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Review

Indoor Air Quality Control for Airborne Diseases: A Review on Portable UV Air Purifiers

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Abstract: The spread of airborne diseases such as COVID-19 underscores the need for effective indoor air quality control. This review focuses on ventilation strategies and portable air purifiers as key mitigation solutions. Ventilation systems, including natural and mechanical approaches, can reduce pathogen concentrations by improving airflow. However, combining ventilation with portable air purifiers, particularly those using HEPA filters, ESP filters, and UV-C radiation, can enhance Indoor air quality. While HEPA and ESP filters focus on trapping airborne particles, UV-C radiation can inactivate pathogens by disrupting their RNA. A review of UV air purifiers reveals a lack of studies on their efficacy and effectiveness in real-world settings. A thorough investigation into the performance of this mitigation solution is necessary, focusing on varying key factors, such as purifier placement, airflow dynamics, and UV dosage, to ensure optimal effectiveness. High-fidelity computational methods are essential in accurately assessing these factors, as informed by the physics of airborne transmission. Such advanced computations are necessary to determine the viability of portable UV air purifiers in mitigating airborne transmission in enclosed environments such as hospitals and public spaces. Integrating advanced air purification technologies with proper ventilation can improve safety in indoor environments and prevent future disease-related outbreaks.

Keywords: airborne viruses; UV air purifiers; mitigation solutions

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1. Introduction

Disease transmission, a multifaceted process involving diverse routes and mechanisms, can be caused by various pathogens, including bacteria, viruses, fungi, parasites, and prions. Transmission modes vary across pathogen types, with some capable of utilizing multiple routes. The Healthcare Infection Control Practices Advisory Committee (HICPAC) classifies these routes into three categories: airborne, droplet, and contact [1]. Contact transmission occurs when an individual interacts with the pathogen either directly through exposure to blood or bodily fluids from an infected individual or indirectly through intermediary sources such as shared surfaces or equipment. Both droplet and airborne transmission occur when pathogens originating from the respiratory tract of an infected individual are disseminated to a susceptible individual. Droplet transmission is characterized by the transfer of pathogens via droplets larger than 5 µm in diameter, which typically traverse short distances before reaching the recipient's mucosal surfaces. Conversely, airborne transmission involves smaller droplets of less than 5 µm that are capable of traveling greater distances from the infection source [2,3]. However, these definitions, established in 1934, are based on research methods limited in their ability to accurately measure airborne particles near the source of infection. To address this, the concept of aerosol transmission [4] was introduced, defining an aerosol as a suspension of solid or liquid particles in air [5]. Despite the emergence of aerosol transmission, the terms "airborne" and "droplet" transmission remain widely used within the scientific community are therefore employed throughout this thesis.

Infectious diseases transmitted via the droplet route are primarily caused by three major pathogen classes: viruses, bacteria, and fungi. The earliest documented airborne contagious disease, measles, caused by the measles virus, was identified in the 9th century [6]. Table 1 provides a chronological overview of airborne diseases and their causative pathogens, spanning from the 9th century to the present day, highlighting the diverse array of airborne pathogens. Airborne diseases have inflicted devastating consequences on global populations. For instance, while World War I resulted in 16 million deaths, the subsequent influenza pandemic caused an estimated 50 million fatalities worldwide [7]. The COVID-19 pandemic, as of 1 June 2024, has affected over 700 million individuals and claimed more than 7 million lives [8]. Despite the World Health Organization (WHO) acknowledging the presence of COVID-19 in December 2019, their official recognition of its airborne transmission was delayed for two years [9]. Figure 1 illustrates the timeline of the pandemic alongside corresponding WHO declarations. Initially, the WHO asserted that COVID-19 transmission occurred solely through direct or indirect contact with infected individuals. A year into the pandemic, with over 1 million deaths globally, the WHO revised its stance, suggesting the possibility of airborne transmission in crowded, poorly ventilated spaces. By the time they acknowledged the potential for droplets to remain airborne for extended periods and travel beyond 1 m, the death toll had surpassed 3 million. On 23 December 2021, after a comprehensive review of case studies and transmission patterns, the WHO officially declared COVID-19 as airborne. By this time, the global death toll had already reached 5.5 million.

Table 1. Airborne diseases and their pathogens (sorted by discovery year).

Airborne Disease	Pathogen (Type)	Year Discovered
Measles	Measles virus (virus)	9th century [6]
Small pox	Variola virus (virus)	1796 [10]
Aspergillosis	Aspergillus fungus (vungus)	1842 [11]
Tuberculosis (TB)	Mycobacterium tuberculosis (bacterium)	1882 [12]
Diphtheria	Corynebacterium diphtheriae (bacterium)	1883 [13]
Meningococcal meningitis	Neisseria meningitidis (bacterium)	1887 [14]
Coccidioidomycosis	Coccidioides fungus (fungus)	1892 [15]
Common cold	Rhinoviruses (virus)	Early 1900s [16]
Whooping cough (pertussis)	Bordetella pertussis (bacterium)	1906 [17]
Histoplasmosis	Histoplasma capsulatum fungus (fungus)	1906 [18]
Influenza (flu)	Influenza viruses (vVirus)	1918 [19]
Adenovirus	Adenovirus (virus)	1953 [20]
Chickenpox	Varicella-zoster virus (VZV) (virus)	1953 [21]
Mumps	Mumps virus (virus)	1967 [22]
COVID-19	SARS-CoV-2 (virus)	2019 [23]

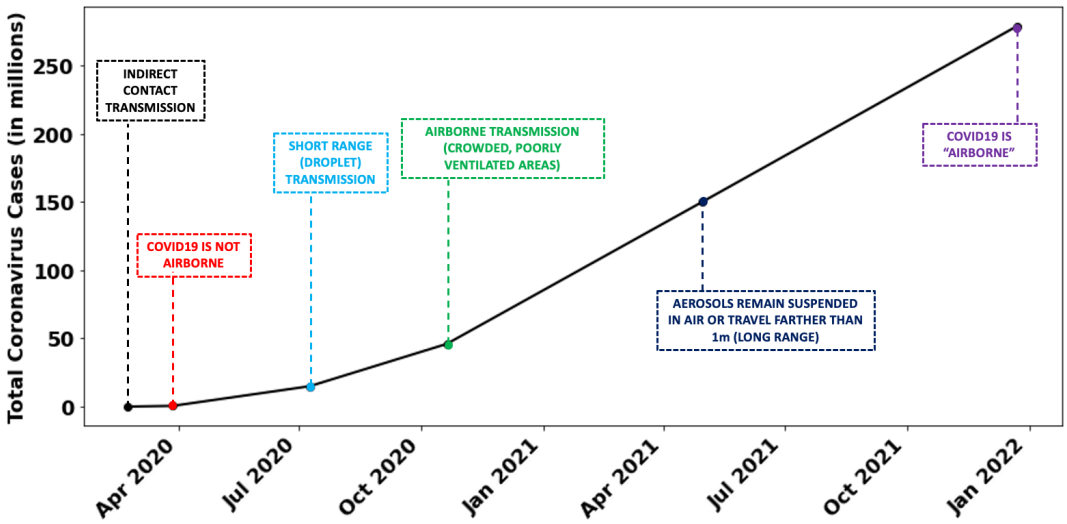

Figure 1. Evolution of global infected cases and the World Health Organization's corresponding declarations during the COVID-19 pandemic.

This historical context underscores the critical importance of comprehensively understanding disease transmission mechanisms, integrating insights from existing literature, as well as from experimental and computational studies and case studies, to facilitate the timely implementation of effective mitigation strategies and prevent future large-scale outbreaks. Given the wealth of research generated during the COVID-19 pandemic, this thesis focuses on airborne viruses, specifically SARS-CoV-2. The remainder of this section delves into case studies that shed light on the transmission routes of SARS-CoV-2 and the efficacy of various mitigation strategies.

2. Case Studies

Case studies of COVID-19 transmission are vital in understanding airborne transmission mechanisms, pandemic trends, and the effectiveness of mitigation strategies. Early research suggested airborne transmission as a possibility [24–26], and geographical analyses of infection spread, in conjunction with mitigation measures, support this as the dominant route [27,28]. A key finding is the significantly higher risk of transmission indoors [29] compared to outdoors [30]. Studies show an 18.7-fold increased odds of COVID-19 transmission in closed environments [31]. While outdoor transmission is less common, it often occurs during large gatherings, such as at parks, construction sites, camps, etc. [32–34]. A systematic review identified exposure duration, frequency, and gathering density as key determinants of outdoor transmission, noting that lockdown measures and mask mandates limited these factors, thereby reducing outdoor SARS-CoV-2 transmission [30]. Conversely, the vast majority (95%) of transmission clusters have occurred indoors [29,30]. Closed environments like hospitals, restaurants, offices, and public transportation have been identified as super-spreading locations [25,35–37]. Systematic and analytical reviews have examined factors contributing to this increased risk through detailed investigation of case studies [38–40]. While some factors relate to human behavior [41,42], contamination of surfaces [43], and the action of sunlight [44,45], the higher indoor transmission rates are largely attributed to inherent differences in airflow dynamics and droplet behavior between indoor and outdoor environments [38]. Thus, the complex, turbulent dispersion of exhaled droplets within confined spaces is primarily driven by intricate flow patterns arising from ventilation systems and various obstacles. Factors such as confinement, low ambient velocities, and limited air dilution contribute to elevated aerosol concentrations in closed environments, increasing the risk of both near-field and far-field exposure to pathogens [40]. The stark contrast in aerosol transmission dynamics between indoor and outdoor environments underscores the need for a comprehensive re-evaluation of the

mechanisms involved in airborne disease transmission. This re-evaluation is essential for the development of effective mitigation strategies to combat future pandemics.

