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Ten questions concerning the paradox of minimizing airborne transmission of infectious aerosols in densely occupied spaces via sustainable ventilation and other strategies in hot and humid climates

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ABSTRACT

Airborne disease transmission in indoor spaces and resulting cross-contamination has been a topic of broad concern for years – especially recently with the outbreak of COVID-19. Global recommendations on this matter consist of increasing the outdoor air supply in the aim of diluting the indoor air. Nonetheless, a paradoxical relationship has risen between increasing amount of outdoor air and its impact on increased energy consumption – especially densely occupied spaces. The paradox is more critical in hot and humid climates, where large amounts of energy are required for the conditioning of the outdoor air. Therefore, many literature studies investigated new strategies for the mitigation of cross-contamination with little-to-no additional cost of energy. These strategies mainly consist of the dilution and/or the capture and removal of contaminants at the levels of macroenvironment room air and occupant-adjacent microenvironment. On the macroenvironment level, the dilution occurs by the supply of large amounts of outdoor air in a sustainable way using passive cooling systems, and the removal of contaminants happens via filtering. Similarly, the microenvironment of the occupant can be diluted using localized ventilation techniques, and contaminants can be captured and removed by direct exhaust near the source of contamination. Thus, this work answers ten questions that explore the most prevailing technologies from the above-mentioned fronts that are used to mitigate cross-contamination in densely occupied spaces located in hot and humid climates at minimal energy consumption. The paper establishes a basis for future work and insights for new research directives for macro and microenvironment approaches.

1. Introduction

During the last decade, extensive research focused on the concept of healthy indoor environment and the effect of indoor air quality (IAQ) on the wellbeing and productivity of occupants. An acceptable IAQ level is defined based on different aspects: the first aspect is the removal and mitigation of transport of active contaminants such as bacteria and viruses in the room, which are expelled by infected humans via respiratory activities [1–4]. The second aspect consists of meeting indoor carbon dioxide (CO₂) maximum concentration level in the space which is typically less than 1000 ppm [5]. Another aspect is the elimination of internally and externally generated air pollutants found indoors, that are potentially harmful for the human health and well-being [6]. On this matter, there is mounting evidence of the importance of increasing outdoor air supply for the achievement of healthy indoor environment. The increase in ventilation rate (i.e. the supply of outdoor air [7]) amplifies the dilution of indoor pollutants, removes excess of CO₂, and reduces indoor odor and airborne transmission of pathogens, enhancing thereby the IAQ for occupants [8–10]. Dal & Zhao [11] showed that the probability of cross-infection in confined spaces decreased as ventilation increased.

Nonetheless, when considering hot and humid climates, the conditioning and dehumidification of the supplied air to occupied spaces become mandatory, as thermally stressful environments adversely affect the thermal comfort and performance of occupants. When considering densely occupied spaces such as educational classrooms, the need for outdoor air and dehumidification increases and becomes more critical for reduction of airborne transmission of infectious aerosols. However, increasing the ventilation rate results in a higher burden of energy consumption, which opposes the current need to have energy-efficient buildings. Note that in hot and humid climates, there is a perpetual need to condition the outdoor air that is frequently at high levels of temperature and humidity, which adds to the energy consumption of the
buildings. Moreover, the proximity of occupants and the possibility of having infected and healthy persons present in the same space add further challenges to the design of the air distribution system. However, having specific seated positions in these areas make room for both innovation and predictability in effectively designing air distribution systems that deliver the clean air efficiently and provide the thermal conditions for comfort when and where needed in the space. Hence, advancement and development strategies in air distribution systems are needed. These strategies for densely occupied spaces mainly include the dilution and/or the capture and removal of contaminants at both the macroenvironment level, and the air surrounding the occupants at microenvironment level.

When considering the room air macroenvironment, the dilution of indoor air requires sustainable passive cooling strategies that are able to deliver the needed outdoor air supply (Fig. 1). Such techniques should be suitable for hot and humid climates to provide the needed dehumidification and cooling levels for the large amounts of outdoor air with minimal impact on the environment. As for the capture and removal of contaminants from the macroenvironment air, it consists of three fronts in high occupancy spaces: (i) the first front consists of carbon capture and dehumidification techniques \([12,13]\) for the removal of CO\(_2\) and H\(_2\)O from indoor air in the aim of decreasing the outdoor air supply, followed by (ii) the use of efficient indoor filters like High-Efficiency Particulate Absorbing (HEPA) filters for the efficient removal of pollutants \([14,15]\), and (iii) the use of ultraviolet germicidal irradiation (UVGI) for direct killing of certain types of bacteria and viruses \([16,17]\) (Fig. 1).

Similar to the macroenvironment level, there are efficient dilution techniques that target the microenvironment air surrounding the occupant. These localized ventilation techniques are named “personalized ventilation” (PV). They ensure the dilution of the breathing zone (BZ) of occupants by delivering cool and clean air directly at breathing level \([18,19]\). PV systems can also be integrated with non-air based cooling systems that provide thermal comfort to occupants, rendering the PV operation only dedicated for air quality fulfillment. Furthermore, the capture and removal of contaminants at the microenvironment level has been also implemented by the use of personalized exhaust (PE) system. PE is used to exhaust the contaminants at the source (near the BZ) as a mean to prevent their dispersion into the room air \([20,21]\). The combination of these dilution/removal microenvironment techniques (i.e. PV + PE) is further proven to enhance the protection level and reduce the cross-contamination in the indoor space \([22]\). Other contaminants’ removal technique at the source is the disinfection of clothing where expelled contaminants may have been deposited \([23]\). Clothing has the potential to act as a vehicle for spread of infection, and can be regarded as a component of the chain of infection transmission during normal daily activities \([24]\). Respiratory viruses are one of the infectious agents that have the potential for spread via clothing \([26]\). The disinfection can occur either by using disinfecting material for clothes \([25]\) or by using “disinfection tunnels” where people pass before entering the indoor space \([26]\).

The main purpose of this paper is to raise conceptual questions concerning advanced strategies and effective air distribution systems that provide protection against cross-contamination in indoor spaces in

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**Nomenclature**

- AbC/AdC: Absorption/adsorption chillers
- ATD: Air terminal device
- CC: Chilled ceiling
- DPIEC: Dew point indirect evaporative cooling
- DV: Displacement ventilation
- \(\varepsilon_V\): Ventilation effectiveness
- IAQ: Indoor air quality
- IF: Intake fraction
- IPV: Intermittent personalized ventilation
- MV: Mixing ventilation
- LDDM: Liquid desiccant dehumidification membrane
- PE: Personalized exhaust
- PEE: Personal exposure effectiveness
- PER: Pollutant exposure reduction
- PF: Particle filtration
- PV: Personalized ventilation
- RAD: Room air distribution
- RC: Radiant cooling
- UFAD: Under floor air distribution

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**Fig. 1.** Illustration of the different strategies for cross-contamination mitigation in densely occupied spaces.
an energy efficient way in hot and humid climates. We aim to establish a basis for future work and insights for new research directions in this area for dealing with densely occupied spaces. Therefore, we present ten applied, overarching questions for the research community to adopt. While answers are provided to each question raised, they are not intended to be absolute, but rather considered an overview to boost further debates regarding these concepts.

2. Ten questions (and answers) concerning the paradox of minimizing airborne transmission of infectious aerosols in high occupancy spaces

2.1. Question 1: how to increase outdoor air supply for proper indoor dilution in hot and humid climate while decreasing energy consumption?

In indoor spaces, it is challenging to control airborne transmission of infectious aerosols as it can easily spread, especially in crowded places [2,3]. Ventilation is recognized as an important factor influencing the transmission of such infectious aerosols [16,27-28]. The purpose of ventilation is the dilution of the entire indoor space (i.e. the macro-environment); the higher the ventilation rate, the more prominent the dilution effect of indoor pollutants, and the healthier indoor air is for occupants [8]. A study by Dai & Zhao [11] reported that the probability of cross-infection in confined spaces decreased as ventilation increased. Nonetheless, higher outdoor ventilation rates will result in more energy consumption, especially in densely occupied spaces where large amounts of outdoor air are required. This opposes the current need to have energy-efficient buildings [30]. When the climate is hot and humid, the amplified cooling and dehumidification loads further increase the energy consumption. Therefore, there is a pressing need for sustainable air conditioning (AC) technologies that allow the provision of cool clean air at minimal energy cost.

