

Energy–Indoor Air Quality Trade-Offs in Respiratory Droplet Removal: A Model-Based Comparison of Distributed Filtration and Centralized Ventilation

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Abstract. This study proposes a new, energy-efficient strategy for mitigating the airborne transmission of infectious diseases in indoor environments, based on distributed filtration. Rather than relying solely on increasing hourly air exchange rates or placing a single air purifier within a room, this work investigates the effect of using multiple small filters distributed throughout the space. A model was designed to quantify this effect, considering particulate matter PM_{2.5} as surrogates for respiratory particles. A school classroom was chosen as the reference case for comparison. The performance of the distributed filtration approach was evaluated compared to the dilution achieved by conventional ventilation, considering both particle removal effectiveness and energy requirement. Specifically, the additional electrical power required to power multiple small filters was compared to the energy required to increase ventilation rates to achieve a similar dilution effect. The results provide a preliminary assessment of the trade-off between energy consumption and indoor air quality when using small-scale, distributed air purification devices to influence the removal of respiratory particles in indoor environments. This approach may represent a complementary strategy to reduce the risk of airborne transmission, particularly in settings where increasing ventilation rates is energy-intensive or technically limited.

1. Introduction

Airborne infectious diseases are spread by respiratory particles released during breathing, speaking or sneezing. These particles span a wide size range and exhibit complex fluid dynamics, including evaporation, dispersion, deposition, and prolonged suspension [1]. For diseases such as COVID-19, smallpox, tuberculosis, and influenza airborne or aerosol-mediated transmission is the main route of infection [2,3]. Exposure can occur through short-range inhalation near an infected individual, or through longer-range transmission when infectious particles accumulate in closed environments [4]. From an epidemiological perspective, airborne transmission is extremely difficult to control, as it depends on the interaction between virological, environmental, behavioural, and fluid dynamic factors [3,5].

Ventilation is recognized as an important factor in maintaining good indoor air quality [3,6]. However, preventing airborne transmission through ventilation alone remains challenging [7]. Achieving very high levels of airborne particle removal may require ventilation rates well above those typically adopted even in healthcare settings [8]. Such flow rates are generally impractical due to energy, comfort, and technical constraints. Therefore, complementary mitigation strategies are needed.

Promising alternatives include electrostatic devices and fan-assisted filtration systems. Electrostatic approaches include ionic wind devices designed to remove droplets from indoor air [8], as well as high-voltage sanitization systems derived from industrial electrostatic precipitators and adapted for the reduction of airborne pathogens, including SARS-CoV-2, in indoor environments [9]. Fan-and-filter systems, including Portable Air Purifier (PAP), represent another practical strategy for increasing particle removal. However, conventional applications typically rely on centralized Heating, Ventilation and Air Conditioning (HVAC) system or the placement of a single purification unit within a space. Less attention has been paid to distributed configurations, in which multiple small-scale filtration devices are placed within the occupied space to locally modify air flow patterns and promote particle deposition and removal.

In this context, the present study investigates small-scale distributed filtration as a complementary strategy for reducing the persistence of respiratory particles in indoor environments. The effectiveness of this approach is modelled based on the experimental framework proposed by Li et al. [10], which exploits small-scale air purification technology, and is compared with the dilution achieved through conventional ventilation, represented using the well-mixed model proposed by Burrridge et al. [11]. The comparison is carried out under the assumption of a well-mixed indoor environment and focuses on the trade-off between particle removal performance and energy consumption.

2. Materials and Methods

This section describes the methodological framework and the modelling assumptions used to evaluate the effectiveness of distributed filtration compared to conventional ventilation. The study focuses on a representative indoor environment, utilizing experimental data to characterize the spatiotemporal removal of respiratory particles and comparing these results with centralized air exchange strategies in terms of both indoor air quality and energy consumption.

2.1 Computational Domain and Grid Discretization

The simulation is based on a reference classroom measuring $10\text{ m} \times 5\text{ m}$, yielding a total floor area of 50 m^2 . This configuration is directly comparable to the 55 m^2 ($10\text{ m} \times 5.5\text{ m}$) case study analyzed by Burrridge et al. [11]. To account for spatial variability, the computational domain was discretized into 50 cells with a $1\text{ m} \times 1\text{ m}$ and a 4 m height, as considered by Burrridge et al. [11] for modernly constructed classrooms. This procedure enables the precise modelling of air purifier placement by allowing the model to determine, for every individual cell, whether a device is present or not.

