Particle concentration and indoor air quality in naturally ventilated patient rooms-A field study in a hospital building in Bucharest, Romania

The Role of Portable Air Purifiers in Reducing Particle Concentration in Patient Rooms

Mohamed Elsayed [*1], Natalia Lastovets[1], Ville Silvonen [2], Anni Luoto[1,3], Topi Rönkkö [2], Piia Sormunen[1,3]

1 Tampere University, Faculty of Built Environment
Korkeakoulunkatu 5
33720 Tampere, Finland
**Corresponding author: mohamed.elsayed@tuni.fi*

2 Aerosol Physics Laboratory, Faculty of Engineering and Natural Sciences, Tampere University
Korkeakoulunkatu 6
33720 Tampere, Finland

3 Granlund Oy
Malminkaari 21
00700 Helsinki, Finland

ABSTRACT

In response to the COVID-19 pandemic, there has been a significant emphasis on improving indoor air quality (IAQ), particularly within hospital buildings. Despite developments in integrated central advanced mechanical ventilation and filtration technologies in new hospital buildings, challenges persist in installing them in existing and old hospital buildings relying on traditional natural ventilation. In this context, portable air purifiers have been developed and utilised in hospital facilities as a solution to reduce airborne particulate matter (PM) concentrations and the potential airborne infection risk. However, there have been a limited number of IAQ studies in hospital buildings due to the unique operational environments of hospitals and the associated risks for researchers while conducting in-situ research in hospital facilities, especially in naturally ventilated hospital buildings. This has resulted in a knowledge gap concerning the measured effectiveness of portable air purifiers in traditionally naturally ventilated hospital buildings. To address this gap, a one-week measurement campaign was conducted at a naturally ventilated hospital building in Bucharest, Romania. The campaign aimed to assess PM concentrations before and after utilizing portable air purifier units in two distinct patient rooms — an intensive care unit (ICU) and an isolation room. Additionally, the study involved measuring various aspects of indoor environmental quality (IEQ) parameters, including CO_2 levels, temperature, and relative humidity. Values of measured parameters were used for infection risk calculation. The effectiveness of the air purifier units was determined by comparing indoor and outdoor (I/O) PM concentration ratios before and after using the air purifiers. PM measurement results indicated a significant reduction in $PM_{2.5}$ I/O ratios of (78% - 93%) with air purifier use. The findings from the infection risk assessment highlight the potential benefits associated with the employment of portable air purifiers featuring high-efficiency particulate air (HEPA) filters in reducing PM concentration and increasing the total Air Changes per Hour (ACH) in naturally ventilated patient rooms.

KEYWORDS

Hospital natural ventilation, infection risk, portable air purifying technologies, indoor air quality, airborne particulate matter

1 INTRODUCTION

Following the COVID-19 global pandemic, there has been significant emphasis on maintaining good indoor air quality (IAQ) and minimizing cross-infection risks within hospital buildings (Agarwal et al. 2021). IAQ in hospital buildings is influenced by indoor and outdoor air pollution, human activities, and ventilation systems (Roberts et al. 2022). Various ventilation systems, including mechanical, natural, and hybrid systems, are utilized to provide fresh and clean air for patients, medical teams, and visitors (Jung et al. 2015). While natural ventilation provides fresh air with low energy consumption compared to advanced mechanical ventilation systems (Olsson 2017), its effectiveness in maintaining consistent airflow, supporting air filtration and purification, and regulating air temperature and humidity is often inferior to advanced mechanical ventilation systems (Edwards et al. 2024). Moreover, the quality of the delivered air through natural ventilation is affected by various factors such as outdoor air pollution level, wind speed, indoor space arrangement, exhaust shaft placement, and opening size, etc., (Almhafdy et al. 2024). Contemporary mechanical ventilation and filtration technologies, on the other hand, overcome the issues with natural ventilation, and when properly designed, they effectively and efficiently maintain good IAQ (Wu, Rong, and Luhung 2018). However, while it is easy to implement advanced mechanical and filtration systems in new hospital buildings, challenges persist in installing them in existing and old hospital buildings that rely on traditional natural ventilation (Gilkeson et al. 2013).

In Romania, there are 543 hospitals in the country, 488 of them are in urban areas (Petre et al. 2023). Previous research highlighted the relatively higher risk of all-cause mortality due to polluted air and particularly particulate matter (PM) concentrations from vehicle emissions in urban areas in Romania (Bodor, Szép, and Bodor 2023). This risk is higher in naturally ventilated buildings in which pollution source control is difficult, and outdoor air PM pollutants could penetrate the building through openings, envelope, and ventilation shafts (Chamseddine and El-Fadel 2015). New hospital buildings equipped with advanced mechanical ventilation and filtration systems have been designed to uphold and maintain IAQ by eliminating particles that may carry air pollutants (Nourozi et al. 2023). The construction of new hospitals in the public sector in Romania in the last 30 years is very rare (Mihăilă et al. 2020). In addition, there was an increase in hospital mortality cases from 24.7% in 2014 to 31.4% in 2019 of the total mortality in Romania. 62.5% of these cases were reported in hospitals in urban areas (Vladescu, Ciutan, and Musat 2019). This could be influenced, among other factors, by air pollution (Ab Manan, Aizuddin, and Hod 2018).