Similar to the several airborne diseases, SARS-CoV-2 virus propagates from an infected source to a susceptible individual through droplet (direct and indirect) and airborne transmissions, as shown in Figure 2. Airborne virus like SARS-CoV-2 primarily target and establish infection within the upper and lower respiratory tracts of the host. Expiratory activities such as talking, coughing, and sneezing [2,46] generate pathogen-laden respiratory droplets through two fundamental mechanisms [47]. The first mechanism involves the instability [48] and eventual fragmentation of the mucus lining due to airflow-induced shear stress, leading to droplet formation. The second mechanism involves the rupture of the thin liquid film lining the small airways during the cyclic opening and closing of these passages during breathing, leading to the generation of small droplets [49]. Exhaled droplets from infected individuals typically contain soluble, non-volatile matter (Na^+, K^+, Cl^-, lactate, and glycoprotein) comprising up to an approximately 0.71% mole fraction, in addition to viral particles [50]. The characteristics of exhaled droplet clouds, including velocity, size distribution, and number density, are dependent on the specific expiratory activity performed by the infected individual. Numerous studies have attempted to quantify the characteristics of exhaled droplet clouds, revealing substantial variation across different expiratory maneuvers. However, reported results exhibit significant variability due to limitations in sampling methods and instrument sensitivity, particularly for larger droplets [51–53].

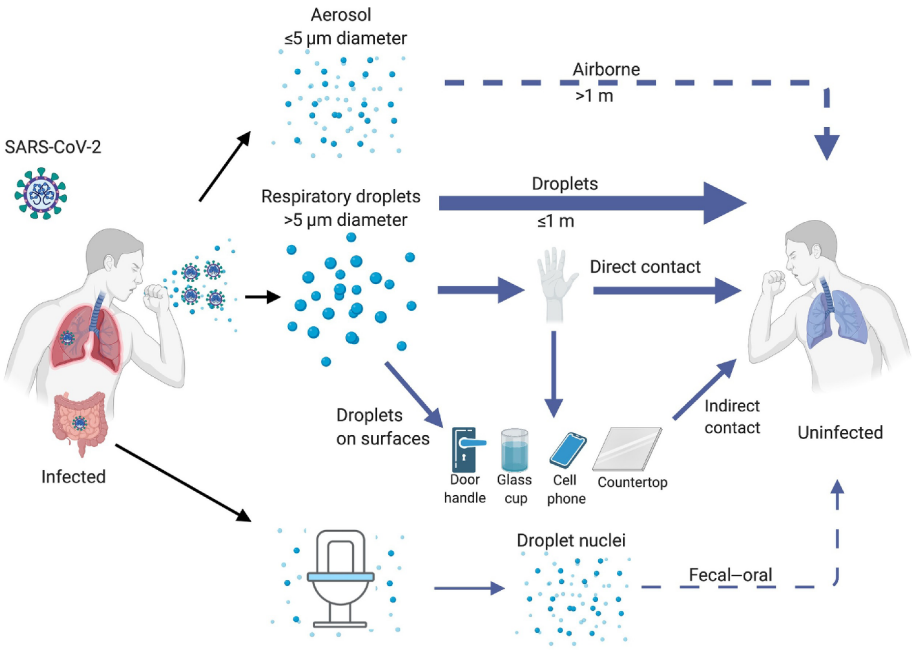

Figure 2. Transmission routes for SARS-CoV-2 virus to travel from an infected source to a susceptible individual [54].

Reported droplet sizes range from 0.1 to 1000 µm, with size distributions often described as continuous, bimodal, or trimodal [55,56]. Numerous studies have employed modern data-fitting algorithms and equations to replicate experimental data for computational, experimental, and statistical purposes [57–59]. The viscosity and surface tension of a droplet are important features that can also control droplet size distribution, particularly by coalescence and breakage phenomena. In the case of virus-laden droplets, the surface tension and density of these particles are found to be similar to those of water, and the viscosity of these droplets is higher than that of water by one or two orders of magnitude, making them less prone to coalescence and breakage [60–63]. Regarding number density and ejection velocity, a single sneeze is estimated to generate on the order of 10^4 droplets

with velocities approaching 20 m/s [55]. Coughing produces 10 to 100 times fewer droplets with velocities around 10 m/s. The expiration jets associated with coughing and sneezing are turbulent, with Reynolds numbers on the order of 10^4 [64]. Just like sneezing and coughing, normal breathing and talking are acknowledged to atomize droplets. It has been discovered that half a minute of speech can release a liquid of volume equivalent to a cough [65,66] and that the ejection velocity during normal breathing and sneezing can exceed 5 m/s [67].

The subsequent behavior of exhaled droplets is governed by a complex interplay between their intrinsic properties and environmental factors such as temperature and humidity [2,68]. Depending on these factors, droplets undergo several physical phenomena, such as advection, evaporation, coalescence, and breakage, before entering into a susceptible host, as shown in Figure 3. They may either settle rapidly onto surfaces, potentially leading to contamination, or undergo rapid evaporation, remaining suspended as droplet nuclei capable of long-range transport. These droplet nuclei, comprising non-volatile matter and any entrained pathogens, represent a crucial vector for airborne disease transmission. The critical droplet size threshold differentiating settling behavior from airborne persistence has been estimated to range between 50 and 150 µm, with variations attributed to fluctuations in temperature and humidity [2,69].

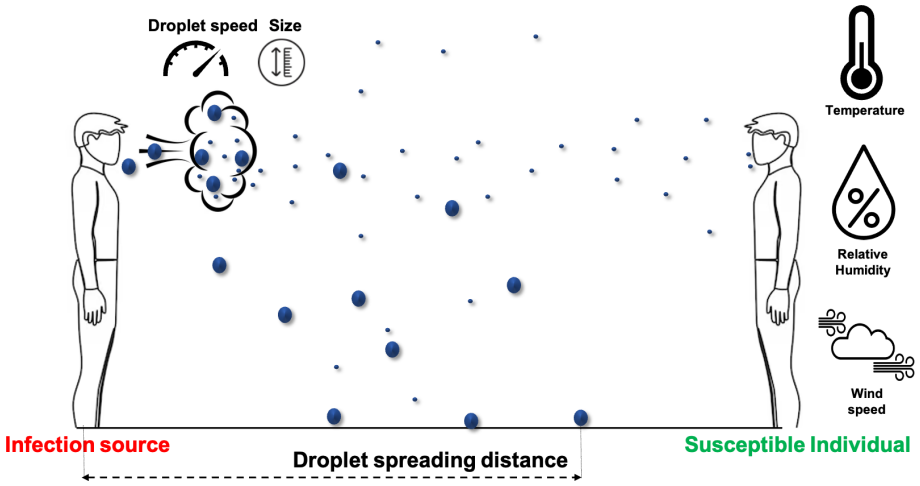

Figure 3. Factors influencing the evolution of expelled droplets during disease transmission from an infected source to a susceptible individual.

Droplets with sizes larger than the critical diameter are separated from the ejected puff of particles and end up being deposited on surfaces before becoming fully evaporated. In the context of the COVID-19 pandemic, these droplets are responsible for indirect contact transmission via contaminated surfaces and droplet transmission. A surface contaminated by SARS-CoV-2 or SARS-CoV-1 virus is a potential source of infection transmission for several hours [43]. On the other hand, the medium/small aerosols present in the puff are constantly undergoing advection and evaporation and turn into droplet nuclei with sizes smaller than 10 µm [47].

The velocity at which the ejected puff is expelled plays an important on in the advection of droplets. While the distance traveled by these large droplets is around 3–6 feet [69,70] during breathing or coughing activity, droplets during a violent respiratory act like sneezing are found to settle 20 feet from the infection source. One should note that ambient air currents in the direction of droplet expulsion can enhance the range of these settling droplets. With an air current of 4 km/h, droplets expelled from a cough in the same direction were found 20 feet from the infection source [60]. For droplet nuclei, the settling velocity is significantly lower; therefore, they remain with the puff and travel greater distances, remaining suspended in air for a longer time. When the settling velocity is

less than the ambient turbulent fluctuations, the motion of particles suspended in air is governed by ambient air flow.

The rate of evaporation of a single aerosol depends on a variety of factors, such as relative humidity, air temperature, and the relative velocity between aerosols and ambient air. It plays an important role in determining the distance traveled by the droplets. Studies have shown that the droplet spreading distance is longer and the aerosolization rate is lower during winter than summer, indicating the importance of weather conditions for airborne transmission [71,72]. Experimental studies indicate that higher temperatures and lower humidities lead to higher evaporation rates, which increase the critical droplet diameter [2,69]. Computational studies support the hypothesis that the evaporation of droplets cannot be ignored while performing simulations to understand airborne transmission [73,74].