Many literature studies listed in Table 1 investigated different low-energy cooling techniques that are suitable for hot and humid climates [31,32]. Such techniques provide cool outdoor air in a sustainable manner by relying on renewable energy resources including absorption/adsorption cooling [33-36], dew point indirect evaporative cooling (DPIEC) combined with desiccant dehumidification systems [37-40], as well as wind-driven ventilation [41,42] and earth to air heat exchangers [43,44]. Adsorption/absorption chillers (AdC/AbC respectively) are thermally driven heat pumps that rely on low-grade thermal energy (such as solar and waste heat) [35]. Thomas et al. [45] evaluated the energy consumption of an air conditioning system including a solar driven AdC system. They reported 34.9% reduction in the energy consumption was achieved compared to conventional cooling system. A study by Alahmer et al. [46] investigated the performance of an AdC system driven by solar thermal energy, and showed that the solar driven AdC system reduced the energy consumption by 34% with respect to a conventional vapor compression cooling system. Furthermore, the combination of DPIEC with desiccant air dehumidifier has been reported in literature to be an effective solution for energy saving in building. Miyazaki et al. [39] integrated a DPIEC with a fixed-bed desiccant dehumidifier for air-conditioning purposes, and reported that the system has a promising COP value of 0.75 as a waste-heat-driven air-conditioning system. Wind-driven ventilation is another passive technique that relies on pressure difference to drive the airflow. Specifically, wind catchers are architectural passive cooling elements designed to improve indoor thermal comfort without energy consumption [31]. A study by Ji et al. [42] showed that 17% of the cooling load was educed due to the implementation of wind catchers in residential buildings in the hot and humid weather of Beijing (China). The use of the ground as a heat sink is another viable solution for conditioning the air at reduced energy consumption. This is possible by using earth to air heat exchangers (EAHE), consisting of pipes buried in the soil, while an air circulation system forces the supply air through the pipes for cooling purposes [32]. Another efficient strategy that provides extensive energy savings is the use of enthalpic recovery units [47]. The enthalpic recovery ventilators (ERV) transfer both sensible heat and moisture (latent heat) between the exhausted indoor air and the supplied outdoor air [47, 48]. Thus, the incoming outdoor air is pre-cooled and dehumidified. A study by Nasif et al. [49] assessed the performance of an ERV. The performance of a heating, ventilating, and air conditioning (HVAC) system coupled to the enthalpy exchanger was simulated and the results showed savings of up to 8% in annual energy consumption in a hot and humid climate.

However, the provision of outdoor “clean” air itself may contain undesirable gaseous contaminants at concentrations above recommended thresholds. Concentrations of outdoor-originating pollutants are considered a major contributor to concentrations of indoor pollutants [50]. The exposure to outdoor air pollutants is an issue especially when considering highly polluted urban environments: the impact of outdoor particles on the indoor environment is particularly important in places where outdoor air pollution is serious. Outdoor pollutants include particulate matter (PM2.5 and PM10), Nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), sulfur compounds, bioaerosols, ozone etc. [51]. Note that some of these pollutants may be generated indoors as well (like VOCs and PMs). Therefore, the supplied outdoor air needs adequate treatment before entering the indoor space. This can be achieved by many literature-reported and tested strategies, such as air filtration and adsorption techniques [50,52,53]. Such methods are recognized for cleaning the outdoor air to reduce occupant exposure to harmful externally-generated pollutants. Particle filtration (PF) is an effective and low cost air cleaning technology for particle capture [54]. PF systems are widely used within HVAC systems to reduce concentrations of particles in indoor air [52]. PF systems usually employ mechanical filters where the closely spaced layers of fibers catch and collect particles. Other types of PF systems are electronic air filtration systems generating ions to electrically charge particles and collect them on cleanable metal plates [52]. Adsorption techniques are differentiated between physical and chemical: In physical adsorption,
the adsorbate molecules adhere to the adsorbent materials in a physical bonding by molecular attraction (van der Waals forces) – a process also known as “physisorption” [55]. In chemical adsorption, a chemical bond is created between the contaminants and adsorbent material. This bond is referred to as “chemisorption” [56]. Solid particle dust and some organic gas pollutants can be directly removed by physical adsorption, and sulfides and nitrous oxides, heavy metals and VOCs can be removed by chemical adsorption.

2.2. Question 2: what strategies are used to minimize outdoor air requirements in the space macroenvironment while mitigating cross-contamination in hot and humid climates?

Passive AC techniques are suggested in question 1 when large amounts of outdoor air are supplied to the indoor space to mitigate cross contamination, in the aim of reducing the penalty on energy consumption. However, apart from the energy cost associated with cooling and dehumidifying the ventilation outdoor air, there is need for treating it as it can contain outdoor-air pollutants as previously discussed [54]. This need for decontaminating the outdoor air emphasizes the fact that outdoor ventilation (i.e. the supply of outdoor cooled air to the indoor space) is not always a viable economical option, as the outdoor air requires extensive energy consumption not only for cooling and dehumidification purposes, but also for exempting it from any plausible pollutants. **Reducing the outdoor air intake while cleaning the indoor air** would therefore be an attractive method to provide improved IAQ at reduced energy cost [66]. This is especially applicable in regions experiencing haze periods, dust storms and thermal inversion conditions [66–68], where the use of outdoor ventilation will be costly as the treatment of the polluted outdoor air may drastically increase the energy burden. However, when considering cleaning the indoor air, the used filtering processes are not 100% efficient and require additional airflow filtering to exempt the indoor air from contaminants [69]. Therefore, there is a need to slightly increase the filtered circulated airflow. Thus, there is a set of criteria to choose whether to disinfect the supplied outdoor air or the recirculated air inside the space by using air-cleaning strategies [54]: to save energy when reducing the outdoor ventilation air in combination with indoor-air cleaning, the energy consumed per unit of clean air delivery for indoor-air cleaning must be less than that required per unit of outdoor air supply. Furthermore, to be economically attractive, the total cost per unit of clean air supply for air cleaning must be less than or equal to the total cost per unit air supply for ventilation. These criteria will assure that indoor concentrations of indoor-generated pollutants are maintained at low levels in a cost-effective way. Thus, the cost of such cleaning techniques must be considered a priori, and implemented within the cost assessment of the overall cooling system, to form a holistic perspective. Note that generally, the cost of filtering the indoor air is much less than that related to the energy required for cooling, dehumidifying and treating the outdoor air. Indoor air cleaning techniques involve applying filtration or purification of the recirculated indoor air, or filtering air locally in the room. This is achieved by using filters like high-efficiency particulate air filter (HEPA) or ultraviolet germicidal irradiation (UVGI) lamps [70–73]. Many literature studies investigated these strategies for contaminants’ reduction and/or removal from the indoor air.

A method widely used for air filtration is the implementation of filters in the HVAC ducting system [74] or in a portable air cleaning unit [75]. The in-duct filtration consists of retrofitting the filters into the ducting system to filter the incoming outdoor air or the return air or both of them simultaneously. Lam et al. [76] reported the efficient integration of in-duct filters to the existing ventilation systems to achieve ultra-low suspended particles in commercial offices. However, in-duct filters are only capable of purifying the supplied air to the indoor macroenvironment. In comparison, portable air cleaning units are placed at close proximity to the occupants, targeting their microenvironment to prevent transmission of infectious airborne aerosols [77]. Such filters have been considerably studied in literature for their effectiveness in removing airborne particles and reducing their concentration in indoor spaces [78,79] as well as reducing cross infection [80]. Boswell et al. [80] assessed the effectiveness of a portable HEPA filtration unit at reducing methicillin-resistant *Staphylococcus aureus* (MRSA) environmental surface contamination. They concluded that the rate of MRSA environmental contamination was significantly reduced by 75–93% using portable HEPA-filtration unit. Zhai et al. [81] studied the potential reduction of cross-contamination of different installations of air purifiers (on table standing and floor-standing purifiers) in two typical public spaces (restaurant and ballroom) as compared to the use of the existing central-air conditioning systems. They concluded that table air purifiers provide effective means to help mitigate airborne transmission of pathogens, reduce the dispersion of particles, minimizing thereby the particle deposition on occupants. In addition, the upward flow of the purifier pushes the particles toward the ceiling rather than distributing it horizontally, which reduces cross infection. In a recent study by Cooper et al. [82], occupants reported the portable air cleaners to have a ‘cooling’ effect, which rendered the predominant driver of portable air cleaners use was thermal comfort rather than IAQ. The fact that the air purifiers had a cooling effect may lead residents to use the air purifier more often in the cooling months irrespective of the actual air quality. This should be considered in future investigations of portable air cleaning units’ implementation in indoor spaces.