This mesh-based approach provides a more spatially accurate representation than the zero-dimensional (0D) "well-mixed" model developed by Burrridge et al. [11], which considers only the aggregate combined effects of all filtration units. Numerous studies highlight that the spatial setup of filters is critical in the determination of purification efficiency. Notably, Ostmann et al. [12] employed computational fluid dynamics (CFD) simulations to investigate aerosol transport under various scenarios, including natural ventilation, mechanical ventilation, and different air purifier

locations. Their research demonstrated that the purifier's position leads to inhomogeneous protection levels for occupants; in some cases, certain placements can even be counterproductive by transporting unfiltered air directly toward specific students. Implementing a mesh in the considered environment is therefore essential to account for these phenomena in the considered study.

2.2 Computation and Modelling of Filtration Efficiency in each cell

For simplicity and to be able to compare our study to others in literature, airborne droplets will be assumed equivalent to PM2.5 particles. This assumption has been made so that the models developed by Burrige et al. [11] can be adapted to the present research.

A single $1\text{ m} \times 1\text{ m} \times 4\text{ m} = 4\text{ m}^3$ cell will now be considered. Each cell, for simplicity, will be assumed to either contain one or no PAP. The filter efficiency of the purifier will be assessed, with the aim to find an average value of efficiency approximately valid in the entirety of the cells assumed to contain a PAP.

The filtration performance is characterized using empirical data (obtained by Li et al. [10]) of normalized particulate concentration (c/c_0 , where c_0 is assumed to be initial PM2.5 concentration) as a function of distance from the PAP. The model accounts for various temporal snapshots, specifically at 60 s, 120 s, 180 s, 300 s, 600 s, and 900 s from the start of the purification process, as well as the natural decay observed after 900 s in the absence of active filtration. In the present paragraph, the purification efficiency will be computed for the 1 m^2 cells that in the following parts of the study will be considered to contain the PAP.

For meso- and micro-scale particulate matter (PM2.5 and PM1), Li et al. [10] notice a localized increase in concentration in the immediate vicinity of the PAP compared to c_0 . This phenomenon is attributed to several factors [10]: the disruption of larger particle aggregates into smaller ones due to device-induced turbulence, the evaporation of volatile components from larger droplets driven by temperature gradients between the source and the environment, and electro-convective turbulence diverting particles away from the device. In these proximal areas, concentration peaks can reach values between 1.2 and 1.7 times the initial concentration.

To ensure physical consistency and avoid negative efficiency values in the proximity of the PAP, following Li et al. [10] suggestions, the efficiency (η) is defined relative to an "effective maximum concentration" (c_{max}), set at $1.7\text{ }c_0$. Practically, we consider c_{max} to be an "equivalent initial concentration" considered after the initial spike in concentration occurs. The efficiency is thus formulated as:

$$\eta = 1 - \frac{c}{c_{max}} \quad (1)$$

By substituting c_{max} with $1.7\text{ }c_0$, the relationship becomes:

$$\eta = 1 - \frac{c}{1.7\text{ }c_0} = 1 - \frac{c/c_0}{1.7} \quad (2)$$

This relationship allows for the derivation of spatial and temporal efficiency variations based on experimental normalized concentration data. Li et al. [10] study considered an experimental setup of $0.8\text{ m} \times 0.8\text{ m}$ of area, thus the collected data for the quantity c/c_0 is available for distances between 0 m and 0.454 m from the PAP. Since we model elementary cells in the considered classroom with dimensions $1\text{ m} \times 1\text{ m}$, we need to know the values of the ratio c/c_0 for distances between 0 m and 0.5 m . As previously mentioned, the height of each cell was assumed to be 4 m , so we can expect purification efficiency to decrease noticeably with height. However, assuming that both the PAP and a person who could eventually act as a PM2.5 source inside of the cell are situated at similar height, and thus that the purification of air does not involve

the upper layers of the cell, such factor will be neglected, and the efficiency will be computed considering a maximum distance from the purifier of 0.5 m.