In response to these transmission dynamics, countries worldwide implemented various mitigation strategies during the COVID-19 pandemic to curb droplet and airborne transmission. While a 3–6 foot social distancing recommendation was proposed to reduce droplet transmission [75,76], its efficacy in crowded outdoor settings was limited, as wind can disperse droplets up to 6 m. Consequently, many countries resorted to complete lockdowns to suppress the spread of infection. The use of N95 and surgical masks was also recommended, as they can shield individuals from large droplets and droplet nuclei (inward protection) [77] and mitigate droplet spread during exhalation (outward protection) [78–80]. Additionally, the use of hydro-alcoholic solutions and regular hand washing were promoted to disinfect contaminated hands and reduce indirect contact transmission [76,81]. Respiratory etiquette, such as covering the mouth and nose during coughs or sneezes, was encouraged to disrupt the transmission chain, although its effectiveness in completely blocking droplet release and dispersion is limited [82]. Plexiglas walls/barriers were installed at restaurants, banks etc. to reduce droplet transmission between individuals. The success of these mitigation measures hinged on individual compliance, and they did not directly address air quality, particularly in closed environments. The WHO; the Centers for Disease Control and Prevention (CDC); and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [75,76,83] have established guidelines to control the spread of airborne infectious diseases in indoor environments such as buildings and public spaces. These guidelines focus on enhancing ventilation, improving air filtration, and maintaining hygiene practices. The WHO advocates for adequate airflow, mask wearing, and regular sanitation to minimize transmission risks. The CDC promotes a layered approach that includes proper ventilation, high-efficiency filtration systems, air-cleaning devices such as HEPA filters, physical distancing, and regular hygiene. ASHRAE Standard 241 further supports these strategies by defining specific clean airflow requirements, utilizing advanced air filtration and UV technology and implementing an infection risk management mode during high-risk periods. Together, these guidelines aim to mitigate airborne pathogen transmission and improve indoor air quality to safeguard public health. Given that aerosol dispersion is influenced by complex flow patterns in confined spaces and in line with the the WHO's declaration that "everyone has a right to breathe healthy indoor air" [84], fluid dynamics-based mitigation solutions are crucial for ensuring quality air in enclosed settings. The next section explores air quality control methods developed with the goal of providing pathogen-free breathing air.

3. Air Quality Control

In the past semi-centennial, several researchers worked on understanding and improving indoor air quality (IAQ), especially to mitigate the airborne transmission of pathogens, by conducting case studies, as well as experimental and numerical studies [85–87]. Poor IAQ leads to not only high exposure risk and infection spread but also headaches, breathing difficulties, fatigue, etc. [88,89]. The risk-reduction techniques proposed or investigated to control IAQ in any indoor setting are generalized into the following categories: ventilation (natural and mechanical) and portable air filtration.

Regular sanitation of public spaces like hospitals and subways is conducted using UV surface disinfectants or by fogging machines that release a dispersion of a fine mist of disinfectants in air, which improves air quality [90].

3.1. Ventilation

Ventilation is the process of introducing and distributing outdoor air or appropriately treated recirculated air into a building or a room [91]. Throughout the years, there have been several studies conducted on indoor ventilation and its role in the airborne transmission of diseases, as well as minimum requirements to mitigate disease transmission in different indoor settings. A first comprehensive review on ventilation and its impact on airborne transmissions until 1960 was conducted by Wells WF, Riley, and O'Grady [68,92] indicating that the infection rate among susceptible hosts is higher in poorly ventilated regions. A multi-disciplinary systematic review using the research articles published from 1960 to 2007 on the role of ventilation in airborne disease transmission was performed by Li Yuguo et al. [85]. This review highlights that indoor spaces with low air-exchange rates, specifically less than 4 Air Changes per Hour (ACH), have been linked to the transmission of tuberculosis [93], measles [94], and influenza [95] in hospitals, pediatric offices, and aircraft, respectively. An experimental study conducted on mice inside a cage with three different ventilation rates indicated that infection risk is inversely proportional to the ventilation rate [96]. Smoke puff studies conducted inside hospital wards concluded that airflow patterns are directly related to the infectious spread of diseases like chickenpox [97], tuberculosis [98], small pox [99], etc. These findings, along with those of other studies, affirm that ventilation rates and airflow patterns in enclosed spaces play a crucial role in infection transmission.

Several ventilation strategies based on such studies have come up in the past decade to improve IAQ and provide thermal comfort for different indoor settings. These ventilation strategies are primarily categorized into two categories: Mechanical Ventilation (MV) and Natural Ventilation (NV). A multi-disciplinary systematic review on different types of mechanical and natural ventilation systems and their efficiency in mitigating the exposure risk was conducted by Al-Rikabi [88].

This review highlights that, based on the inlet–outlet placement in a closed environment, there are 11 types of mechanical ventilation systems in use today. These systems can be grouped into three categories: uniform steady-state systems, such as mixing ventilation and diffuse ceiling ventilation; non-uniform steady-state systems, such as displacement ventilation and stratum ventilation; and unsteady ventilation systems, such as intermittent ventilation. Figure 4 provides an illustration of the aforementioned ventilation systems. Several numerical and experimental studies on these ventilation systems have been conducted inside various enclosed spaces, like classrooms, office space, elevators, bus cabins etc., to study the induced flow patterns and the resultant dispersion of pathogen-laden droplets. Some studies have compared their impact on the spread of airborne infection by testing different ventilation systems inside the same indoor space. To calculate the probability of infection spread or compute surface contamination due to respiratory activities such as breathing, talking, coughing, and sneezing, the Wells–Riley model [68,100] is employed.

The Wells–Riley infection prediction model is a widely-used mathematical framework for estimating the probability of airborne disease transmission in indoor environments. It calculates the infection risk (P) by considering factors such as the number of infectious individuals (I), the ventilation rate (Q), and the duration of exposure (t). A key concept in this model is the "quanta" (q), which represents the infectious dose required to cause infection in a susceptible person. The infection probability for a susceptible individual can be expressed as $P = 1 - e^{\left(-\frac{Iqbt}{Q}\right)}$, where b is the breathing rate of a susceptible individual. While the Wells–Riley model provides a useful estimate for predicting infection spread, its accuracy is limited by simplifying assumptions, such as the uniform distribution of infectious particles in the room and constant quanta generation, which may not always

hold true in real-world scenarios. As a result, some research studies prefer to evaluate the effectiveness of mitigation solutions based on the contaminant concentration in the room.

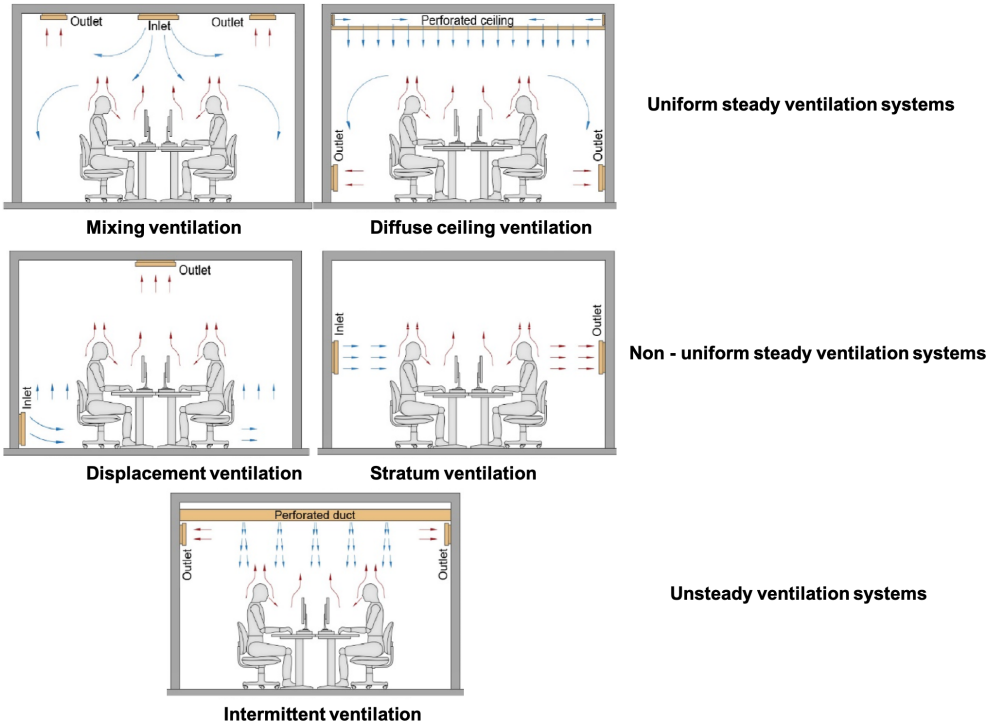

Figure 4. Illustrations of different mechanical ventilation systems [88].

Indoor environments with uniform steady ventilation systems like mixing ventilation [101] and diffuse ceiling ventilation [102] have the highest exposure risk compared to other ventilation systems [103]. It was found that high supply and exhaust pose higher infection risks with uniform steady ventilation systems [104,105]. These studies correct the ideology that a higher ventilation rate does not guarantee better mitigation of infection spread [104,106]. Non-uniform steady ventilation systems such as displacement ventilation [101] and stratum ventilation [107] show minimal contamination levels [108–111] when compared to mixing ventilation and diffuse ceiling ventilation. Unsteady ventilation systems seem to be less effective than uniform steady air systems due to periodic on/off cycles in the air supply, as the concentration of contaminants increases when the air supply is off [112].