A more thorough viral disinfection method that has been studied in literature is using ultraviolet (UV) irradiation. In this method, the disinfection of air occurs by the use of UVGI lamps either integrated inside the HVAC ducts or mounted at ceiling/wall upper room level. Several field studies assessed the efficiency of in-duct UVGI (ID-UVGI) in mitigation of cross-contamination via recirculating route of HVAC systems [83–85]. Foarde et al. [83] studied the implementation of 12 lamps into the HVAC ducts. They reported high levels of inactivation efficiencies (~90%). Laboratory research has proven that the deactivation effect of the UVGI is primarily a function of two factors: the intensity of the UVGI energy and the duration of exposure [86–89]. However, the bacteria’s residence time is relatively short in the case of ID-UVGI due to the high speed of air in the supply duct. Therefore, a high UV output is needed which affects the system energy efficiency. Consequently, more attention has been paid to room-mounted (ceiling or wall) UVGI lamps. Nonetheless, human exposure to UV light should be minimized to avoid skin and eye irritation [90]. Short-term overexposure to UV radiation is known to cause erythema (reddening of the skin), photokeratitis (inflammation of the cornea), and conjunctivitis (inflammation of the conjunctiva, also known as pinkeye) [91]. Therefore, one recommended application of UVGI is to irradiate the upper part of the room by UV lights mounted in deep louvers at the ceiling level [92–94]. This helps minimizing radiation exposure of occupants in the lower part of the room. Kanaan et al. [95] studied the effect of the UV lamp power on reducing cross-infection. They found that using a total lamp power of 30 W reduced the concentration of bacteria in the breathing zone of the occupant by 31% below the minimum limit for healthy air recommended by ASHRAE [96]. The inactivation process of upper-room UVGI can be enhanced by generating an upward flow that facilitates the transport of pollutants toward the irradiated zone and by promoting high levels of mixing in rooms [97]. Note that further guidelines for UVGI applications are available at [94,98]. Kanaan et al. [99] investigated the performance of upper-room UVGI in a typical two-bed patient room with three different ventilation systems: mixing, downward and displacement ventilation. They reported that UVGI can achieve an efficiency of 99.8% in the occupied zone for both mixing and downward ventilation systems whereas an efficiency of 78% is achieved in the case of displacement ventilation.

Many literature studies compounded the germicide capacity of UV-rays with commercially available filters [100–103] to mitigate cross contamination and provide an acceptable IAQ. For this purpose, the UV lamps could be placed in a position to directly irradiate the filter surface.
or the air stream. D’Orazio et al. [101] assessed the two previously described positions of UV lamps with respect to a HEPA filter implemented in HVAC ductwork for their disinfection potential. The results obtained demonstrated that for disinfection purposes, the irradiation of HEPA filters by UV provides better results than irradiation of the air streams. Kashkooli et al. [100] studied the impact of the location of a commercial portable air cleaning device (HEPA filter/UV light) on its capacity for microbial decontamination of indoor air. They concluded that in all positions, the air cleaning device had removed the microbial particles efficiently with a minimum removal effectiveness of 98.67% and a maximum removal effectiveness of 99.46%. Note that many studies assessed the impact of different operating parameters on the decontamination efficiency of different air cleaning strategies in numerous space types and are summarized in Table 2. It is worthy to mention that these air cleaning strategies – mainly UVGI and portable air cleaners – are generally chosen based on the application and function: usually UVGI is adopted in hospitals and rarely in residential buildings [104,105], while air cleaners are more found in office spaces and residential houses [106,107]. Thus, there is a relationship between the type of air cleaning system and the place of application, however, there is no clear recommendation based on occupancy density. This however can be a topic of utmost priority for future work.

While air filtration technologies play an important role in terms of removing airborne contaminants and increasing IAQ, they also play a significant role in the HVAC system’s energy consumption and operating cost [108,109]. A rigorous economic analysis of such systems thus requires the simulation of both the performance in terms of air quality enhancement and the annual energy use and cost. Therefore, the life cycle costs (including filters’ initial cost and replacement) and energy costs should come into play during the air filtration technology selection process. Furthermore, for air filters, the filter pressure drop should be considered, since switching to lower pressure drop filters helps reducing energy costs [109]. Accordingly, in the filter industry, the development of new materials allowed the production of lower pressure-drop media while still preserving high particle capture efficiencies, which maintains the ability to improve the IAQ while reducing energy costs concurrently [109]. Rosenfeld [110] have reported that the upgrade of the filtration system of an office building to more efficient filters have led to financial benefits resulting from an improved indoor environment that exceeded the costs of filtration by as much as a factor of twenty. As for the UVGI system, the system’s initial cost will vary by space and square footage, as well as the amount of coverage needed [111]. As for the operation and maintenance costs, they include the cost of electricity to operate the lamps, increased cooling load, and maintenance (lamp replacement). A study by Lee et al. [112] showed that the UVGI system in an office building added no more than 0.3% to the total energy consumption.

2.3. Question 3: how to decontaminate indoor air while preventing CO₂ and moisture buildup in the space at reduced macroenvironment outdoor air intake?

Although the use of decontamination technologies ensures clean air free of contaminants, these techniques do not eliminate the buildup of CO₂ and water vapor in densely occupied spaces. In other words, they do not reduce the need for outdoor air intake and for dehumidification of both outdoor and return air to lower the CO₂ concentration and the relative humidity to acceptable levels in the conditioned spaces. Ensuring acceptable levels of CO₂ indoor is a primary criterion in any implemented ventilation system since high CO₂ concentration has negative effects on productivity, perception, and health of humans [119]. Thus, the removal of CO₂ from indoor spaces is essential, especially from densely occupied spaces where CO₂ production is considerably large and requires high amounts of outdoor air for dilution to acceptable levels. Furthermore, apart from generation of CO₂ occupants generate water vapor and hence the indoor relative humidity should be monitored too. To reduce energy use in hot humid climates while meeting CO₂ and relative humidity requirements, carbon capture and dehumidification techniques are necessary to be implemented in densely occupied spaces where air is recirculated. These techniques target the macroenvironment by reducing the level of CO₂ and water vapor in the indoor air.

In recent years, CO₂ capture technologies have been evolving with

| Table 2 | Research studies on the decontamination effectiveness of air cleaning strategies. |
|---------|--------------------------------------------------------------------------------|
| Air cleaning type | Space | Operating conditions/studied parameters | Optimum particle removal efficiency | Reference |
| Portable HEPA filter | Hospital ward | Airflow rate through the portable air cleaner | Effective air change rate³: 5.6 ACH | [79] |
| HEPA/UV portable air cleaner | Aerobiology chamber | Position of the air cleaner in the space | 99.46% | [100] |
| UVC and HEPA filters in HVAC ducts | Experimental | Position of the UV-C lamp with respect to the HEPA filter | Decay rate²: 0.189 per minute | [101] |
| Ceiling mounted UVGI | Office | UV power output | 36% | [95] |
| Wall mounted UVGI | Environmental chamber | The inlet air speed of the ventilation system | 96.9% | [113] |
| Wall mounted UVGI | Test chamber | Types of UVC lamps | Decay rate: 0.4745 per minute | [114] |
| Portable HEPA filters | Room of a typical apartment | Position and orientation of the air cleaner with respect to the pollutant source | 49% | [115] |
| Portable air filter | Small lecture room | - Airflow rate - Filtration efficiency | CADR² = 259.2 cfm | [116] |
| Portable air filter | Workshop environment | - Position of the air cleaner with respect to the air-conditioner - Filtration efficiency | -90% | [117] |
| Portable HEPA filters | Room of a typical apartment | - Position of the air cleaner with respect to the furniture - Air ejection angle | 67% | [106] |
| Portable HEPA filters | Office room | Position of the air cleaner with respect to the supply and exhaust location of different ventilation systems | CADR = 139.06 cfm | [107] |
| Portable HEPA filters | Bedroom | - Airflow rate of the air cleaner - Position and orientation of the outlet air | 80% | [118] |