Using Excel, efficiency η was computed using formula (2) for every value in the range (0, 0.454) m. Then, a linear regression was fit to estimate efficiency at distance 0.5 m. For the regression, only the values of efficiency between 45.38% and 40.67% were considered, since the overall variation of efficiency cannot be approximated as linear. The values obtained at 300 s were considered.

Table 1. Purification efficiency measured at different distances from the purifier, along with the corresponding square areas swept by the radius at each distance, based on Li et al. [10], after 300s.

Distance from the Purifier [cm]	Enclosing square area [m^2]	Purification efficiency [-]
0.5	0.000102469	86.51%
7.4	0.021848764	60.86%
15.5	0.073654924	45.38%
30.5	0.275521429	40.96%
45.4	0.452177941	40.73%
50.0	0.176694473	40.67%

In Table 1, the results of said operations are shown. As can be seen, efficiency is very high in the proximity of the filter, but more than halves after half a meter, going from 86.51% to 40.67%. For simplicity, a mean value of efficiency has been adopted. Using Excel, a visual illustration to understand the distribution of efficiency has been developed.

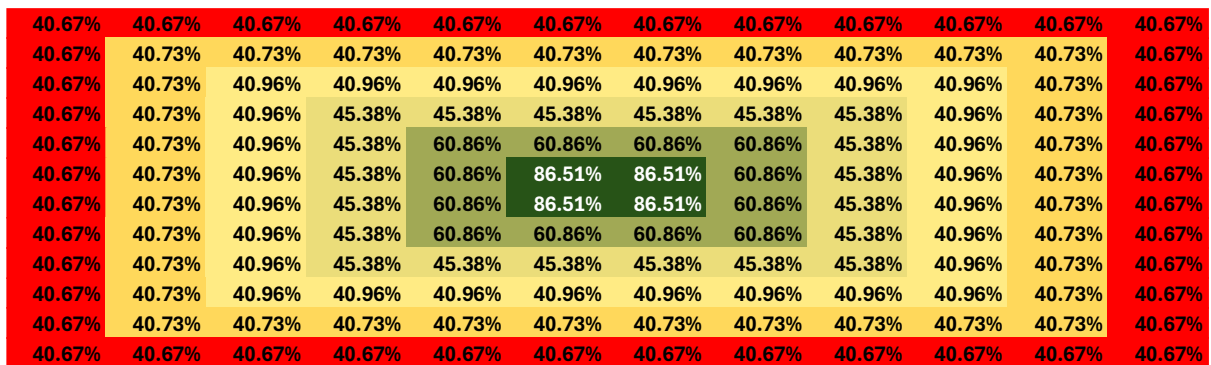


Figure 1. Visual representation of purification efficiency spatial distribution in a rectangular cell, considering a positioning of the air purifier at the centre of the cell. Scheme not in scale with respect to actual distances, as of Li et al. [10]

With the visual aid provided by Figure 1, the areas of the regions with different values of efficiency have been computed. For example, we have computed that an efficiency of 86.51% is achieved in a square of area $0.000102469 m^2$, while an efficiency of 60.86% is achieved in a square frame of area $(0.021848764 - 0.000102469) m^2 = 0.021848764 m^2$, and so on. Afterwards, a

weighted average of the efficiency has been obtained, using the calculated areas as weights. The result was an average efficiency of 41.57% over the 1 m² cell containing the PAP.

2.3 Analytical analysis of PM2.5 concentration

Burridge et al. [11] modelled analytically the dynamic change in concentration of PM2.5, CO₂ and RNA in the classroom considering a scenario in which the class is naturally ventilated through one window, with initial conditions for the concentrations equal to external ones, and multiple HEPA filters are present inside of the classroom, and a maximum number of 32 occupants acting as a source of particulate, carbon dioxide and viral RNA; the model also took into account the settling rate of particulate and RNA and the decay rate of viral RNA, respectively defined as the rate of sedimentation of particle on surfaces and the rate at which pathogens biologically inactivate.