Indoor air quality (IAQ) and thermal comfort can also be enhanced by introducing fresh air through windows, doors, and other openings. Natural ventilation, a passive strategy utilizing natural airflow, can provide outdoor air in moderate climates and mitigate airborne transmission. Common wind-driven natural ventilation strategies include single-side, cross, and wind-catcher ventilation, as illustrated in Figure 5. Many numerical and experimental studies have been carried out inside classrooms, office rooms, buses, etc., to study the efficacy of each of these strategies. Some studies have compared these strategies with other natural ventilation systems and/or with mechanical ventilation systems [88]. Cross ventilation, achieved through dual-side windows, generally outperforms single-side ventilation [113,114]. However, in specialized facilities like hospitals, not all natural ventilation systems meet stringent clinical standards [115,116]. Research suggests that simple architectural modifications, such as optimization of window placement and size, can significantly improve contaminant removal through natural ventilation [117,118]. However, this approach may be limited in areas with insufficient wind to achieve the required ventilation rate, highlighting the fact that the efficacy of natural ventilation systems cannot be guaranteed at all times.

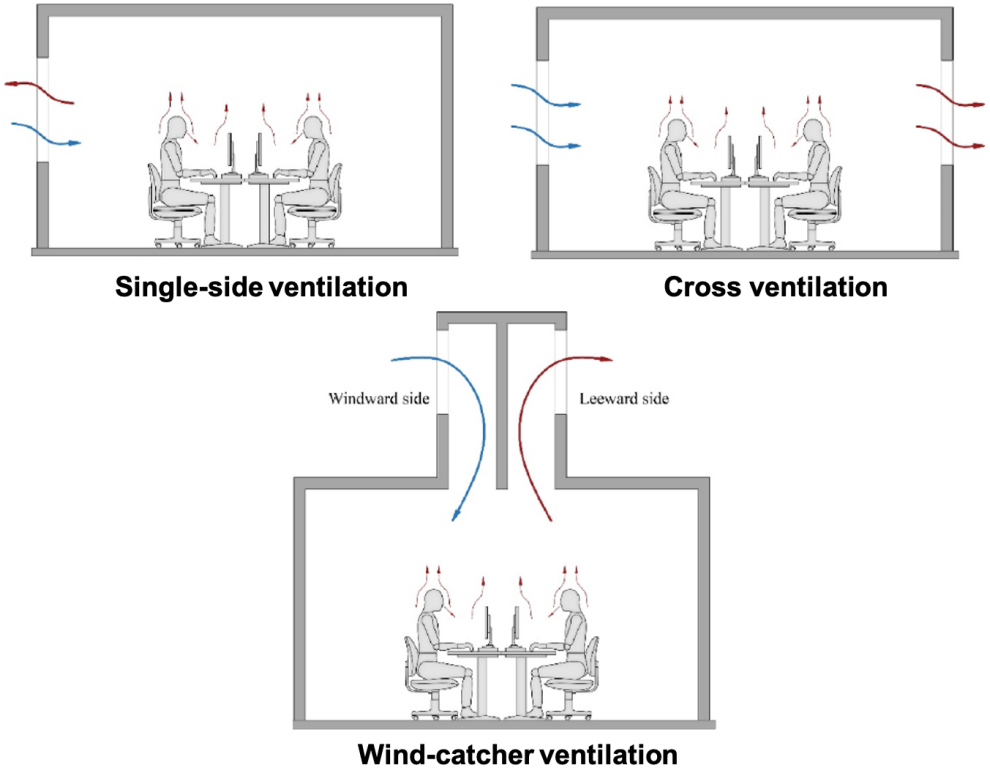

Figure 5. Illustrations of different mechanical ventilation systems [88].

Given the strengths and limitations of both mechanical and natural ventilation, a flexible strategy that integrates elements of each would be ideal for future pandemic preparedness. Studies have highlighted the importance of modifying ventilation systems in enclosed spaces to optimize airflow and reduce pathogen exposure, with recommendations to reposition exhausts and inlets as necessary [119,120]. Additionally, integrating high-efficiency particulate air (HEPA) filters or UV lamps within ventilation units can inactivate pathogens before distributing air throughout a room. Emerging technologies such as personal ventilation devices also show promise in reducing both short- and long-range transmission risks, although further research is needed to confirm their efficacy [105].

While these measures can inform the design of new indoor spaces, retrofitting existing environments remains a practical approach to infection control. However, implementing such measures may face challenges due to the resource-intensive nature of mechanical ventilation upgrades and the dependency of natural ventilation on external conditions. Models like the Wells–Riley model provide useful infection estimates but lack the ability to account for complex, dynamic airflow patterns and occupant density variations found in real-world settings. Future research could benefit from the exploration of hybrid ventilation models that combine mechanical and natural systems, creating adaptable, energy-efficient solutions for air quality and infection control. Additionally, integrating portable HEPA filters or UV air purifiers in enclosed areas offers an immediate, cost-effective way to lower infection risks, particularly in high-density or poorly ventilated environments [121].

3.2. Portable Air Cleaners (PACs)

The objective of the design of a portable air cleaner (PAC) is to enhance indoor air quality (IAQ) in enclosed spaces. In poorly ventilated environments, PACs can mitigate airborne transmission through various filtration mechanisms [92]. Commercial PACs employ diverse technologies to capture or destroy pathogen-laden particles, depending on the particle size, inactivation technology, and specific indoor environment. PACs can be classified into three categories: mechanical filtration, electrical filtration, and UV light filtration [86]. Mechanical filtration removes particles by capturing them in filter media, whereas electrical filtration utilizes electrostatic attraction to trap particles. UV

air purification, on the other hand, inactivates pathogens within particles by disrupting their RNA. Among PACs with mechanical filtration devices, commonly used devices in indoor spaces are panel filters, pleated filters, and HEPA filters [86]. Among them, HEPA filters are highly recommended for capturing sub-micron-sized particles like droplet nuclei [121,122]. In the domain of electrical air filtration devices, electrostatic precipitators (ESPs) are the most commonly recommended and applied to capture micron and sub-micron particles. Among UV air purifiers, UV-C lamps are recommended to inactivate infectious airborne particles. The application of portable HEPA filters and electrostatic precipitators inside classrooms and offices have been examined by several researchers, comparing their efficiency against other filtration mechanisms. A summary of available literature on these mechanisms and the application of these devices in real-life scenarios is presented below.

3.2.1. Mechanical Air Filters: HEPA Filters

HEPA filters are typically manufactured by pleating microfiber glass or other fibrous media consisting of multiple layers of randomly arranged fibers with diameters ranging from 2 to 500 nm [123]. Particles entering the HEPA filter are entrapped by one of the following three mechanisms: (1) impaction, (2) interception, or (3) diffusion [124]. If a sieving mechanism is included in this design, they are called ultra-low particulate air (ULPA) filters [125]. This intricate design enables the capture of particles not only >1 µm but also those in the sub-micron range [124]. The particle removal rate of a HEPA filter varies depending on the size and power of the portable air cleaner (PAC). Except for sub-micron particles, HEPA-based PACs have a high removal efficiency, and they can remove all particles in a short period of time (such as 5 min) [126,127]. An efficiency study performed on a single HEPA filter-based PAC showed significant improvement in aerosol concentration when compared with a room with no filter [128]. The impact of these filters on room ventilation has been tested by varying the rate of ventilation within a closed room. Depending on the type of ventilation system, increasing the air exchange rate can either enhance or reduce the effectiveness of the filter. A higher air exchange rate may improve contaminant removal by introducing fresh air more frequently, but it can also reduce the contact time between airborne particles and the filter, thereby lowering its inactivation potential. Conversely, a low ventilation rate results in reduced airflow and longer residence times for contaminants within the room, leading to lower overall effectiveness of the HEPA filter [129]. The effectiveness of HEPA filter-based PACs also depends significantly on their placement within a closed environment. Positioning a PAC in a location where the majority of the room's air flows ensures that a larger volume of contaminated air passes through the filter. This allows the purifier to capture more airborne pathogens, thereby minimizing the risk of infection spread. Conversely, improper placement with poor airflow may reduce a purifier's performance [128]. While this filtration mechanism seems to be a viable option, one has to consider such filters become sinks of bio-hazardous pathogens [130]. Overall, experimental and numerical studies conclude that the application of HEPA filters along with mechanical or natural ventilation can effectively reduce the airborne virus concentration inside a closed environment.