² Effective air change rate: it determines how many times the purifier can purify the entire room air within 1 h.
³ Decay rate: it describes the decrease in the number of contaminants due to purification or inactivation per unit time.
⁴ CADR: the clean air delivery rate is the fraction of particles removed from the space multiplied by the airflow rate through the device.
emergence of new generation of highly porous solid adsorbents, known as metal-organic frameworks (MOFs) [120,121]. The most appealing property of MOFs is that they can be custom-synthesized to exhibit high capacity for CO$_2$ in dilute airstreams [122]. This CO$_2$ capture technology has gained attention in HVAC applications where it is based on removing the excess CO$_2$ from the indoor air using adsorption [123]. It can potentially save energy as it enables the use of a fraction or fully recirculated indoor air in the supply vent [124]. In addition, it reduces the outdoor ambient air intake to small amounts dedicated to the regulation of indoor O$_2$ levels and other pollutants levels as VOCs and PM within the IAQ constraints, leading to significant energy savings [125]. Adsorption/absorption technique in carbon capture beds is implemented, and it relies on an adsorbent/absorbent to capture the CO$_2$ and then regenerate it [12]. Such operation is cyclic, introducing fluctuation in the absorbed/adsorbed CO$_2$ during the capturing and regeneration period [125]. Renewable energy (such as solar, wind, hydropower and bioenergy) can be deployed for the regeneration of such beds, which brings out their sustainable operation [126]. Cheng et al. [13] reported an alkanolamine bed to be an effective absorbent for reducing CO$_2$ concentration from 1000 ppm–100 ppm over a long period of time. Another study by Wang et al. [127] evaluated the CO$_2$ capture on amine-impregnated solid adsorbents in the range of 400–5000 ppm where the cyclic performance was assessed with the adsorbents regenerated under a mild temperature. Sinha et al. [128] proposed a CO$_2$ capture system that removes CO$_2$ from the indoor air through concentration swing adsorption cyclic process. They reported this direct air capture of CO$_2$ as feasible strategy for reduction of energy requirements from enclosed environments since the outdoor air intake fraction is considerably decreased. These CO$_2$ capture devices generally focus on decreasing the indoor CO$_2$ concentration level; however, the strategy should simultaneously consider the indoor humidity level increase due to the generation of water vapor by occupants and moisture present in outdoor air intake. The study of Kim et al. [129] investigated the moisture capturing performance of a CO$_2$ capture device for air ventilation in buildings. They reported that it is possible to maintain a comfortable humidity ratio indoor when using CO$_2$ capture devices for an effective air recirculation process.

Apart from CO$_2$ and water vapor capture that allows the reduction of outdoor air requirements while using sustainable energy sources, recent findings in literature showed the likely use of such techniques in decontaminating the air from pollutants by killing active germicidal contaminants. A study by Li et al. [130] highlighted the potential of zinc-imidazolate MOF (ZIF-8) of air pollution control by inactivation of bacteria. This opens the horizon for a holistic use of these techniques in bio-contaminant deactivation and sheds light on the photocatalytic antibiotic capability of MOFs for public health protection. Future work should focus on the MOFs development as material with the dual characteristics of carbon capture and bacteria/virus deactivation as an effective method for use in HVAC applications. However, the decrease in the production cost of MOFs remains an important requirement envisaging their possible industrial availability [131].

2.4. Question 4: what are the state-of-the-art air distribution systems used to provide outdoor air and capture contaminants at the occupant-adjacent microenvironment?

The increase of outdoor air supply (i.e. dilution of indoor space) and/or the integration of indoor air cleaning methods, and decarbonizing the recirculating air for reduction of energy burden, are methods that help mitigate effectively the cross-contamination effect between occupants in indoor spaces by targeting the room microenvironment room air (Fig. 1). However, recent studies focused on other cross-infection control strategies that directly target the microenvironment of occupants, named source control strategies. These methods are effectively designed to reduce airborne transmission of infectious aerosols transmission between occupants at a minimal energy cost: air distribution systems are generally integrated with innovative localized ventilation like personalized ventilation (PV) and/or personalized exhaust (PE) devices.

PV devices provide users with enhanced breathable air quality by delivering a jet of cool clean air towards the upper-body part – namely the face [132]. This enables the relaxation of the requirements of the macroenvironment in terms of temperature and air quality (Fig. 2(a)). PV also provides the user with the advantage of adjusting the delivered airflow conditions (flow velocity, direction and temperature), allowing occupants to test their microenvironment according to their thermal preferences [133]. Different designs of air terminal devices (ATD) have been examined for their effectiveness in diluting the breathing zone (BZ) of the users and reducing cross-contamination: the round movable panel (RMP), vertical desk grill (VDG), computer monitor panel (CMP), horizontal desk grill (HDDG), ceiling PV (CPV) and chair-based PV (CBPV) (refer to Fig. 2(b)) [134,135]. Melikov et al. [134] investigated the performance of five ATDs for a PV system with regard to occupants’ quality of inhaled air. They found that the most effective ATD that was able to provide the highest protection level was VDG.

Most of the studies in literature have evaluated the implementation of PV for sparsely occupied spaces and clinics. Nonetheless, when considering densely occupied spaces, there are challenges hindering the practical implementation of PV systems, such as visual or physical obstruction to occupants, lack of available ‘free area’ to implement PV system, change in room infrastructure when multi-stations of PV units are installed, etc. Based on the preceding considerations, many literature studies suggested the fitting of PV into “built-in furniture” of the space [136–141]: chair [142,143], desk [144,145], ceiling mounted [146–149] and ductless PV (DPV) [144,150] (shown in Fig. 2(c)), or headset incorporated PV [157,151]. Alsaud et al. [150] evaluated the performance of a desk-mounted DPV system in a typical office setup. The investigations showed a significant improvement in inhaled IAQ when ductless system was used compared to the casewhen no DPV was used: the ventilation effectiveness index increased up to 98%. Bolashtikov et al. [137] studied the headset incorporated PV nozzle potential for increasing the inhaled air quality. They concluded that this wearable PV unit was able to increase up to 94% the portion of clean air into the inhaled air and reduce the risk from airborne disease transmission. Makhoul et al. [146] assessed the performance of ceiling mounted PV in reducing particle migration between office stations. They found that the suggested PV was effective in reducing the cross-contamination from the macroenvironment to the microenvironment region around the occupant, and low intake fraction (defined as the pollutant mass inhaled by an exposed person per unit mass of emitted pollutants from the source [152]) of the order of $10^{-4}$ was achieved for different particle sizes.

Many other studies in literature focused on removing contaminants directly from the personal microenvironment of the source occupant before they are dispersed into the surrounding bulk airflow. This contaminant removal process is known as PE and is accomplished using localized suction orifices near the infected person to ingest the individual’s thermal plume and exhaled air and exhaust them from the occupied space [153]. The orifices can be placed at different locations inside the occupant’s micro-environment as shown in Fig. 2(d), either above the shoulders (shoulder PE) or overhead (Top PE) [154]. The ability of PE devices in improving the quality of inhaled air and reducing cross-infection has been extensively elaborated in literature [20–22, 154–156]. Dygert et al. [20,21] studied numerically and experimentally the effectiveness of using PE devices to mitigate cross-contamination within an aircraft cabin. They showed an average reduction of 40–50% in personal exposure to cross-contamination from neighboring passengers. Ahmed Qasim et al. [157] developed a novel local exhaust ventilation system integrated in office’s workstation. This system was able to reduce the concentration of contaminant in the micro-environment area by up to 61%.

It is noteworthy to mention that the retrofitting of such localized air distribution systems in densely occupied spaces is not practical in real
life application like classrooms or theatres. In such crowded places, there may be no available space for the integration of these systems. Furthermore, the ducting may shield the sight of occupants. Thus, it is important for future work to consider the practical implementation of localized air distribution systems in densely occupied spaces. This includes further development of highly-efficient ergonomically-feasible PV air terminal devices that are either wearable or integrated with furniture with ultimate aim of supplying clean air to the breathing zone of the wearer or occupant. Furthermore, such applications of personalized systems may be regarded as exclusive, due to the high installation cost \[132\]. Thus, the cost of the adopted localized ventilation system must be considered when assessing the savings resulting from their implementation.