As previously mentioned, in this study droplets are assumed equal to PM2.5, and CO₂ and RNA will not be considered. Moreover, the classroom here considered is assumed not to have windows nor natural ventilation. To adapt the formulas developed by Burridge et al. [11], the terms accounting for natural ventilation will be used for mechanical ventilation instead. Moreover, our analysis will be extended not just to HEPA filters, but also to passive filters, such as those used by Li et al. [10]

In this research, an adaption of the model developed by Burridge et al. [11] will be performed to a discretized spatial environment. A similar classroom with the same number of occupants will be considered. The classroom will be considered as adiabatic. Two different scenarios will be compared from an energetic and purification perspective: only 10 PAPs are used in the classroom, without HVAC; only a HVAC system, without any PAP, giving the same air purification performance.

The considered formula for this study is the following:

$$\frac{dP}{dt} = \frac{S_P}{V} - \left(\frac{\dot{V}}{V} + \kappa_P + \eta \frac{\dot{V}_F}{V} \right) P + \frac{\dot{V}}{V} P_{out}, \quad (3)$$

where P is the PM2.5 concentration (in $\mu\text{g}/\text{m}^3$), t is time (in s), $\dot{V}$ is the volumetric flow rate due to mechanical ventilation (in m^3/s), V is the considered volume (in m^3), κ_P is the settling rate (in s^{-1}), η is the purification efficiency, $\dot{V}_F$ is the Clean Air Delivery Rate (CADR) provided by the PAPs (in m^3/s), and P_{out} is the outside PM2.5 concentration (in $\mu\text{g}/\text{m}^3$).

Since passive filters, such as those described by Li et al. [10], do not possess a properly define CADR, an alternative parameter was defined to substitute $-\eta \dot{V}_F/V$ in equation (3) to cover a greater variety of applications. From eq. (3) we derive that the term $-\eta \dot{V}_F/V$ must be in the form of a concentration gradient, therefore it can be written as $dP/dt = -k P$, where the parameter $k = \eta \dot{V}_F/V$. Solutions to such equations are $P = P_0 \exp(-k t)$, where P_0 is the initial PM2.5 concentration. Since filter efficiency is 41.57% after 300 s, we'll have that after said time $P = P_0(1 - 0.4157) = 0.5843 P_0$. Thus, considering $P_0 = 1 \mu\text{g}/\text{s}$ and $P = 0.5843 \mu\text{g}/\text{s}$, we obtain $k = 0.001791136 \text{ s}^{-1}$. This parameter is valid for all filters with the considered efficiency characteristics after the same period.

Eq. 3 then becomes:

$$\frac{dP}{dt} = \frac{S_P}{V} - \left(\frac{\dot{V}}{V} + \kappa_P + k \right) P + \frac{\dot{V}}{V} P_{out} \quad (4)$$

2.4 MATLAB calculations considering only PAPs, no HVAC

A MATLAB (version R2025b) code was created to solve eq. (4) in each cell of the mesh that contains a PAP. The aim was to analyse the contribution to PM2.5 concentration of the PAPs for the 32 cells containing one, assuming each PAP is positioned in a cell with a person acting as a PM2.5

source. The code defines the PM2.5 mass balances through MATLAB's "ode45" function. Concentration profiles are obtained by integrating the governing equations over time accounting for source terms, ventilation, and settling and removal kinetics. The code finally outputs the final concentration of PM2.5 after the period given as input. For simplicity, the other cells have been considered as having a constant PM2.5 concentration equal to $P_0 = 6 \mu g/m^3$, as used by Burrige and al. [11]

Regarding the first scenario, the following values for the parameters were considered: $S_p = 0.139 \mu g/s$ (as by [11]), since we aim to consider the particularly disadvantaging case of a person contained in the considered cell; $V = 4 m^3$; $\kappa_p = 0.000111 s^{-1}$ (as by [11]); $k = 0.001791136 s^{-1}$; $P_{out} = P_0 = 6 \mu g/m^3$. A period of 1800 s, equal to 5 h, was considered, to account for a typical scholastic day.

An Excel model was then created to compute energy consumption of PAPs and to compute the actual concentration of PM2.5 in the whole classroom after five hours (18000 s). A grid of 50 cells was created, each representing a $1 m^2$ square and given either a configuration "No purifier" or a configuration "Purifier", as shown in Figure 2. In future developments of this work, a third configuration could be created, i.e. "Near Purifier", to account for buffer zones between "Purifier" and "No purifier" regions. As of now, this option was neglected out of simplicity of the model.

