% outdoor air supply and (iii) prolonged operation (for 2 h before and after the time of occupation of the venue) at minimum ACH. On the contrary, the conventional operation of the HVAC unit was considered as running at minimum ACH for the time of occupation of the venue with a ratio of 80% of recirculated air and 20% of outdoor air [50].
- The annual energy consumption of the HVAC unit was calculated based on Eqs. (2) and (3) considering the indoor design temperature and relative humidity, 100 days of heating demand and 60 days of cooling demand. The average temperature and relative humidity of the outdoor air in winter were considered as 5 °C and 80% RH, while in summer as 21 °C and 70% RH, representative of a typical UK outdoor air condition.
- The internal heat gains in buildings and public transports were estimated based on [84,124,125].
- The COP of the vapour compression cooling system was assumed as 2.4.
- The heating process was assumed to be performed by using natural gas for offices and gyms, while using electrical heating in buses and trains [68], with only sensible heating and no humidification considered.
- The energy consumption for the operation of the fans was estimated based on Eq. (4), considering ΔP_{fan} as 180 Pa and 200 Pa for MERV 8 (used in the conventional case) and MERV 12 (considered as the recommended HVAC practice) filters [126] and η_e is 0.7, operating 300 days per year.
- The cost of electricity and natural gas were assumed as £0.11/kWh and £0.03/kWh [127], respectively.
- The capital cost of the liquid desiccant technology was based on the equation for the specific cost depending on the air volume supply air developed in Ref. [128], while the annual operating cost was assumed as 5% of the capital cost [128].

The results of the calculation of the increase in annual energy, ΔE (MWh/y), and operating costs, $\Delta OPEX$ (£/y), of the HVAC unit due to modifications in operation to reduce airborne viral transmission, are shown in Table 5 for some selected applications in buildings or public transports together with the potential annual OPEX savings achievable with the liquid desiccant technology, ΔLD (%), while Fig. 8 shows more in detail the effect of the different measures on the main energy costs for the selected case studies. In the figure, fan energy consumption increases with the pressure drop due to the use of HEPA filter, increased ACH and prolonged operating hours; while heating, cooling and reheating energy consumption increases due to no air recirculation, increased ACH and prolonged operating hours.

As shown in Table 5 and Fig. 8, the implementation of the recommended guidelines for airborne viral transmission reduction would negatively impact the energy consumption and economics of the HVAC operation, particularly in large scale buildings, such as in offices, malls, *etc*., and where large air change rates are supplied, such as in gyms, hospitals, *etc*. In addition, the increase in the heating demand due to the avoided air recirculation would result in a significant increase in the electricity consumption if the process is performed in cold climates with electric heating. To further understand the effect of the main HVAC recommended measures (reduced air recirculation, prolonged operating hours of HVAC unit and increased ACH) on the energy consumption, a sensitivity analysis was conducted, as shown in Fig. 9 for the case study of the office.

It is clear from Fig. 9 that higher air changes per hour, lower air recirculation ratios and prolonged operation of the HVAC unit largely impact the energy consumption of the HVAC unit in the reference case study. In particular, the increase in ACH (+276%) and no use of recirculated air (+138%) have a primary impact on the energy consumption of conventional HVAC units, being responsible for energy costs that are more than twice that of conventional operation.

Based on the estimation of the capital and operating costs of the liquid desiccant technology for the different application cases, the economic feasibility of replacing the conventional HVAC system (operating accordingly to the main guidelines for airborne viral transmission reduction) was assessed by using three different metrics - the payback period, the internal return rate (IRR) and the ratio between the net present value (NPV) and the CAPEX of the liquid desiccant system. These metrics would allow not only to evaluate the economic feasibility of the technology but also include the time value of the money over its lifespan. The full equations considered the economic feasibility analysis are reported in Appendix 4. In addition, three different scenarios were considered to link the economic figures with possible periods of increased measures, taking into account the case of return to normal operation of the HVAC unit and an intermediate scenario, where the recommended guidelines are only applied during the colder months of the year. Fig. 10 shows the results of the economic analysis, which was obtained considering a discount rate, *i*, of 5% and the lifespan of the technology of 20 years [129].

As illustrated in Fig. 10, the application of HVAC guidelines to reduce airborne transmission largely affects the economic

Table 5
Estimation of the increase of annual operating costs due to recommended HVAC practices in buildings or public transports.