2.5. Question 5: what is the effect of combining PV with PE on cross-contamination?

After investigating the benefits of the PV and PE systems separately, the interest of research studies concentrated on combining these two systems together and assessing the resulting effectiveness with the aim of ensuring good dilution and creating a germ-free microenvironment \[22,156,158\]. The PV system was shown in literature to promote contaminants’ transport between occupants in the cases where the user is infected: a study by Katramiz et al. \[159\] showed the effect of PV use by an infected person sitting either in tandem or face-to-face with respect to a healthy person using PV in an office space, and assessed the exposure levels. They reported that with the use of PV, the face-to-face seating provided better protection for the healthy person, as the PV jet used by the infected person dispersed the exhaled contaminants in the opposite direction away from the exposed person. Furthermore, they found that the exposure level is increased in the case where the healthy person is not protected by PV (i.e. not using PV - based on his/her thermal preferences). Therefore, PE was an effective complementary system that can extract the exhaled contaminants at the source (i.e. near the BZ of the infected person) and contain the PV jet, which mitigates the dispersion of the pollutants. The ability of PE in reducing the spread of PV-entrained contaminant depends on its location with respect to the PV and its suction flow rate. If placed at the same level and opposite from the PV outlet, with careful design of its suction flow rate, the PE system is able to pull the PV jet towards it, thus preventing it from developing in the room and mixing with the indoor air. Moreover, The PE suction phenomenon allows for easier delivery of the PV clean air directly to the BZ of the users by purging their respiratory flows and thermal plumes (refer to Fig. 3).

Many studies in literature assessed the ability of different PV/PE combinations in providing good inhaled air quality and are summed up in Table 3. Yang et al. \[154\] numerically studied the ability of PV + PE used by both infected and healthy people in reducing cross contamination. They found that the use of VDG with top PE at a gauge pressure of –30 Pa completely sucked exhaled contaminants from the infected occupant, preventing thereby their spread and transmission to the healthy occupant. Junjing et al. \[22\] experimentally investigated the ability of shoulder PE in increasing the amount of PV air reaching the BZ of a healthy occupant, when the latter changes his/her seating position.
axially and radially. They found that PE operating at 10 L/s increased the inhaled PV clean air within a 30° and 0.2 m shift from the PV outlet, while PE at 20 L/s increased the inhaled PV clean air within a 60° and up to 0.4 m shift from the PV outlet. Hence, the aforementioned research conducted on the integration of PE with PV highlights the potent effect the PE system has on the effectiveness and practicality of the PV system implementation.

The above-mentioned studies considered non-densely populated spaces (like office spaces and clinic) for the implementation of the PE + PV system. However, for densely occupied spaces, the combination of PE with PV should deliberate new novel designs that can be either wearable or embedded in furniture with little to no ducting. This is crucial for the practical implementation of such systems in real life applications like classrooms or theaters, where occupants are at close proximity. Accordingly, the background ventilation system should be adequately chosen to assist the localized air ventilation system in providing the required air quality and thermal comfort levels to occupants. Future research should thus focus on the practicality of integrating PV + PE system operation with background macroenvironment and investigate its optimal design for effective simultaneous delivery of clean air and removal of pathogens at source for densely occupied spaces.

2.6. Question 6: ‘how to assess the air quality provided by the different air distribution systems?’

The use of localized air distribution systems like PV and PE results in non-homogeneous contaminants’ distribution in the space. Thus, it is essential to assess the air quality provided to the occupants upon the use of these systems. This is considered as a measure of the success of the PV/PE systems implementation. In this context, different indices have been used in literature to assess the air quality provided by these localized ventilation systems and are summarized in Table 4. All the indices are calculated at the occupant’s breathing zone (BZ) – defined as a spherical control volume having a radius of 1 cm located at 2.5 cm away from the occupant’s nose [162].

One approach for understanding whether a particle level of emission is acceptable or requires mitigation is through the use of a well-known index: the intake fraction (IF). The latter has been proposed as the primary label for quantifying the emission-to-intake relationship and has been defined by Nazaroff [152] as the pollutant mass inhaled by an exposed person per unit mass of emitted pollutants from the source. Many researchers reported intake fractions associated with human respiratory activities under different micro and macroenvironment ventilation conditions. Li et al. [135] adopted the IF index to assess the cross contamination of two types of PV systems (desk-mounted and chair-based PV) for different particle sizes emitted during breathing activity. The highest intake fractions were observed when using desk mounted PV. In this case, the intake fraction recorded values between 2.54E-04 and 1.91E-03. Yang et al. [163] measured the effectiveness of the PE suction device at controlling cross-contamination risks between an infected person and a healthy person in a consultation room. They reported the lowest IF (between 1E-03 and 4E-03) when the top suction device was operating.

Two other indices have been introduced to express the reduction of the concentration of pollutants in the inhaled air with respect to (i) the exhaust air and is called the ventilation effectiveness index ($\epsilon_V$), and (ii) the average room air and is called the pollutant exposure reduction index (PER). These indices are used to assess the air distribution efficiency in rooms and around human body. Cermak et al. [164] assessed the occupant exposure under different PV ATDs using the ventilation effectiveness index. They reported a lower concentration of pollutants (lower $\epsilon_V$) in the BZ of the manikin using VDG than with the manikin using RMP. Dygert et al. [21] studied the reduction in personal exposure of passengers in an aircraft cabin under different PE types. They showed a reduction in personal exposure to cross contamination from neighboring passengers of 40–50%.

The personal exposure effectiveness index (PEE) is another index that has been used in literature to evaluate the inhaled air quality resulting from the integration of different PV ATDs. It is defined as the amount of personalized air in inhaled air, and is equal to one when 100% of personalized air is inhaled and zero if no personalized air is inhaled. Hence, a higher PEE index means a higher amount of clean air in the inhaled air. Melikov et al. [134] tested the performance of five ATDs for a PV system in regard to the quality of inhaled air assessed using the PEE. The highest index was achieved by a VDG ranging between 0.4 and 0.6 for a wide interval of flow rates ranging between 5 L/s and 20 L/s.

Based on the objectives of the work, the adoption of the appropriate index is important to translate the effectiveness of the system under
investigation (PV/PE). For example, if the aim is to assess the exposure of healthy occupants to contaminants emitted by an infected person, the \( iF \) index should be used. However, if the purpose of the work is to assess the efficiency of PV use in terms of dilution of the BZ, the PEE index is recommended for adoption. In the studies assessing the performance of PV/PE under different background ventilation systems, the \( eV \) index is advised for use.

It is noteworthy to highlight that the above-mentioned indices require the knowledge of the concentration of contaminants at the breathing zone of the person, as well as in the supply and return air. Thus, particles monitoring sensors are needed. Optical particle counter sensors provide fast and accurate measurement of concentration of particle using single particle counting technology [165]. The monitoring strategy should take into consideration the limits of accuracy and cost of these sensing devices and their need for calibration. This may have an implication on the cost of the system as it relates to the system operational cost.

2.7. Question 7: how to select the proper operational and physical conditions for the standalone PV system for reduced cross-contamination?

Many literature studies focused on the implementation of different PV ATDs for the provision of protection to occupants, without the integration of PE. Such studies highlighted the importance of the background ventilation system choice, as the effective implementation of each PV ATD depends on the room flow field conditions established by the room air distribution (RAD) system. The design of the PV system and the interaction of the PV airflow and room airflow should be carefully considered in order to achieve minimal transport of pollution between occupants [174]. Commonly investigated RAD systems include: mixing ventilation (MV) [159,162], displacement ventilation (DV) [150, 175], or under floor air distribution (UFAD) [18,168]. MV systems provide a mixed environment in the occupied zone with uniform conditions of temperature and concentration of contaminants. In DV equipped spaces, the air is supplied directly into the occupied zone at low momentum and higher temperatures. Thus, DV systems create quiescent stratified environments with low turbulence, and vertical gradients of temperature and concentration of contaminants. As for UFAD, it is a partial stratified ventilation system: high momentum air enters the room by swirl diffusers placed on the floor, creating high mixing levels throughout the room.

The criteria followed to unravel the most effective combination of PV/RAD mainly consider the effectiveness of the combined system in reducing cross-contamination in the indoor space, providing acceptable levels of breathable air quality to the user, and minimizing energy consumption. To achieve the same amount of breathable air quality, the needed supply flow rate of clean air from the PV when used in different macroenvironment air conditioning system might differ. In literature, many studies assessed different combinations for their ability in providing good breathable air quality and are summed up in Table 5. Li et al. [135] studied two different PV types supplying air in two different directions (chair-based and desk-mounted) with both DV and MV systems. They found that with a DV background system, better inhaled air quality is achieved with chair-based PV: the clean air is delivered to the breathing zone of the occupant with the same upward direction as the DV. Whereas, with MV background system, the airflow supply direction of the PV has no impact on the inhaled air quality. Shen et al. [168] investigated pollutant transmission under the combination of two types of PV terminals (RMP and VDG) and three kinds of typical background ventilation systems (MV, DV and UFAD). They reported an improvement in the inhaled air quality in PV/MV conditions compared to the case when no PV was used. Whereas, in PV/DV and PV/UFAD conditions, the air quality decreased compared to the no PV case but remained better than PV/MV conditions. In addition, considering IAQ, VDG operating at small flow rates and RMP operating at high flow rates are favorable. Melikov et al. [134] evaluated the ability of five PV ATDs in providing acceptable inhaled air quality. They concluded that the highest exposure effectiveness of 60% was achieved by a VDG providing personalized air upward to the occupant’s face combined with both mixing and displacement ventilation. The literature studies are not conclusive in the proper selection of PV that is well-matched with existing RAD. It is important that matching PV with RAD should be done while considering the feasible implementation, the needed renovation work in old buildings, the ability to deliver clean air to breathing zone, and the energy consumption of combined system. Future work should establish a guideline and recommendations on matching the appropriate type of PV and its operation for a given macroenvironment RAD. It is worth mentioning that when using PV, the macroenvironment should be maintained at a threshold temperature value that is generally lower than 30 °C, between 26 °C and 29 °C [176]. This is important to avoid causing thermal draft problems, which may aroused due to high differences between microenvironment and macroenvironment air conditions for the standalone PV system for reduced cross-contamination.