Classroom Model									
No Purifier	No Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier
No Purifier	No Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier
Purifier	No Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier
No Purifier	No Purifier	No Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier	Purifier
No Purifier	No Purifier	No Purifier	No Purifier	No Purifier	No Purifier	No Purifier	No Purifier	No Purifier	No Purifier

Figure 2. Classroom visual model implemented on Excel.

Clearly, this subdivision of the system does not properly account for the fluid dynamic contamination between adjacent cells. However, it will serve to have a first approximation of the desired results.

Each cell was given a value of filter efficiency, power consumption, PM2.5 concentration in the cell volume after 1800 s, PM2.5 mass in the cell volume after 18000s. PAP with the same power consumption as those used by Li et al. [10] were considered: since they consumed 25 kV and 0.25 mA, the power consumption for each PAP is of 6.25 W. Cells containing purifiers are considered to have a filter efficiency of 41.57%, while those not containing purifiers have a filter efficiency of 0%.

2.5 MATLAB calculations considering only HVAC, no PAPs

After computing PM2.5 concentration after 18000s in the room, an analytical model of the same classroom, with the same number of occupants, without PAPs but using only HVAC for purification. The objective was to compute the volumetric airflow rate and power consumption of the HVAC system to have the same decrease in PM2.5 concentration after 18000s. As previously mentioned, the class was assumed to be adiabatic, which means that the only power required by the HVAC system was that used to heat and cool the volumes of air taken from outside and inserted into the classroom as air change for purification.

It is necessary to isolate from Eq. (4) the term $\dot{V}$, considering $k = 0$ since no PAPs are present. In this scenario, the parameters assume the following values: $V = 10 m \times 5 m \times 4 m = 200 m^3$, the total volume of the classroom; $S_p = 32 \times 0.139 \mu g/s = 4.448 \mu g/s$, since in this scenario the considered volume contains 32 people; dP/dt was approximated as $\Delta P/\Delta t = (P_f - P_0)/18000$,

where P_f is the PM2.5 concentration after 18000 s as computed in §2.4 and $P_0 = 6 \mu g/m^3$ is the initial PM2.5 concentration in the room; $P_{out} = P_0 = 6 \mu g/m^3$ is the PM2.5 concentration of outside air. Isolating $\dot{V}$, Eq. (4) becomes:

$$\dot{V} = \frac{V}{P_f - P_{out}} \left(\frac{S_P}{V} - (\kappa_P + k)P_f - \frac{P_f - P_{out}}{18000} \right) \quad (5)$$

After obtaining the volumetric airflow rate, we can compute the required number of air changes per hour as $n = \dot{V}/V$. Finally, we can compute the power $\dot{E}$ needed to give the HVAC system to heat or cool the air as by Eq. (6):

$$\dot{E} = \dot{Q}/COP = \rho \dot{V} c_p (T_c - T_e)/COP, \quad (6)$$

where $\rho = 1.27 \text{ kg}/\text{m}^3$ is air density [11], $c_p = 1.005 \text{ kJ}/(\text{kg K})$ is air specific heat, COP is the coefficient of performance of the HVAC system, T_e is the outside air temperature, and T_c is the average air temperature in the classroom. Regarding the COP , typical air-based systems have an average COP ranging from 2.5 to 3.5 in winter [13], so we will assume the value $COP = 3$. For a first approximation, we will not distinguish between summer and winter cases for COP calculation. Numerous outside temperatures were used, and specifically the ranges $(-10, 20)^\circ\text{C}$ for winter and $(26, 40)^\circ\text{C}$ for summer were considered. The average air temperature inside the classroom is set at 20°C in winter and 26°C in summer.

3. Results

By solving Eq. (4) on MATLAB we obtain the PM2.5 concentration for the scenario of the classroom with 32 PAPs and without HVAC, considering a single 4 m^3 cell with a person and a PAP as our system. After 18000 s, the computed parameter is $P = 18.2664 \mu g/m^3$. This value is significantly higher than the considered initial condition P_0 , but is expected to be significantly smaller than the concentration we would obtain after the same period in the absence of PAPs. To compute such a configuration, k must be set equal to zero: the result is $P = 271.4234 \mu g/m^3$. This value is high due to the reduced volume of the analysed cells. In particular, the model shows that the PM2.5 concentration plateaus after $\approx 3000 \text{ s}$, and the value does not change thereafter. The MATLAB-generated plot of P over time can be seen in Figure 3.