3.2.2. Electronic Air Filters: ESP Filters

Electrostatic precipitators (ESPs) are the most common type of electrical filters used inside ventilation ducts and as PACs. Electrostatic precipitation is a technique to remove suspended particles in a gas using an electrostatic force [131,132]. With a high voltage supply, a strong electric field is established, which charges airborne particles and collects them near an oppositely charged plate [5,130]. These filtration devices are mainly used in industrial applications, but studies have shown their application in indoor spaces like houses, offices, and factories. ESPs are commonly classified as single-stage or two-stage filters. In single-stage filters, both charging and particle removal from a gas stream are performed by the same set of electrodes, therefore using a very high voltage of 50–70 kV [133]. If different sets of electrodes are used for charging and collecting the aerosols, it is two

stage precipitator and it requires only 12–15 kV [133]. The performance of these filtration devices is commonly computed in terms of the clean air delivery rate (CADR) or particle removal rate [134]. The CADR is a measure that considers the airflow rate through the cleaner, wit the particle removal efficiency presented in m^3/h. Tests of PACs developed with ESP filtration in laboratories and in real-life scenarios show that the CADR of a PAC depends on its placement inside a closed room with respect to the infection source [135]. Experimental studies also indicate that the CADR of a PAC depends on the electric power provided. The higher the electric power, the higher the CADR [136]. But this has to be treated carefully, as it can lead to the production of hazardous byproducts in indoor and transportation environments, such as ozone from corona discharge and/or the ionization process [137]. Therefore, by regulating the amount of electric PACs with ESP filtration mechanisms, experimental and computational studies support this mechanism being used to mitigate the airborne transmission cycle.

3.2.3. Mechanical vs. Electronic Air Filters

While HEPA and ESP are the most commonly used mechanical and electrical filtration mechanisms as portable air cleaners, there are several other PACs with different filtration techniques that can serve the purpose of mitigating airborne infections. One has to identify the best and most cost-effective solution to reduce the concentration of infectious particles in any indoor environment. Therefore, the efficiency/efficacy of a PAC, as well as its effectiveness, should be tested in an enclosed space. Efficiency is the percentage of particles removed in a single pass through the filter, as explained below. Effectiveness is a dimensionless quantity that shows how effective as PAC is in reducing the concentration of contaminants in a real-life setting [130]. When HEPA filters are compared with other mechanical filters, HEPA-based PACs exhibit the highest CADR [138]. When HEPA and ESP filters are compared, some experimental studies [138–141] have revealed that HEPA-based PACs have higher CADR values, while some other studies [136] have indicated that ESP-based PACs have the highest CADR among tested filters. To compare HEPA or particle filters with electric filters, one should remember that the CADR of an electrical filter can be improved by providing more electric power. HEPA filters also require electric power to function. Therefore, to identify better PACs, the electric power used by a PAC can be normalized according to the clean air delivery rate (CADR). The specific electric power for an ESP is typically half the specific power needed for a mechanical filter [130]. But there are some deviations to this, as some studies have shown that HEPA filters achieve better performance than ESP-based PACs [138]. Therefore, its not simple to make generalizations and say which filtration mechanism is the optimal strategy. One can consider the application of an electrostatically assisted mechanical filters as a possible mitigation solution to prevent airborne transmission [142].

A comparison between HEPA and ESP filters reveals important considerations for selecting the most effective air purification approach for different indoor environments. While HEPA filters generally achieve higher clean air delivery rates (CADRs) across studies, ESP filters can offer comparable or superior CADRs when powered adequately. However, ESP systems require careful regulation due to the potential productions of ozone and other byproducts during the ionization process. This trade-off suggests that while ESP filters may provide efficiency at a lower specific energy cost, HEPA filters offer a safer, more reliable option, especially in high-occupancy settings where ozone byproducts are a concern.

Additionally, research on optimal PAC placement, airflow interaction, and power normalization highlights the complexity of finding a universally optimal solution, indicating the need for tailored approaches. For spaces where both energy efficiency and a high CADR are critical, electrostatically assisted mechanical filters may offer a promising compromise by combining HEPA and ESP technologies. This hybrid approach could provide a balanced solution, particularly in environments with stringent air quality demands, although further research is necessary to validate its effectiveness across diverse settings.

While ultraviolet (UV) disinfection PACs have been proposed as a potential solution for air purification, particularly in the context of the COVID-19 pandemic, empirical data regarding their efficacy and effectiveness in real-world settings remain limited. The pandemic has stimulated increased research into the application of UV radiation in air filters to inactivate viruses, resulting in a few studies exploring its potential. However, to comprehensively evaluate the efficacy of UV-based PACs and their effectiveness in a real-world setting, a thorough examination of existing research on UV radiation's role in microbial inactivation and various studies conducted on these portable air cleaners should be performed.

3.3. UV Air Purification

UV radiation in the range of 200–315 nm is considered ultraviolet germicidal irradiation (UVGI) [143] and is known to prevent the spread of infectious diseases. UV-C lamps generating wavelengths in this range are commonly used to disinfect surfaces, water, and air [144]. UVGIwas first discovered in 1845 by Downes and Blunt [145] when they observed that the growth of micro-organisms is prevented by exposure to sunlight. They then continued to study the effects of lights on different micro-organisms. Experiments on microbial inactivation by light exposure conducted by Tyndall [146] revealed that the inactivation rate varies for different durations of exposure, wavelengths used in the light spectrum, and doses of radiation provided. Initial investigations focused on the rate of inactivation of pathogens against wavelengths, testing for UV-C (100–280 nm), UV-B (280–315 nm), UV-A (315–400 nm), visible (400–700 nm), and infrared (700–10^6 nm) ranges. Geisler's experiments [147] indicated that UV radiation from sunlight and electric lamps was more effective than longer wavelengths. By increasing radiation intensity, all wavelengths have shown lethal effects with long durations of exposure. Bang [148] discovered that UV-B and UV-C wavelengths are more effective than UV-A radiation. Duclaux's work [149] revealed that bacteria, fungi, and other microbes have different sensitivities to sunlight exposure and inactivate at different rates. Later, several studies began to quantify this microbial sensitivity of different pathogens to UVGI by modifying the dose of radiation. When the photons from UV radiation are absorbed by microbes, its desoxyribose nucleic acid (DNA) is damaged and renders its ability to reproduce [150]. All these experiments were conducted with pathogens on a surface like a Petri dish or in liquid.

In 1935, Wells [151] extended the application of this method to airborne pathogen-laden aerosols and showed that UVGI can inactivate airborne infectious agents. Sharp [152] tested airborne disinfection using UVGI in an in-duct heating, ventilation, and air conditioning (HVAC) system. Since these initial investigations, more studies have come together in regards to the study of airborne pathogen disinfection through UV radiation. Jensen [153] inactivated five different viruses using UVGI and found that their sensitivities differed in air when compared to deactivated experiments performed on plates or in water. It has been established that when exposed to an adequate dose of UV-C light, airborne pathogens can be deactivated, which suggests a potential application for IAQ control. This is accomplished successfully by following ways: (1) upper-room UVGI installation or (2) UVGI-integrated HVAC systems.

3.3.1. Upper-Room UVGI

Upper-room Ultraviolet Germicidal Irradiation (UR-UVGI) technology utilizes shielded UV lamps suspended from the ceiling of populated spaces, as shown in Figure 6, to create an irradiation field above occupants, effectively inactivating airborne pathogens [154,155]. This approach takes advantage of natural convection currents to transport airborne microorganisms through the UV field, enabling the rapid disinfection of large air volumes. The effectiveness of this system in disinfecting large volumes of air depends heavily on the fluid dynamics within the room, making airflow patterns crucial in the design and operation of UR-UVGI systems. The efficacy of this technology in inactivating viruses such as chickenpox and measles in school settings was first demonstrated by Wells [156].

Subsequent experimental studies in isolation wards, commercial spaces, and residential areas have confirmed its effectiveness [157–159]. Computational fluid dynamics (CFD) studies [160–162] on naturally or mechanically ventilated hospital wards and test chambers have further demonstrated the efficiency of UR-UVGI by integrating air mixing, UV fields, and microbial degradation. These studies have also led to the development of mathematical models [163,164] to assess airborne contamination in rooms equipped with ceiling-mounted UVGI technology. Research aimed at enhancing the effectiveness of UR-UVGI has explored various strategies, including the use of ceiling fans, optimization of UV lamp placement, adjustments to room ventilation rates, modifications to ceiling height, and variations in UV lamp power [162,165–167]. The effectiveness of UR-UVGI diminishes with higher air exchange rates, as this reduces microbial exposure to the UV lamps. Rooms with higher ceilings and UR-UVGI systems have been shown to contain lower levels of contaminants compared to rooms with lower ceilings. Additionally, while 254 nm UV lamps are commonly used, 222 nm UV-C radiation has also demonstrated a high rate of pathogen inactivation. The combination of low-speed ceiling fans and UR-UVGI has proven more effective than the absence of fans. As research continues, new approaches and innovations are emerging to further enhance the efficiency of this mitigation solution [168,169].