Table 4

| Index expression | Considered parameters | References |
|------------------|----------------------|------------|
| \( \frac{M_{ex}}{M_{e}} \) | - \( M_{ex} \) is the contaminants mass at breathing zone of the exposed person - \( M_{e} \) is the contaminants mass emitted from the source/infected person | [21,156,159,163,166,167] |
| \( \frac{C_{e}}{C_{e}} \) | - \( C_{e} \) is the concentration of contaminants at the BZ - \( C_{e} \) is the concentration of contaminants at the exhaust | [164,168] |
| \( \frac{C_{e}}{C_{e}} \) | - \( C_{e} \) is the concentration of contaminants in the inhaled air without PV use - \( C_{e} \) is the concentration of contaminants in the inhaled air with PV use | [18,134,150,169] |
| \( \frac{C_{0}}{C_{0}} \) | - \( C_{0} \) is the concentration of contaminants in the clean air supplied (usually zero) | [170,171] |
| \( \frac{C_{0}}{C_{0}} \) | - \( C_{0} \) is the concentration of contaminants in the PV supplied air | [134,154] |
| \( \frac{C_{0}}{C_{0}} \) | - \( C_{0} \) is the concentration of contaminants in the ambient air | [20,21,172,173] |
temperatures [177]. Thus, in the periods when the natural ventilation is a viable solution, then it can be added an added value to the system operation indeed. These periods are expected however to be short seeing the application is for hot and humid climates where the outdoor air condition is lower than this threshold value, mechanical ventilation is thus indeed. These periods are expected however to be short seeing the application is for hot and humid climates where the outdoor air condition is lower than this threshold value, mechanical ventilation is thus needed. A study by Safaa et al. [176] investigated a control strategy of a mixed air conditioning system (including both mechanical and natural ventilation) that targets the stabilization of the macroenvironment space air. Therefore, there are different operational and physical constraints ensuring high breathable air quality with low mixing levels with the surrounding relaxed macroenvironment. Melikov et al. [132,134] were the first to evaluated the performance of intermittent PV (IPV) when integrated with different HVAC systems such as mixed ventilation (MV) and displacement ventilation (DV). They reported elevated turbulence levels in the IPV jet surrounding due to its intermittency, especially with increasing frequency. This led to enhancement of comfort in warm conditions compared to steady PV. Nonetheless, the high turbulence levels increased pollutant entrainment into the jet, deteriorating thereby the inhaled air quality.

Many research studies have evaluated the performance of different PV systems in terms of operational and physical constraints ensuring high breathable air quality with low mixing levels with the surrounding relaxed macroenvironment. Melikov et al. [132,134] were the first to comprehensively introduce the concept of PV and assess the performance of different ATDs. They recommended that for optimal use of PV devices, the latter need to be carefully designed such that the occupant’s BZ is always located in the potential core region of the jet. Furthermore, the supplied PV jet operation range should be selected such that it is able to penetrate the free convective and respiratory flows generated by the occupant. Thus, the effective implementation of any PV system requires the reduction of mixing of the clean and cool PV jet with the surrounding warm and polluted air: the core region of the PV – that is mainly not mixed with the surrounding air – must reach the BZ of the PV user. This should also accommodate for the possible changes in the occupant face location. Therefore, there are different operational and physical constraints dictating the effective implementation of PV systems. The operational variables and constraints are summarized as follows:

1) **PV jet turbulence level and velocity:** The highest quality of inhaled air is achieved when the PV air reaches the occupant’s face unmixed with the polluted room air and the free convection air, which is typically polluted and warm [132]. However, the PV jet is known to be turbulent, promoting mixing with the macroenvironment air as well as interacting with the free convection flow surrounding the occupant’s body. This may engender the contaminants’ entrainment to the breathing zone, deteriorating thereby the quality of the air inhaled by the occupant. Thus, close attention should be paid to the turbulence level of the delivered PV jet when considering cross-contamination reduction. Furthermore, the PV jet reaching the face should be strong enough to penetrate the free convection air layer (i.e. thermal plume). Thus, the supply velocity of the PV jet should also be carefully considered when implementing PV system.

2) **Nature of the PV jet:** The nature of the PV jet plays a significant role in defining the level of mixing obtained: many literature studies investigated the performance of a PV ATD that supplies cool and clean air in a dynamic fluctuating way - This is known in literature as intermittent PV [170]. Such PV type improves people’s thermal comfort in warm environments due to increased body heat losses and thermal sensation overshooting effect. Al-Assaad et al. [167,178] evaluated the performance of intermittent PV (IPV) when integrated with different HVAC systems such as mixed ventilation (MV) and displacement ventilation (DV). They reported elevated turbulence levels in the IPV jet surrounding due to its intermittency, especially with increasing frequency. This led to enhancement of comfort in warm conditions compared to steady PV. Nonetheless, the high turbulence levels increased pollutant entrainment into the jet, deteriorating thereby the inhaled air quality.

3) **Distance to face:** The distance between the PV ATD and the face plays a significant role in defining the potential core region of the PV jet: at small distance (between 30 and 40 cm), the PV jet reaches the BZ at a higher velocity, penetrating the free convective flow of the occupant more easily, which enhances the inhaled air quality [175]. This is due to the low entrainment of contaminated room air, which is associated with the short travel distance from the PV supply to the occupant’s face. At longer distances (between 40 and 50 cm), there is significant entrainment of contaminated room air by the PV jet flow, which jeopardizes the inhaled air quality [175]. In addition, eye dryness and irritation is crucial to investigate when considering the distance towards the face, as small distances combined with high PV jets may engender eye discomfort [132].

4) **Direction of PV jet:** It is settled that the strong interaction of the PV jet with the free convection flow induces high levels of mixing and

| PV type | Background ventilation system | $Q_{VA}$ (l/s) | $T_{RA}$ (°C) | $Q_{PV}$ (l/s) | $T_{PV}$ (°C) | References |
|---------|-------------------------------|----------------|-------------|---------------|--------------|------------|
| Chair based PV | Mixed ventilation (MV) | 57 | 18 for DV | 0.8 | 20 | [135] |
| Desk mounted PV | Mixed ventilation (MV) | 20 for MV | 1.6 | 6.5 | [135] |
| Round movable panel | MV | 100 | 17 | 7 | 17 | [168] |
| Vertical desk grill | Under-floor air distribution (UFAD) | 80 | 20 | 80 | 20 | [18] |
| Round movable panel | MV | 80 | 20 | 80 | 20 | [18] |
| Vertical desk grill | UFAD | 80 | 20 | 80 | 20 | [18] |
| Movable panel | MV | 80 | 20 | 80 | 20 | [134] |
| Computer monitor panel | MV | 80 | 20 | 80 | 20 | [134] |
| Vertical desk grill | MV | 80 | 20 | 80 | 20 | [134] |
| Personal environment module | MV | 80 | 20 | 80 | 20 | [134] |
| Round movable panel | MV | 80 | 20 | 80 | 20 | [134] |
| Vertical desk grill | MV | 80 | 20 | 80 | 20 | [134] |
| Ceiling mounted PV | MV | 80 | 20 | 80 | 20 | [134] |
| Desk mounted PV | MV | 80 | 20 | 80 | 20 | [134] |
| Horizontal and vertical desk grill | MV | 80 | 20 | 80 | 20 | [134] |
| Round movable panel | MV | 80 | 20 | 80 | 20 | [134] |
| Movable panel | MV | 80 | 20 | 80 | 20 | [134] |
| Headset | MV | 80 | 20 | 80 | 20 | [134] |
| Vertical desk grill | MV | 80 | 20 | 80 | 20 | [134] |
| Round movable panel | MV | 80 | 20 | 80 | 20 | [134] |

Table 5
Research studies that assessed different PV ATD systems with different air distribution systems.
thus, entrainment of polluted room air. The direction of the PV jet is a main factor that influence this interaction. For example, in the case of VDG, the PV jet is supplied in an upward direction with the free convection flow, resulting in mixing between the clean and cool PV air with the warm and polluted free convection air. This hinders the inhaled air quality as well as the provided thermal comfort. To reduce the downside of this undesired mixing, VDG is proposed to be combined with DV [168].