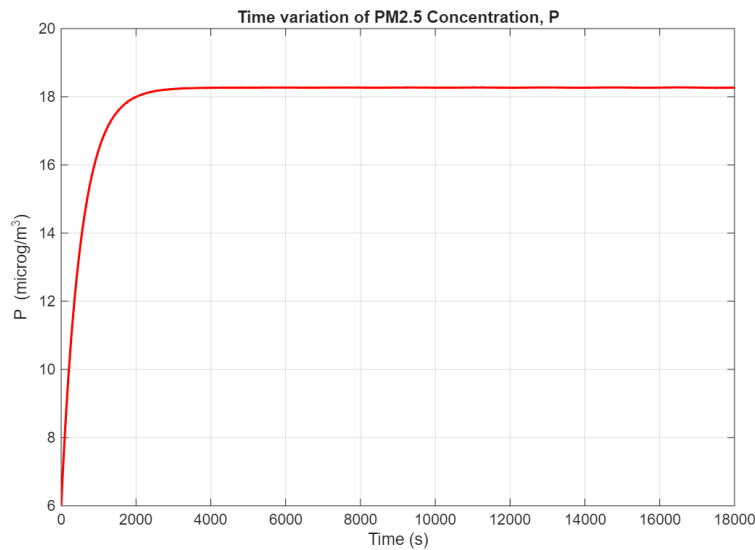


Figure 3. MATLAB plot of the PM2.5 concentration over time. The value plateaus at $18.2664 \mu g/m^3$ after $\approx 3000 \text{ s}$.

This behaviour can be explained by considering that the value of S_p ($0.139 \mu\text{g/s}$) is high with respect to k ($0.001791136 \text{ s}^{-1}$) and κ_p (0.000111 s^{-1}). Initially, the person inside the cell generates PM2.5 at a faster rate than the removal by settling and filter purification. After some time, a large enough amount of PM2.5 is present in the cell so that the removal can affect a portion of particles sufficient to balance the generation. This can be explained by noting that particle generation is a constant phenomenon producing the same amount of particles each second, while removal due to filtering and settling is a particle-count-dependent phenomenon: the fewer particles present in the air, the fewer particles are removed by the filter, whereas the more particles are present, the more effective the removal becomes, given that both filter efficiency and settling rate are constant. By setting $S_p = 0 \mu\text{g/s}$, we can use the MATLAB code to assess the combined effect of the filter and the settling rate on particle removal: after 100 s, the overall removal efficiency is 17.32%; after 300 s, it rises to 43.48%; after 900s, it reaches 81.95%; after 18000 s, it reaches 99.99%. In this case as well, the MATLAB code shows that the value plateaus after ≈ 3000 s. This confirms that removal due to settling and filter purification is a progressive phenomenon, reaching approximately unitary efficiency after a sufficiently long time.

In the cells not containing a PAP nor a person, the initial concentration $P_0 = 6 \mu\text{g/m}^3$ is removed only through the settling of particles. To compute PM2.5 concentration after 18000 s for void cells, we set in the code $S_p = k = 0$, and obtained $P = 0.8136 \mu\text{g/m}^3$. This result corresponds to the natural sedimentation of particles on the cell surfaces.

In the Excel classroom model, each cell was assigned the following values:

- Power consumption of 6.25 W if in the “Purifier” configuration, or 0 W if in the “No Purifier” configuration.
- Filter efficiency of 41,57% if in the “Purifier” configuration, or 0% if in the “No Purifier” configuration.
- PM2.5 concentration after 18000 s of $18.2664 \mu\text{g/m}^3$ if in the “Purifier” configuration, or $0.8136 \mu\text{g/m}^3$ if in the “No Purifier” configuration.
- PM2.5 mass after 18000 s of $73,0656 \mu\text{g}$ if in the “Purifier” configuration, or $3.256 \mu\text{g}$ if in the “No Purifier” configuration.