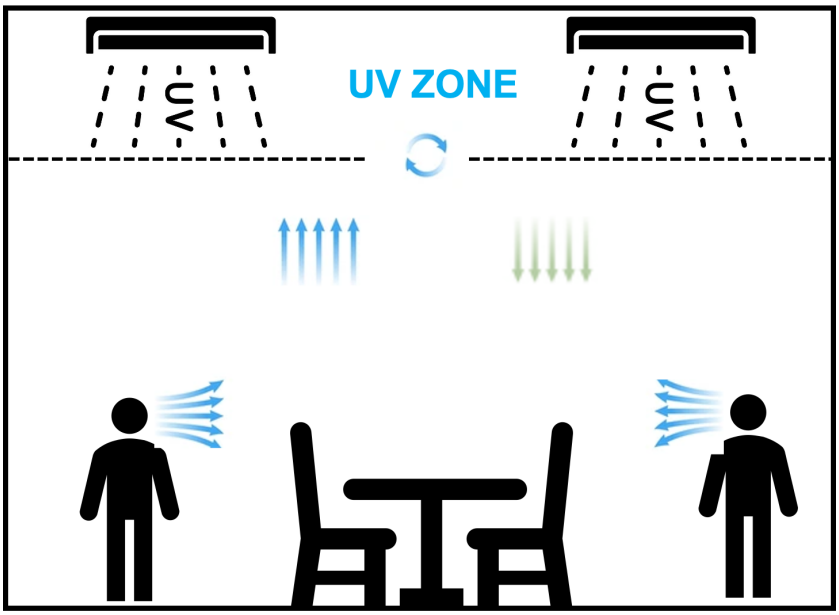

Figure 6. General representation of an upper-room UVGI (UR-UVGI) setup.

Based on the research findings, UR-UVGI technology shows significant potential as a mitigation solution to prevent airborne transmissions. However, it also comes with some inherent limitations. The effectiveness of this technology is mainly confined to the upper part of a room, typically above 7 feet, and it relies heavily on air circulation to transport pathogens to the UV-exposed zone. Poor air circulation can diminish the technology's overall impact, potentially leaving the lower, occupied zone untreated. The efficacy of UVGI depends heavily on both the intensity of the UV radiation and the duration of exposure, with certain pathogens requiring stronger or longer UV exposure to be effectively neutralized. Since this mitigation solution is designed to be used while people are present in the room, preventing UV radiation leakage from the shielded zone is critical, as exposure to UV radiation can be harmful and potentially lethal to humans. Ensuring proper shielding and safety measures is essential to maintain the effectiveness of the system without compromising occupant safety. Furthermore, installing UVGI systems, especially in existing buildings, can be complex and costly, often necessitating significant retrofitting. Despite these limitations, when properly implemented and maintained, UR-UVGI can be a valuable tool in reducing airborne pathogens.

3.3.2. UV-Integrated Ventilation

UV radiation can be integrated into HVAC systems by installing an array of UV lamps within the ventilation ducts as shown in Figure 7, where a high-intensity UV field is generated to effectively inactivate pathogen-laden particles entering the system. These HVAC systems are carefully designed to confine UV exposure to within the ducts, ensuring the safety of occupants while also disinfecting surfaces within the HVAC components. Although this approach may consume more electrical power compared to standard HVAC systems, it significantly enhances the inactivation of airborne pathogens. Additionally, proper shielding is essential to limit UV irradiation to the ducts, preventing any exposure to occupants. Experimental studies such as in ICU settings and car HVAC systems [170–172] have demonstrated improved air quality through the application of UVGI in ducts. Computational studies [173–175] have also simulated various UV lamp configurations and air velocities within ducts to evaluate their impact on inactivation rates. Both experimental and numerical findings suggest that factors such as lamp placement within the duct, duct length (from inlet to outlet), and chamber size play critical roles in determining the effectiveness of microbial inactivation.

The inactivation efficiency of pathogens within HVAC ducts is influenced by the fluid mechanics inside the ducts, which determine the exposure time of airborne pathogens to UV radiation. This makes the volumetric flow rate of the ventilation system a critical parameter. Optimal performance of UV disinfection in HVAC systems is often observed at lower airflow speeds, as lower speeds allow for longer exposure times, enhancing pathogen inactivation, as demonstrated by Yang [175]. The application of UV-C wavelengths, whether 222 nm or 254 nm, does not appear to significantly alter the inactivation rate [176]. These findings have informed the development of mathematical models and numerical approaches for predicting inactivation within HVAC ducts. To further enhance the efficiency of this mitigation strategy, the combination of UV lamps with HEPA filters and/or micro-static electricity generators is being explored [177,178].

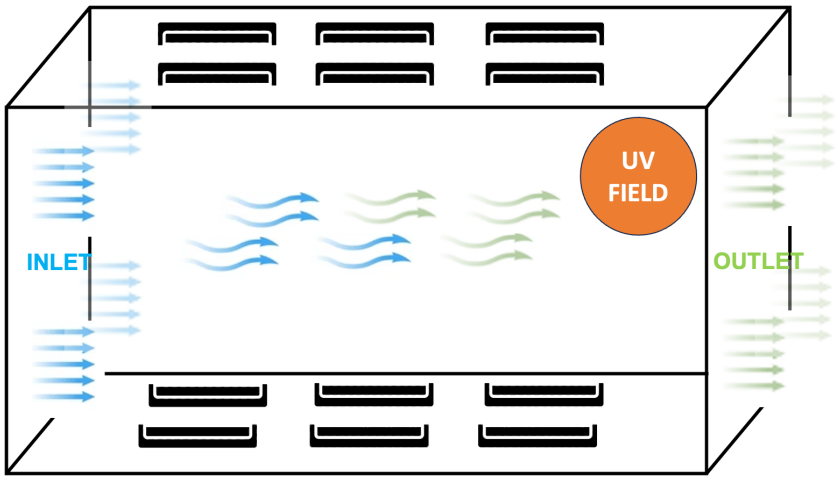

Figure 7. General representation of an array of UV lamps installed inside a ventilation duct.

Similar to UR-UVGI, UVGI integrated into HVAC systems also presents certain limitations. The rapid movement of air through ducts limits the exposure time of pathogens to UV light, potentially reducing its effectiveness, especially against more resistant microorganisms. Shadowing from duct components like filters and bends can create areas where UV light does not reach, allowing pathogens to survive and circulate. While UVGI can inactivate most airborne pathogens entering the HVAC system, it does not address droplets suspended in the room that do not enter the HVAC system. Continuous operation is required to maintain effective UV intensity, which can lead to higher energy consumption and costs, potentially making it less economically viable for some facilities. Additionally, prolonged UV exposure can degrade certain materials within the HVAC system, leading

to inefficiencies and the need for more frequent repairs. Initial installation costs can also be high, especially when retrofitting existing systems, which may be prohibitive for some facilities. There are also health risks associated with UV systems, as improper installation or leakage could expose maintenance personnel or building occupants to harmful UV radiation. Nonetheless, when properly implemented and maintained, UVGI-integrated HVAC systems offer a viable solution for reducing indoor contaminant concentrations.

3.3.3. UR-UVGI vs. UV Integrated Ventilation

Upper-room UVGI and UV-C-integrated ventilation systems both use ultraviolet light to reduce airborne pathogens, but they differ in their setup, operation, and areas of application. Upper-room UVGI systems involve the installation of UV-C lamps high on walls or ceilings, creating a disinfection zone in the upper part of a room where air circulates naturally or with the help of fans. This setup is best for smaller, localized spaces such as classrooms or offices, as it relies on air mixing within the room to move contaminated air into the UV-C-treated area. The system is easy to install, does not require modifications to HVAC systems, and minimizes UV exposure of occupants by keeping the light confined to the upper room. However, it may be less effective in larger spaces or rooms with poor air circulation, and it only disinfects the air, not surfaces.

In contrast, UV-C-integrated ventilation systems involve the installation of UV-C lamps directly in HVAC ducts or air-handling units, disinfecting air as it moves through the ventilation system before being distributed throughout the building. This approach is ideal for treating air across larger or multi-room facilities, ensuring consistent air quality throughout. While more complex and costly to install due to the need for integration with HVAC systems, it is highly effective for whole-building air disinfection and poses no risk of UV exposure to occupants, since the light is confined within the ducts. Unlike surface disinfection methods, both systems focus solely on airborne pathogens, with the choice between the two depending on the size of the space, installation feasibility, and specific air treatment needs.

In summary, both upper-room UVGI and UV-C-integrated ventilation systems provide effective solutions for reducing airborne pathogens in indoor environments, yet their optimal use varies depending on the application needs. Upper-room UVGI is particularly well suited for smaller spaces where direct integration with an HVAC system is not feasible, offering straightforward installation with minimal risk of occupant exposure. However, its efficacy is limited to areas with sufficient air circulation to bring contaminants into the UV-treated zone. On the other hand, UV-C-integrated HVAC systems excel in large, multi-room facilities, providing consistent disinfection across the entire building. Such a system is contained within the ductwork, avoiding any direct exposure to occupants but requiring careful installation and maintenance to address limitations like shadowing in the ducts and potential material degradation. Each system has unique operational benefits, and in settings where both local and central disinfection are needed, a combined approach may offer the most comprehensive solution. Future research could explore hybrid systems that leverage localized treatment by upper-room UVGI in combination with the broad reach of HVAC-integrated UV-C, providing an adaptable, layered approach to indoor air quality management.