5) **Geometry of the ATD:** The diameter of the ATD influences the potential core region of the supplied PV jet, which thereby influences the efficiency of the clean air delivery. The length of this core region is typically 4–5 opening diameters for an ATD with a circular opening, and 4–5 times the length of the smaller side with a rectangular opening [132]. Hence, a longer core region is obtained when using a circular outlet when compared to a rectangular outlet with the same cross-section area. Note that the jet generated from a square cross-section transforms quickly into a circular jet with relatively high initial turbulence intensity. This causes velocity fluctuations and mixing of the jet with the surrounding polluted air and decreases the length of the potential core region, negatively affecting thereby the effective and intact delivery of clean air towards the BZ [132]. On another hand, the bigger is the ATD, the wider is the PV jet reaching the face, which increases the face coverage area and gives the PV user more freedom to move the head within a certain range (Fig. 4). However, one should remember to increase the delivered flow rate when increasing in the ATD size, so that the velocity of the PV jet reaching the face remains higher than that of the thermal plume for successful penetration.

In summary, the effective implementation of PV requires the proper selection of the PV dimensions, distance from the occupant to allow the core of the PV to reach the breathing zone without mixing while accounting for the possible deviations of the occupant location. The PV design should use PV flow rates that will not cause eye dryness, thermal draft, and increase in the energy consumption.

2.8. **Question 8: What is the required occupant behavioral adaptation related to the PV usage?**

To control the PV operation, there are mainly three parameters: the airflow rate and direction, and the temperature of the supplied air. However, simultaneously controlling these parameters is difficult to implement and is not commonly practiced. Typically, one parameter, which is the airflow rate, is allowed to be controlled by the user.
Recently, the control can be achieved via physiological inputs from the user using non-invasive techniques to predict the occupant thermal comfort and adjust the PV flow rate accordingly [181]. The integration of PV in multi-occupants indoor spaces presents difficulties when considering cross-contamination reduction, as it may enhance the dispersion of contaminants [18]. Literature studies showed that for occupants to be protected, they must all operate the PV system, especially in tandem positioning where the PV system increases the transport of contaminants towards the back in the direction of the seated occupants [164]. However, the design concept behind the PV system is to provide the users with the privilege of having personal control over their microenvironment conditions based on their thermal preferences. Thus, when operating the PV system, users’ behavior is influenced by thermal comfort rather than air quality; a study by Chen et al. [182] investigated the control of PV operation based on the thermal needs of subjects and their responses. Observed patterns in the subjects’ behavior showed that indeed the PV operation is largely linked to perceived thermal comfort. Such human subject experiments on PV have been performed in hot and humid climates, revealing large individual differences with regard to preferred air movement [183,184]. Therefore, occupants are usually provided with control of velocity (i.e. flow rate) and direction of the personalized flow [132]. Nonetheless, individual control comes with a downside: With individual control of the PV flowrate, it becomes hard to control the dispersion of contaminants between occupants, since this is related to the seating configuration (face-to-face or in tandem) and the fact that some occupants may prefer to turn off the PV system [135,159,164]. A study by Katramiz et al. [159] investigated the effect of individual PV flowrate control on contaminants’ dispersion between two occupants due to respiratory activities (coughing and nose-breathing) for different seating configurations. Large exposure levels were found when the PV users were seated in tandem and the infected user preferred PV flowrates that are larger than those preferred by the healthy occupant sitting in the back. Thus, they recommended a practical way to “protect” all occupants while reducing possible infection transport: all PV users should operate the PV at the same flowrate, assuming that any PV user a “potential infected user”. The recommendation is thus to fix the PV flowrate at a “safe” level for the occupants and give them the freedom to control the temperature of the PV jet to accommodate their personal comfort preferences. Indeed, individual temperature control of the PV jet may pose technical challenges; nonetheless, it is worth investigating to improve thermal comfort while maintaining protection from cross-infection.

The development of an autonomously controlled PV without user intervention hinges on the availability of fast predictive correlations of thermal comfort from environmental parameters and non-invasive physiological measurements of face and/or wrist temperature. In the recent study of Shan et al. [185], artificial neural network was used to develop a model to predict personal thermal comfort based on three skin temperatures of wrist, neck and at the location 2 mm above the wrist. Their developed model, however, depended on wearable instruments to measure the skin temperatures. Recent studies have been trying to develop thermal comfort models that use the least number of influential parameters [186]. Aryal and Becerik-Gerber [187] conducted experiments on human subjects and measured the facial and wrist skin temperatures along with subjective votes of thermal sensation comfort. They deduced that room temperature followed by facial temperature and then wrist temperature could be used to predict thermal comfort. With modern advancements in non-invasive measurements using thermography or other non-invasive devices to detect facial and wrist temperatures, researchers can accurately correlate these parameters as well as room conditions to thermal comfort of the seated occupant [186,188–191]. More experimental testing is needed in this area to validate correlations under extensive room and PV conditions. Real time access to an occupant’s dynamic thermal comfort allows the PV and RAD systems’ controllers to adjust continuously their operational settings while maintaining acceptable thermal comfort levels [192,193]. More research is needed in this area for development of reliable comfort prediction means and smarter noninvasive detection systems for design and implementation of autonomous control of PV-RAD. This would ensure that occupants do not need to alter PV setting to conditions that may risk cross-contamination. If physiological inputs (non-invasive) are available, then future work may lead to development of PV automatic control that allows the simultaneous change of both PV flow rate and temperature as an option available to designers for achieving both comfort, good breathable air quality while minimizing cross-contamination. It is worth mentioning that there are other factors that influence the thermal comfort of the occupant like past thermal experiences, cultural norms, age, gender, etc. [194,195]. Thus, even if the PV system automatically controlled, the user should always be free to control and override the operative conditions of the PV system to meet his/her thermal comfort preferences – based on these unmeasurable factors.

On another note, the use of personalized ventilation systems results in a relaxed room air macroenvironment in terms of temperature and quality. Therefore, when people move away from the “protected clean zone” covered by the supplied personalized flow (by leaving their workstations, moving inside the room), they become endangered to pathogens that exist in the room air, or even releasing more pathogens in the room air in case of infection. In such cases, the use of masks is recommended [196–198]. Wearing masks properly is an integral part of the individual management based on conscious behavior. Other guidelines that are integrated within the conscious behavior of occupants include keeping a good hygiene level (frequent hand washing), covering mouth and nose with a bent elbow or a tissue when coughing or sneezing, frequently cleaning and disinfecting surfaces, especially the ones that are regularly touched by everyone (such as door handle), etc. [199–202].

2.9. Question 9: How to combine non-air based comfort systems with PV for minimisation of cross-contamination at reduced energy cost?

While the use of PV may reduce the energy consumption when compared to typical HVAC systems, its operation still requires the treatment of the outdoor air. Before being supplied to the occupant, outdoor air must be adequately cooled to meet the corresponding occupant thermal preferences. Nonetheless, it is critical to find ways to reduce the energy consumption of the outdoor air treatment process - a key factor affecting the energy-saving of any cooling system. Non-air-based comfort systems are systems that target the comfort of occupants indoor, eliminating the need to cool the air prior to supplying it to the space.