Venue	Volume (m^3)	Occupation (hours)	T_{Indoor} (°C)	RH_{Indoor} (%)	ACH minimum	ACH maximum	ΔE (MWh/y)	ΔOPEX (£/y)	ΔLD (%)
Office	25,000	12	23	50	6	10	3,474.8	119,480	91.76
Gym	5,000	16	20	50	6	15	1,460.3	53,550	91.33
Bus	95.16	18	21	60	4	10	7.78	540.3	73.99
Train	/	18	21	60	0.83[a]	1.2[a]	27.06	1,782.3	77.19

[a] Air volume flow rate (m^3/s) per train carriage [123].

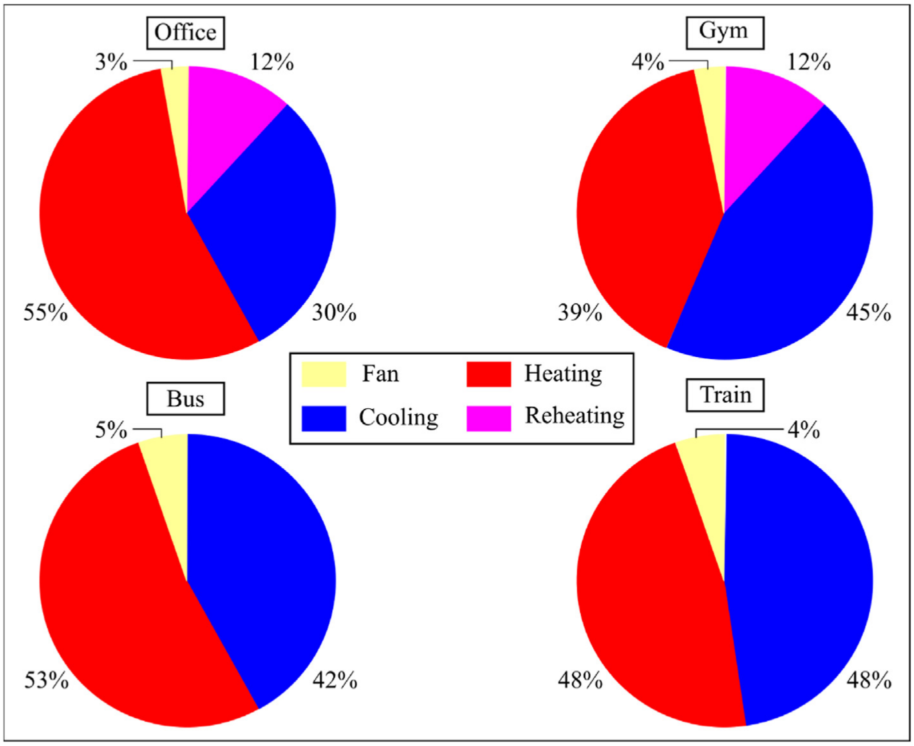

Fig. 8. Pie charts showing the effect of the HVAC measures on the increase of energy costs for the selected case studies.

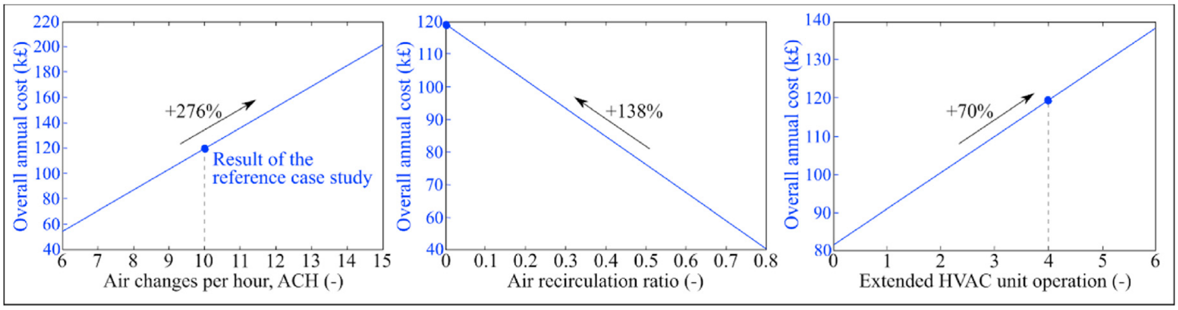

Fig. 9. Sensitivity analysis of the effect of HVAC recommended measures on energy consumption of the case study of the office.