To compute the overall power consumption, we simply sum the power consumption of every cell, and we obtain the total power consumed by the PAPs: $6.25 \times 32 + 18 \times 0 = 200 \text{ W}$. To compute the overall PM2.5 concentration in the classroom after 18000s, we sum the PM2.5 mass after such period and divide it by classroom volume ($V = 200 \text{ m}^3$): $P = (73.0656 \times 32 + 3.256 \times 18)/200 = 11.98 \mu\text{g/m}^3$.

This value was then used to compute the number of air changes per hour necessary for a HVAC system acting in the same classroom without the PAPs to achieve the same purification effect as the PAPs. By applying the procedure described in §2.5 considering the just found value $P_f = 11.98 \mu\text{g/m}^3$, we would obtain $\dot{V} = 0.343 \text{ m}^3/\text{s} = 1236.357 \text{ m}^3/\text{h}$, which translates in $n = \dot{V}/V = 1236.357/200 = 6.18$ air changes per hour.

This value exceeds the number of air changes per hour required by standards such as ASHRAE 62.1 [14] to guarantee acceptable indoor air quality, which sets the minimum air clean airflow rate to 5 L/s/person , corresponding to $576 \text{ m}^3/\text{h}$ in a class of 32 people, which translates to an air change rate of 2.88 h^{-1} . Moreover, Wood et al. [15] have collected data from 322 UK classroom and found that the average maximum airflow rate per person in a scholastic year is 6.8 L/s/person , and using the same approach as before this would translate to an air change rate of 3.92 h^{-1} . A statistical study of UK classrooms has been considered since the data collected by Burridge et al. [11] was obtained in the same geographical scenario. The number of air changes

per hour computed in our scenario is higher than both that prescribed by ASHRAE 62.1 and the average maximum value used in UK classrooms, but it still appears to be realistic and usable in practice. It can be therefore concluded that an HVAC system could also work for the purification of the classroom. However, even though the air change rate of 6.18 h^{-1} is sufficient with respect to the requirements set by ASHRAE 62.1, it is not enough with respect to the standard ASHRAE 241 [16], which sets the minimum equivalent clean airflow rate for classroom to 20 L/s/person to mitigate infection risks, which would correspond to an air change rate of 11.52 h^{-1} . In case of high-risk scenarios, a much stronger filtration is required than that described in the present analysis.

When comparing power consumption, however, we find that the same level of removal is achieved by PAPs using noticeably less power. A room equipped with 32 PAPs would consume 200 W to supply the purifiers, to which an additional power consumption should be added to account for other air quality factors such as CO_2 and further particulate control. As a first approximation, we can consider the air change rate of 2.88 h^{-1} as by ASHRAE 62.1 for such concept, to account for the minimum number of air changes per hour required by standards for CO_2 remotion. Since the same agents (CO_2 , particulate matter, etc.) are addressed in both the HVAC-only and PAP-only scenarios, the difference in air change rate between the two amounts to $6.18 - 2.88 = 3.30 \text{ h}^{-1}$. In other words, both scenarios consume energy to have a baseline air change rate of 2.88 h^{-1} : beyond that, the PAP-only scenario requires an additional 200 W to run the purifiers, while the HVAC-only scenario requires additional power to achieve 3.30 h^{-1} more of ventilation for pathogen removal.

We can use the volumetric airflow rate to compute the required power consumption by the HVAC system with respect to the outside temperature T_e , as described in §2.5. In Figure 4 the results are shown graphically. In particular, the absolute value of the power consumption by the HVAC system (considering an air exchange rate of 3.30 h^{-1}) was graphed in both scenarios, and the PAP-only scenario has been added as well for comparison.