One common non-air-based comfort system is the hydronic radiant cooling (RC) system. Such systems are mainly building integrated systems in the form of radiant building surfaces like walls, floors or ceilings – known as chilled ceilings (CC) [203]. Hydronic RC systems are gaining an ever-increasing interest due to the advantages they present from both thermal comfort aspect and energy-saving potential [204,205]. They provide the required thermal comfort conditions by transferring heat mainly by radiation and less by convection, eliminating thereby the local thermal discomfort caused by draughts [206]. Furthermore, their ability of using relatively high water temperatures for cooling (up to 24–25 °C [207]) results in great overall energy efficiency improvement [208]. Moreover, they offer discreet conditioning of spaces where there is no noise due to fan operation. However, RC system does not provide acceptable levels of air quality indoor, which needs to be independently provided by another system. This engaged researchers to consider integrating personalized ventilation (PV) systems with CC systems. Since CC systems do not induce air movement, the turbulence levels indoor are reduced which favors the effective implementation of PV against transmission of airborne infectious aerosols. In this case, the PV can be solely used for improving the air quality while the thermal comfort conditions are provided by the CC system. Note that the PV
system should be integrated in wearable devices to avoid the obstruction of longwave radiation exchange as well as for practical implementation in densely occupied spaces. Such PV devices are extensively reported in question 4. Having the PV system operated only for air quality purposes eliminates the need to personally control its operation for comfort fulfillment, which is reflected in a reduced turbulence level within the occupied space that would evidently minimize the cross-contamination level. Therefore, the combination of CC + PV may be a viable solution that leads to the delivery of sufficient comfort conditions, without the need for cooling the outdoor air nor for controlling the operation of the PV system, resulting thereby in reduced energy consumption and enhanced protection levels. A study by Lipczynska et al. [209] showed that the CC + PV system is a promising solution for hot climates and substantially decreased the energy consumption.

A problem that hinders the application of CC systems is surface condensation which is especially critical in hot and humid areas [205]. Therefore, CC systems are not allowed to operate at ceiling temperature below dew-point in order to sidestep condensation [206]. This limits the system’s ability to remove the thermal load of the indoor space especially in highly occupied spaces, resulting in the need for another assistive ventilation system such as DV. Combining the CC with DV has been extensively investigated in many studies where part of the load is removed by the CC and the remaining is handled by the DV system. The CC system is typically set at temperature ranges between 19 and 22 °C in presence of the assistive DV system in office spaces to remove loads up to 100 W/m² [210]. A study by Shbeeb et al. [211] showed that using CC at a surface temperature of 17.5 °C allowed 80% removal of load by the CC at densely occupied classrooms. The increase in the cooling load handled by the CC system results in superior comfort levels and reduced volume of DV supplied air leading to lower energy costs [212]. However, the lower supplied airflow rates may endanger the air quality inside the space as the stratification height of the DV system may decrease below breathing level of seated person, leaving occupants expose to contaminated air. To overcome this issue and reduce the possible cross-contamination between occupants, the need arises to incorporate the ductless PV with the CC + DV. The induced room-airflow pattern by the DV helps the use of practical ductless PV designs that are adequate for densely occupied spaces since the supply of clean cool air at low level renders the use of ductless PV viable [150]. The above CC combination with DV and ductless PV is energy efficient solution compared to air-based systems, offering the advantage of reducing cross-contamination if properly designed.

With the aim of operating RC systems at lower temperatures while avoiding condensation, development in RC systems introduced the use of semi-permeable membrane ceiling cooled by liquid desiccant flow [213]. The implemented membranes were used to both cool and dehumidify the space air without direct contact with the desiccant [207,214] since they are permeable to water vapor but impermeable to liquid desiccant. The membrane system relies on a high-concentration desiccant solution to absorb water vapor through the semi-permeable membrane; allowing the cooled ceiling to operate at lower temperatures, which helps the system in achieving effective radiant cooling without the risk of condensation [215]. The choice of the liquid desiccants is primordial in such systems, in terms of safety, system performance, and operation/maintenance costs [216]. Note that these systems present maintenance issues associated with the corrosion resulting from conventional liquid desiccants [217]. A study by Muslimani et al. [218] replaced the chilled ceiling by a liquid desiccant dehumidification membrane (LDDM) system to directly remove both latent and sensible load from the indoor space through the ceiling. They reported the operation of the LDDM with desiccant temperature as low as 13 °C without condensation, while DV air was supplied at higher temperatures (as high as 23 °C). Thus, implementing the dehumidification membrane with DV resulted in a decrease of 49% in energy consumption compared to the conventional CC/DV system. Another study by Keniar et al. [219] showed that the membrane desiccant system mounted on the walls of an office space located in hot and humid climate managed to decrease the indoor relative humidity by 10%. Thus, the LDDM cooled ceiling system can be a possible technique to be integrated with wearable PV devices to reduce the energy needs for air treatment. The ceiling is operated at low temperatures by sustainable measures (like CC, LDDM) to remove the thermal load with minimal risk of condensation while the required air quality is provided by the wearable personalized systems.

2.10. Question 10: considering emission of pollutants from occupants ‘clothing, what are the means to mitigate such undesirable phenomenon in terms of cross-contamination reduction?

In order to ensure an effective control of contaminants dispersion, all indoor pollutants sources must be assessed, including the human sources in terms of airborne particle contamination shed from respiratory activities and clothing [220]. As previously mentioned, the most commonly investigated human sources in literature are the respiratory activities of infected people [159,166]; However, the human body covered with clothes is an important source of ‘personal cloud’ [23]. The clothing fabric has been recognized as a significant vehicle in the collection and transfer of biological particles into the air [221,222]. Particles that are emitted from clothing are composed of previously deposited particulate matter (PM), or generated through frictional interaction of clothing fibers [23,223]. The shedding rates of PM are directly associated with the intensity of occupants’ movements as well as the clothing material [224,225]. A study by You et al. [23] reported that the emission rates of particles from the clothed human body are positively correlated with the human activity intensity. Licina et al. [223] studied the emission rate of particles shed by humans’ clothing under different activity types and intensities, according to precise pre-set behaviors. Once released from clothing, PM can be transported by the person’s thermal plume to the BZ of the occupant, and may be transported to other occupants in the space depending on the nature of the surrounding flow field.

Thus, efforts should be put into investigating ways to reduce the emission of such PM from clothing. One well-known and practical strategy to decontaminate clothing is the use of ‘disinfection tunnels’ or ‘sanitization tunnels’. Such tunnels are located at the entrance of any indoor space (generally densely occupied spaces), spray a disinfecting solution as people walk through them [26,226]. Furthermore, some literature studies reported a specific clothing including decontaminating material that reduces the contamination released by humans [224]. This is known as self-decontaminating clothing. Methods to produce self-decontaminating fabric include coating it with an acknowledged antimicrobial compound whose activity persists; or using a material that has some inherent antibiofilm or microbicidal activity [227]. Campos et al. [25] demonstrated that treatment of fabric with Duritex via thermal bonding can be used to render it self-disinfecting against SARS-CoV-2. However, it is important to emphasize that the obtained antimicrobial effect should not affect the function of the clothing; that is, the fabric should be successfully rewashed without loss of antimicrobial effect [227]. Hence, future work should focus on this aspect of personal protection ways, and investigate more self-decontaminating materials that are adequate for such application, in the aim of protecting occupants against any possible clothing PM release. This does not exclude the consideration of reduction of hand to mouth cross-contamination via utilization of disinfection material of the tables or frequent cleaning of tables.

3. Conclusions

This paper articulated different strategies for the mitigation of airborne transmission of infectious aerosols in indoor spaces at reduced energy cost. The strategies for densely occupied spaces mainly include
the dilution and/or the capture and removal of contaminants both at the room air macroenvironment and occupant-adjacent microenvironment levels.

At the macroenvironment level, it is suggested to reduce the reliance on outdoor air supply, and adopt sustainable air-cleaning techniques that help in decontaminating and re-using the indoor air at reduced energy cost. At the microenvironment level, different strategies can be combined, depending on their feasibility of implementation in highly occupied spaces. The delivery of clean air using PV systems is recommended to be combined with a proper control strategy in practice, based on physiological personal data or on user control of PV parameters. As standards nowadays require a social distancing of around 2 m in spaces in general [228], a strategy should be developed in future work into a standard that dictates the required distancing between occupants in indoor spaces where “occupant-centered” ventilation techniques are implemented, based on the space characteristics (seating arrangement, occupancy density), the ease of retrofitting into the considered space, while taking into consideration the provision of acceptable levels of air quality for enhanced protection level.

Having said that, these techniques help in protecting occupants from infectious disease transmission from sources surrounding them present in the space. However, there are cases where the viruses are closer than assumed – mainly lingering at the clothing surface of people. Thus, future work should consider investigating the use of disinfecting clothing and furniture material that minimize hand to mouth contamination.

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CRediT authorship contribution statement

Nesreen Ghaddar: Writing – original draft, Methodology, Conceptualization, Writing – review & editing. Kamel Ghali: Writing – review & editing, Resources, Methodology, Conceptualization.

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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