feasibility of deploying the liquid desiccant technology in buildings or public transports. The best economic performance is offered by large scale buildings, such as offices, which, for the scenario of continuous application of HVAC guidelines, show a payback period of 4.1 years, an IRR of 24.03% and NPV/CAPEX ratio of 2.03. The payback period can be significant, particularly for small scale public transport applications, such as buses. Higher IRR means higher efficiency of the process from an economic point of view. It was reported that every investment with an IRR over 15% (shown as the recommended value in Fig. 10b) should be accepted [130], while processes with discount rates as low as 3% are found in the literature [131]. As such, the cost-effectiveness of the liquid desiccant technology would be important not only in large scale buildings, such as offices, but also in the gym, where the dehumidification demand is larger and the non-use of recirculated air is responsible for a huge increase in energy demand. The economic performance significantly decreases for the scenarios of the normal operation of the HVAC unit (which would benefit from a smaller CAPEX of the liquid desiccant system due to the lower airflow that would be required) and for the intermediate scenario due to the high capital cost of liquid desiccant technology at the current state of market development and the more limited energy savings that could be achieved by the technology. It is important to note that all the calculations were performed for retrofitting projects, which did not include the capital cost of the conventional HVAC unit. As such, new projects deploying the liquid desiccant technology in the HVAC unit would present a more favourable economic return.

It was concluded that the liquid desiccant technology would be notably valuable in large buildings where humidity control or moisture removal is required, such as in gyms, indoor pools, food processing, libraries, museums, *etc.* [77]. In addition, the virus-scrubbing characteristics of the technology would be particularly beneficial in buildings where there is a higher probability of the presence of viruses or microorganisms, such as healthcare facilities and operating rooms, or in high-footfall enclosed spaces, in the case of a virus outbreak, although such an ability of desiccant solutions to inactivate viruses should be verified for different types of viruses or variants of the SARS-CoV-2 virus. In the current study, the indoor/outdoor air conditions, the building environment and the operating cost of the liquid desiccant technology are case-specific