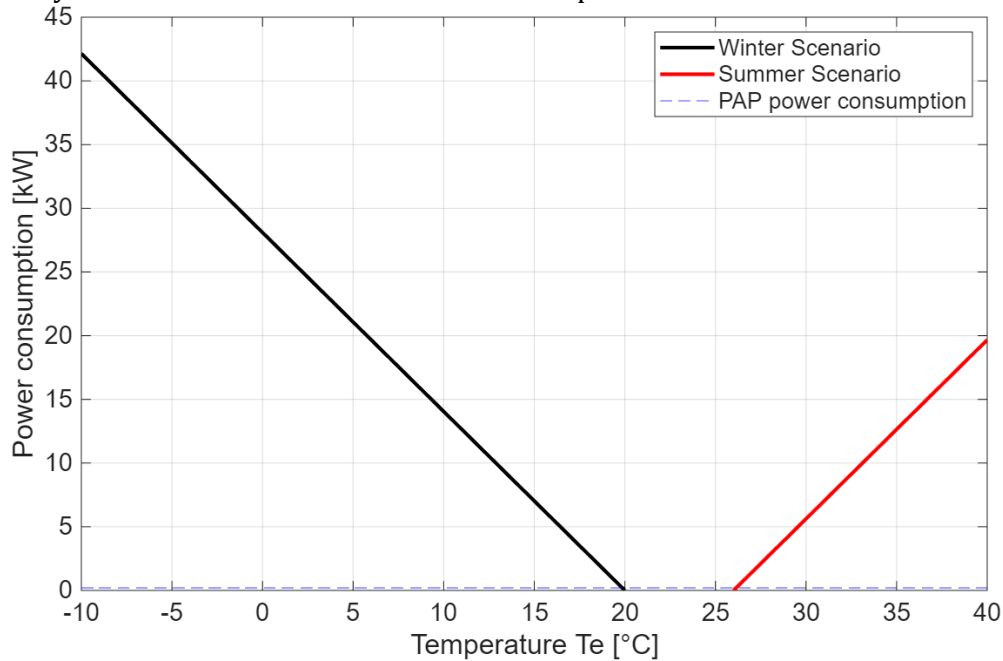


Figure 4. Graphical representation of the relationship between outside air temperature T_e (°C) and power consumption $\dot{E}$ (kW) of HVAC.

4. Discussion

The use of PAPs appears to be advantageous as it brings the PM_{2.5} concentration in the classroom after five hours ($P = 18.27 \mu\text{g}/\text{m}^3$) down to 6.7% of the value it would have without PAPs ($P = 271.42 \mu\text{g}/\text{m}^3$), proving effective in the removal of particulate.

The same result could be reached with an HVAC system with an air change rate higher than that required by the PAP-only scenario by 3.30 h^{-1} .

PAP use therefore appears to be more energy-efficient than mechanical ventilation alone, and these results could support the adoption of PAPs in settings where expanding centralized ventilation is technically or economically constrained. It should be noted that the HVAC system's power consumption was estimated here based solely on the heating and cooling of outside air; this remains a first approximation, as the electronic components of the system would also require additional power.

It is necessary to acknowledge a limitation of the present model. The computational domains were sized to account for the projected effects of the air purifiers; however, they were treated as independent and were not interconnected. Consequently, potential interactions between the airflow fields generated by individual PAPs were not captured. This limitation could be addressed through a more sophisticated computational fluid dynamics (CFD) analysis capable of representing the entire classroom and the interactions among multiple air purifiers. Such an approach, however, would entail substantially greater computational complexity and cost.

5. Conclusion

The present study confirms that distributed filtration represents an effective and energetically sustainable strategy for improving air quality in high-density indoor environments such as school classrooms. The proposed model, based on a discretized spatial domain, demonstrates that the use of 32 PAP units can reduce concentration to 6.7% of the levels reached in absence of PAP units.

The primary advantage of this approach lies in its energy efficiency: considering that both scenarios must guarantee a baseline of 2.88 h^{-1} air change rate as prescribed by ASHRAE 62.1 [14], the additional power demand of the purifiers (200 W) is negligible compared to the supplementary thermal load required by an HVAC system to provide an equivalent clean air delivery rate (6.18 h^{-1} , the baseline of 2.88 h^{-1} with an adding of 3.30 h^{-1}).

This confirms that distributed filtration is not only effective but also the more energetically convenient solution when higher levels of protection against airborne pathogens are required, particularly in contexts where scaling up centralized ventilation is impractical or costly.

Future developments of the research will focus on integrating viral RNA transport and accounting for the fluid dynamic interactions between adjacent cells to better characterize the protection levels offered to individual occupants. Also, a more accurate analysis of heat exchange between classroom and outside environment must be performed. Ultimately, the results suggest that PAPs should be considered a mature complementary technology for infection risk management.

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Please include a completed version of this template as an appendix to any submitted work that has involved the use of generative AI (GenAI) technology ([further information on GenAI and assessment](#)).

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