3.3.4. UV-Based Portable Air Cleaners (UV-PACs)

Another application of UV radiation for airborne pathogen disinfection is the use of a portable air cleaner with UV air purification technology. As mentioned earlier, limited research is available on the performance of UV-based PAC technology. Therefore, an analytical review of the available UV-C radiation-based PACs in the industry, along with peer-reviewed computational and experimental studies, was conducted to assess their effectiveness and efficacy as a mitigation solution. A set of selection criteria used in several published peer-reviewed articles [85,88,179,180] involves following the four phases of a systemic review [85,181]: (1) identification, (2) screening, (3) eligibility, and (4) inclusion of

studies for the review. To perform this review, Google Scholar, PubMed, and Web of Science were used as search engines to collect a list of studies conducted over time. These collected papers were then subjected to multiple steps of scrutiny to retrieve the relevant papers for this study. A flow chart was designed, as illustrated below, to explain the methodology used to perform this review (Figure 8). Using all the keywords illustrated in the flow chart, a total of 3378 papers were collected and. Then, an elimination process was conducted, comprising the elimination of papers beyond the scope of the review by reading the title and keywords. Later, by reading their abstracts, partially skimming their methodologies, etc., the set was reduced to 108 papers. Finally, after an in-depth review, nine papers were chosen for this study. The aim of this review was to compile only scientific articles on UV air purifiers, examining their potential as mitigation solutions by evaluating either experimental or computational results that qualitatively and quantitatively demonstrate their efficacy and effectiveness in real-life scenarios.

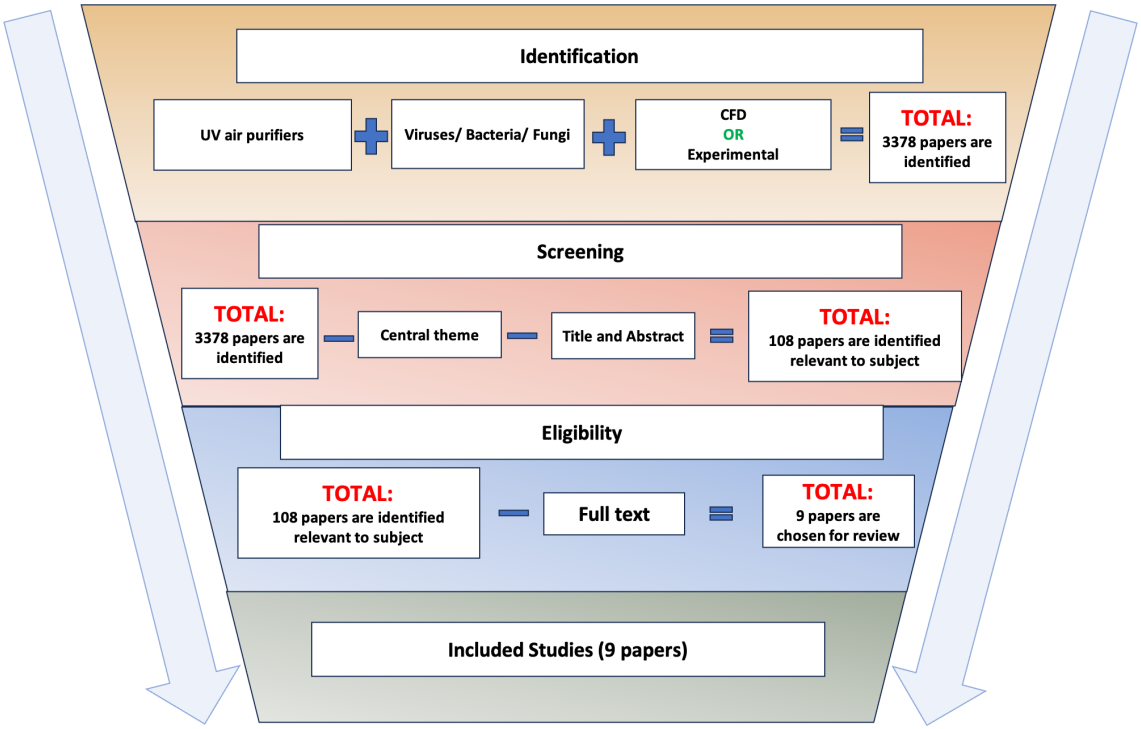

Figure 8. Flow chart explaining the review process for UV air purifiers.

Table 2 provides a summary of the reviewed studies, outlining the configurations of portable air cleaners (PACs), types of pathogens tested, methodologies applied, conclusions drawn, and limitations encountered. A general representation of these purifier designs is illustrated in Figure 9. Among the selected articles, four involve experimental studies, while the remaining focus on computational analyses. Five of these studies investigate PACs that combine particulate matter filtration with UV radiation, while the other three examine purifiers utilizing only UV radiation technology. The studied pathogens include viruses such as SARS-CoV-2 and feline coronavirus (FCoV), as well as a range of bacteria, including tuberculosis and fungi such as staphylococcus aureus.

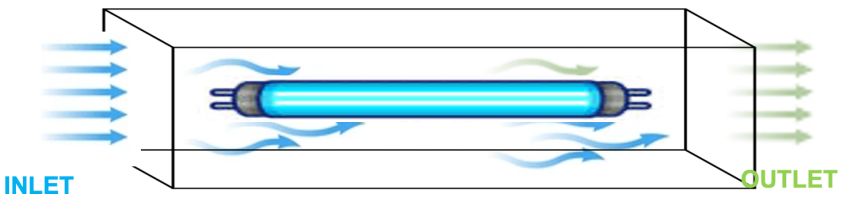

Figure 9. General representation of a UVGI portable air cleaner.

Concerning the experimental studies, three demonstrated the purifier's efficacy, and two evaluated effectiveness in real-life settings. Rausch [182] developed a protocol to rapidly assess the efficacy of UV air purifiers in laboratory conditions. The protocol involves pre-treatment of the sample with enzymes; then, the amount of surviving virus particles is determined using reverse transcription polymerase chain reaction (RT-PCR). The results were validated using UV-C air purifiers, showing their efficacy in viral inactivation. Li [178] explored the efficacy of a PAC that integrates high-efficiency filters with UV lamps, assessing the individual impact of these components on air treatment at various volumetric flow rates and identifying the necessary UV dosage for optimal performance. Samples were collected at different locations in the experimental setup, and a total plate count was performed. Their results showed that the combination of UV with MERV-8 and MERV-13 filters was the most effective configuration for the treatment of pathogen-laden environments. Garg [183] tested the efficacy of a PAC equipped with UV-C lamps both inside ducts and as a standalone unit against the SARS-CoV-2 virus. They verified the efficacy of their UV-PAC by trapping particles on a gelation filter and quantified viral RNA through an RT-PCR test. They extended these findings to study the effectiveness of the purifier in a classroom using the Wells–Riley model, demonstrating the purifier's impact when placed in various classroom locations. Similarly, Messina [184] studied the effectiveness of a PAC equipped with UV-C and HEPA filters in a hospital operating room (OR). Samples were collected using a well-calibrated particle counter. Contamination levels were measured across four different configurations (OR: ON/OFF; PAC: ON/OFF), concluding that contamination was significantly reduced when both the OR and PAC were active.

In summary, these studies collectively indicate that UV radiation technology is capable of inactivating airborne viruses, bacteria, and fungi and can be safely employed in occupied closed spaces. However, while efficacy studies are well documented, performing real-world effectiveness studies is challenging, as it is not feasible to experimentally release aerosolized pathogens in enclosed, occupied spaces.

Among the computational studies, two focus on evaluating the efficacy of a purifier using CFD simulations [185]. These simulations were performed by simulating flow fields using Reynolds-averaged Navier–Stokes (RANS) equations or filtered Navier–Stokes equations, commonly known as large eddy simulations (LESs). These simulations were coupled with the Chick-Watson disinfection model, as commonly seen in inactivation studies of airborne pathogens with UV radiation. This model provides the rate of inactivation (S) of pathogens inside a UV field (I) for an exposure time (t) as $S = 1 - \frac{N}{N_0} e^{-kIt_e}$, where k is a constant value that depicts the susceptibility of a pathogen to UV radiation and N and N_0 represent number of microbes present at times $t = 0$ and $t = t_e$, respectively. Sankurantripati [186] focused on studying UV-PAC efficacy using LES coupled with Lagrangian particle tracking to compute the turbulent dispersion of particles for different volumetric flow rates. This solver was coupled with a UV radiation model and the Chick–Watson model to determine the inactivation rate of a purifier. They provided the minimum UV dosage required for the tested purifier to inactivate SARS-CoV-2 with 95% rate of inactivation.

The remaining three studies focus on evaluating the effectiveness of purifiers using the Wells–Riley model. Kowalski [187] examined the effectiveness of an industrial purifier in a simplified residential room against a standard array of aerosolized pathogens using mathematical modeling to simulate infectivity risk for residents. The purifier's effectiveness was calculated by considering factors such as the volumetric flow rate, UV dosage, pathogen susceptibility to UV-C radiation, and the contaminant concentration in the room. Bergam [188] and Kapse [185] proposed conceptual designs for portable air cleaners that use UV radiation and high-efficiency filtration technology. Bergam focused on eliminating airborne pathogens with HEPA filters periodically cleaned by UV radiation. Their purifier's effectiveness was tested using 2D CFD simulations with the Chick–Watson model in an indoor restaurant setting. Srivastava [189] conducted RANS simulations to assess the performance of a UV purifier in an office building, simulating airflow patterns under natural and mechanical ventilation, which they validated against experimental results. By

placing the UV purifier in various locations, they analyzed infectivity spread using the Wells–Riley model.