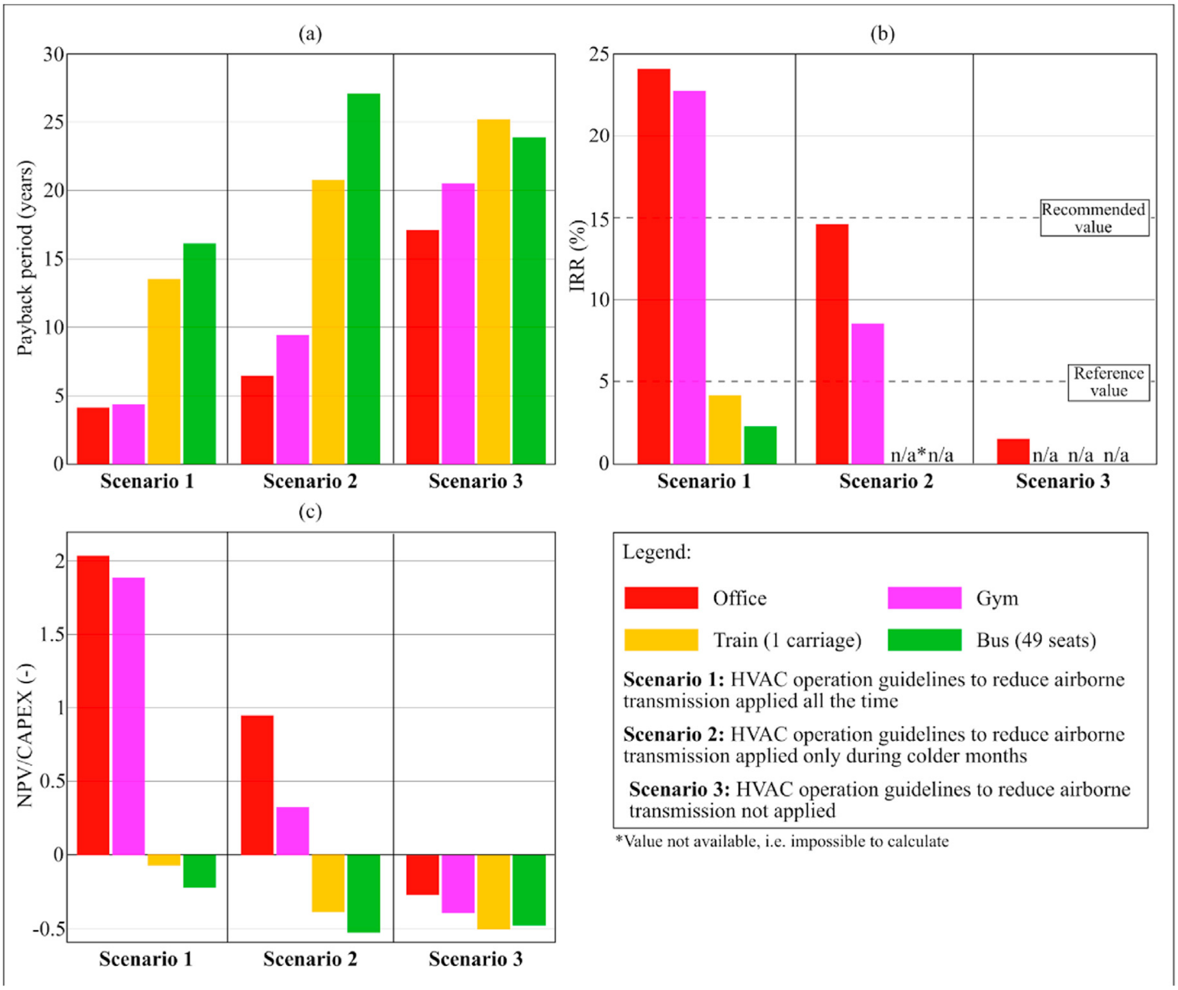

Fig. 10. Results of the economic feasibility analysis for the liquid desiccant technology in some selected buildings or public transports for different scenarios of HVAC guidelines application.

or assumed. Altogether, they presented limitations of the study. A further study should include an in-depth investigation of the effect of these parameters on the energy and economic performance of HVAC units, including economic benefits due to the possible reduced effects from airborne transmission.

7. Conclusion

COVID-19 is a respiratory disease caused by the virus SARS-CoV-2 that has affected millions of people worldwide. Although lacking in research clearly proving how the virus is transmitted and what parameters affect that, the most probable transmission modes currently identified are droplet and fomite transmission. Social distancing, personal protective equipment, quarantine and lockdown measures, have been identified as effective strategies to contain the transmission of the virus. However, growing evidence for airborne transmission has been observed, resulting in higher relevance for HVAC strategies in spaces with high occupancy and showing the importance of including the occupant's safety into the paradigm of future low-energy buildings and public transports.

Main established HVAC strategies to limit the spread of the COVID-19 in buildings and enclosed spaces include the increase of outdoor air and air change rates, the use of higher capacity filters, the use of UV light, *etc.* Although able to reduce airborne viral transmission, these strategies are responsible for an increase in energy consumption and a decrease in thermal comfort, making them not appealing as long-term strategies. In the view of identifying HVAC technologies able to provide a healthy environment for the occupants without affecting energy consumption, this paper demonstrated the potential of the liquid desiccant technology for use in crowded buildings (schools, gyms, libraries, *etc.*), enclosed spaces (elevators, locker rooms, *etc.*) and public transport, particularly for large scale buildings where large air change rates are supplied and humidity control and/or moisture removal is required. The technology could provide benefits in terms of (i) efficient use of energy such as low-grade heat sources, (ii) capacity to independently control temperature and humidity of the supply air, (iii) supply 100% outdoor air, (iv) control of humidity within the range of values less favourable to the growth, proliferation and infectivity of microorganisms (RH between 40% and 60%) and (v) virus inactivation characteristics of the desiccant solutions. The study showed how some conventional desiccant solutions, such as TEG and LiCl, have been largely studied due to their sanitising characteristics. The potential factors involved in the virus inactivation process performed by desiccant solutions (high temperature, increased salinity, effect of Li and Cl ions, exposure time, *etc.*) were suggested together with possible modifications of the solutions to enhance their sanitising characteristics. As a matter of fact, metal ions, such as titanium and copper oxide, could be added to conventional desiccant solutions with beneficial effects in terms of both increased heat and mass transfer and antimicrobial activity. The paper is the first step towards the development of a novel airborne pathogen scrubber system able to draw in the contaminated air, neutralise the airborne particles in the air (viruses, bacteria, fungi, particulates, *etc.*) thanks to the deactivation action of the liquid desiccant solution and push the sanitised air to the environment or recirculate it back to space.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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