The computational methodologies used in these studies attempt to capture the physical phenomena involved in treating aerosolized pathogens with UV purifiers. However, the PAC models developed by Bergam [188], Kowalski [187], and Srivastava [189] do not adequately demonstrate purifier efficacy. Effectiveness studies do not accurately simulate the dispersion of droplets or account for factors such as temperature and humidity, which are critical to the airborne lifetime of pathogens. While Kapse's [185] efficacy study provides a good starting point, it omits accurate representations of phenomena like the heat generated by UV lamps and particle dispersion inside the PAC, which affect pathogen residence time. Current literature on UV-PACs is lacking a high-fidelity methodology that involves accurate prediction of the flow fields and small-scale turbulence that govern the dynamics of pathogen-laden particles. Such a methodology coupled with a UV radiation and disinfection model can provide accurate computation of the rate of inactivation of UV-PACs. It could also be extended to assess the effectiveness of UV-PACs inside closed environments.

The reviewed studies highlight the potential of UV-based PACs as an effective tool for airborne pathogen disinfection yet reveal significant gaps in both experimental and computational methodologies. While laboratory efficacy tests have demonstrated that UV-PACs can inactivate a range of pathogens, translating these results to real-world applications remains challenging due to practical limitations, such as the inability to safely release aerosolized pathogens in occupied spaces. Computational studies, which rely on models like the Chick–Watson disinfection framework and the Wells–Riley model, offer valuable insights but often fall short of capturing critical environmental factors such as temperature, humidity, and complex particle dispersion dynamics. Furthermore, simplifications like the use of Reynolds-averaged Navier–Stokes (RANS) equations or the omission of effects like the generation of heat by UV lamps can limit the accuracy of these models. To advance UV-PAC technology, future research should focus on developing high-fidelity simulations that incorporate small-scale turbulence and realistic environmental variables. Such advanced modeling, combined with rigorous in situ testing, would allow for a more accurate assessment of UV-PAC effectiveness in occupied indoor spaces, providing robust guidance for optimizing these systems in diverse real-world settings.

Table 2. Research on UV air purification technology (sorted by year of publication).

Author (Year)	Portable Air Cleaner (PAC)	Pathogen	Methodology	Test Location	Remarks	Limitations
Kowalski (2013) [187]	3 UV lamps with a carbon-treated particulate screen	Standard test array of residential pathogens	Mathematical model for disinfection	Simplified residential room with inlet and outlet	Tested various airborne pathogens under different UV dosages to evaluate PAC performance in a residential home	Purifier efficacy not explicitly provided, UV lamps' impact unclear. Assumptions about flow fields were made.
Bergam (2020) [188]	HEPA filters and UV-C LEDs	SARS-CoV-2	2D simulations, Chick–Watson model	Virtual indoor restaurant with 4 tables	Developed a PAC design with HEPA filters cleaned by UV-C LEDs	Efficacy not shown through computations or experiments
Messina (2020) [184]	UV-C lamp with HEPA filters	Staphylococcus aureus	Experimental study with particle counter	Tested in hospital OR settings	Highest IAQ observed with PAC active during procedures	Efficacy of purifier and UV lamps unclear. Tested only in one location.
Srivastava (2021) [189]	UV-C lamp and ventilation	SARS-CoV-2	CFD for airflow, Wells–Riley model for infection risk	Office building with computers	Validated airflow patterns and verified infection risk by altering purifier location and ventilation rates	Minimal information about the purifier. Assumed PAC efficacy is 99%.

Table 2. *Cont.*

Author (Year)	Portable Air Cleaner (PAC)	Pathogen	Methodology	Test Location	Remarks	Limitations
Garg (2022) [183]	UV-C lamps	SARS-CoV-2	Experimental study, RT-PCR test, Wiles–Riley model	Lab and classroom	Results show UV radiation doses required for residence time in purifier	Wiles–Riley model lacks full accuracy, needs high-fidelity experiments
Li (2022) [178]	16 UV-C lamps with PM filters (MERV-8, MERV-13)	Viable airborne bacteria	Total plate-count test (CFUs/ml)	Lab and poultry farm	PAC removed PM and inactivated bacteria under different UV dosages	UV lamps' effectiveness not isolated from the PAC
Rausch (2022) [182]	2 UV purifiers	Feline coronavirus	Enzyme pre-treatment and RT-PCR assays	Laboratory setup	Developed a rapid protocol to test efficacy, with a 100% inactivation rate	Focused on protocol development, not real-life scenario testing
Kapse (2023) [185]	Dust filters with UV-C LED arrays	SARS-CoV-2, tuberculosis, and influenza-A	CFD (RANS + k-ω), UV-C methods, and Chick–Watson model	Inside the purifier	Conceptual design aims to inactivate pathogen-laden particles with UV-C LEDs	Pathogen susceptibility constant from the literature for 254 nm UV-C, while LEDs were 279 nm. Study needs real-life testing
Sankurantripati (2024) [186]	2 UV-C lamps with fans	SARS-CoV-2	LES and Lagrangian tracking with a UV disinfection solver	Inside the purifier	Tested efficacy for 3 different flow rates and UV dosages, with 95% inactivation achieved	Constant particle diameter assumed and real-world validation absent

4. Conclusions

The recent COVID-19 pandemic has underscored the critical need to address airborne infections in enclosed spaces, where transmission rates are significantly higher compared to outdoor environments. Historical studies of disease transmission modes have highlighted the importance of understanding how pathogens like viruses, bacteria, and fungi spread, be it through contact, droplets, or airborne particles. This knowledge has been instrumental in shaping the mitigation strategies necessary to control the spread of infectious diseases.

While individual measures like mask wearing, social distancing, and regular sanitation help curb direct transmission, they do not address the quality of indoor air, which is a major factor in the spread of airborne pathogens. Improving indoor air quality (IAQ) through ventilation and filtration techniques is therefore crucial. Studies have shown that optimizing HVAC design and ventilation rates can significantly enhance IAQ, but retrofitting existing buildings or public transport systems is not always practical. This has led to increased interest in portable air filtration technologies.

Three primary filtration techniques—mechanical, electrical, and UV radiation—offer viable solutions for improving IAQ. Mechanical filters, such as HEPA filters, and electronic filters like electrostatic precipitators (ESPs), have been shown to effectively reduce airborne contaminants in enclosed environments. However, mechanical filters can accumulate pathogen-laden particles, eventually becoming bio-hazardous. UV radiation-based filters offer an alternative by inactivating pathogens through RNA or DNA disruption, without trapping them. Among these, UV-C technology has been successfully used in in-duct systems, upper-room UVGI setups, and portable air cleaners (UV-PACs).

Of the three UV filtration methods, UV-PACs offer the greatest flexibility, as they can be deployed in various spaces without requiring integration with existing ventilation systems. While laboratory studies have demonstrated the high efficacy of UV-PACs in neutralizing airborne pathogens, real-world effectiveness studies remain limited due to the inherent risks of testing with aerosolized pathogens in occupied spaces. In this context, computational studies are vital for assessing both the efficacy and effectiveness of UV air purifiers. High-fidelity computational models, informed by the physics of airborne

transmission, are essential to understand how factors like purifier placement, airflow dynamics, and UV dosage affect performance.

This review highlights the significant potential of portable UV-PACs as a flexible, non-invasive solution for improving indoor air quality and reducing the risk of airborne pathogen transmission. UV-C-based technologies provide an alternative to traditional mechanical and electrical filtration methods, with the advantage of inactivating pathogens without trapping them, reducing bio-hazard accumulation over time. In particular, UV-PACs offer versatility, as they can be deployed across diverse environments, from hospitals and offices to public transport, without the need for extensive HVAC integration. Despite promising laboratory results demonstrating high efficacy, the real-world effectiveness of UV-PACs remains challenging to evaluate due to safety risks associated with the testing of aerosolized pathogens in occupied spaces. Current computational studies provide useful insights, but limitations in capturing complex environmental variables such as temperature, humidity, and airflow patterns underscore the need for more advanced modeling techniques. High-fidelity computational models that account for these factors are essential to accurately simulate UV-PAC performance in real-world scenarios. Moving forward, research must focus on developing and validating these computational models, which will enable more precise assessments of UV-PAC placement, UV dosage, and overall air purification efficacy in various settings. This approach is critical not only to enhance indoor air quality but also to prepare enclosed spaces for future infectious disease outbreaks, ensuring that advanced air purification technologies are both effective and broadly applicable across different indoor environments.

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Abbreviations

The following abbreviations are used in this manuscript:

HEPA	High-Efficiency Particulate Air
ESP	Electrostatic Precipitator
UV-C	Ultraviolet-C
PAC	Portable Air Cleaner
CADR	Clean Air Delivery Rate
RT-PCR	Reverse Transcription Polymerase Chain Reaction
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
RNA	Ribonucleic Acid
HVAC	Heating, Ventilation, and Air Conditioning
UR-UVGI	Upper-Room Ultraviolet Germicidal Irradiation
CFD	Computational Fluid Dynamics
IAQ	Indoor Air Quality
COVID-19	Coronavirus Disease 2019
WHO	World Health Organization
HICPAC	Healthcare Infection Control Practices Advisory Committee
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers

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