In this context, previous studies emphasized the benefits of using air purifiers to reduce PM concentrations and lower the probability of infection risk associated with airborne pathogens in naturally ventilated buildings such as homes, schools, and office buildings (Salmonsmith et al. 2023). However, because of the heightened inherent risks linked to conducting in-situ research in hospital facilities and their unique operational environments (Jiang et al. 2024), there have been a limited number of IAQ studies in hospital buildings especially in Romania (Ackley et al. 2024). As a result, there is a knowledge gap concerning the measured effectiveness of air purifiers in traditionally naturally ventilated hospital buildings in Romania. To address this gap, a one-week measurement campaign was conducted in two distinct patient rooms in a naturally ventilated hospital building in Bucharest – an ICU room and an isolation room. The study aimed to assess IAQ by monitoring $PM_{2.5}$ (particles < 2.5µm in diameter) mass concentrations before and after utilizing portable air purifier units. The effectiveness of the air purifier units was determined by comparing indoor and outdoor (I/O) PM concentration ratios before and after using the air purifiers. Additionally, the study involved measuring various aspects of indoor environmental quality parameters, including CO_2 levels, temperature, and relative humidity. Measured parameters were used for infection risk calculation.

2 MATERIALS/METHODS

2.1 Case study description

The two buildings (main building and the isolation ward) hosting the two investigated rooms are part of a larger complex, housing various medical facilities in addition to teaching and research laboratories, and administration, located in the heart of Bucharest city. The complex was constructed in different stages between 1921 and 1941 and underwent renovation between 1950 and 2000, when the use of concrete construction and brick walls was a common practice. Technical information about the buildings was collected through site visits, walkthrough investigations, and a review of architectural and technical drawings provided by the technical team. The ICU room (25.38 m^2) is in the ICU department on the second floor of a four-story main hospital building. The department consists of one main hallway dividing the ICU rooms on opposite sides (north, and south), the investigated ICU room faces north - see Figure 1.

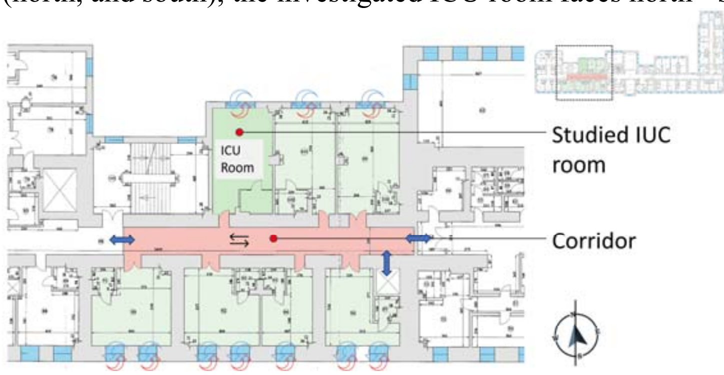


Figure 1: ICU department floor plan - studied room facing north.

The isolation department, located on the second floor of a four-story building, includes an enclosed hallway that divides the isolation patient rooms on both sides of the building, east-west. The isolation patient room under investigation (13.60 m^2) faces east –see Figure 2.

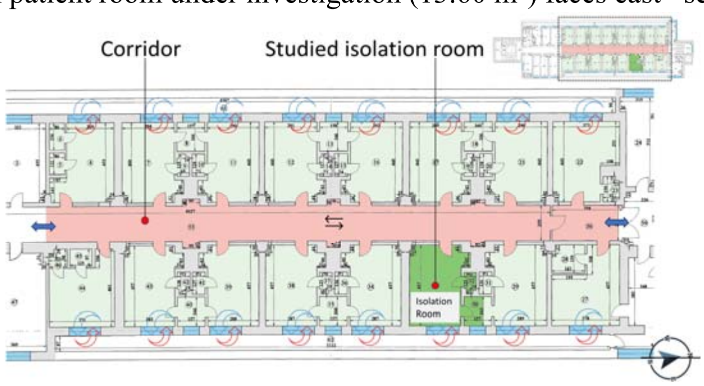


Figure 2: Isolation department floor plan - studied isolation room facing east.

Both buildings were naturally ventilated, with fresh air infiltrating through the openings (i.e., windows and doors), and exhaust air being removed through exhaust shafts. According to the hospital protocol, windows were manually opened every two hours and for fifteen minutes. The investigated rooms were heated by water radiators located under the windows and connected to the central heating system of each building. The designed capacity of the two investigated rooms was for two patients; however, during the monitoring campaign, both rooms housed only one patient. The monitoring campaign lasted for five days during the wintertime (13-17 February 2023). A portable air purifier unit (Air purifier Kuulas+) from ISEC was utilised for each room during the monitoring period - see section 2.4 for more information about air purifier units.

2.2 Research methodology

The study followed six steps (see Figure 3). In Step One, a preliminary visit to the ICU and the isolation rooms was conducted. The objective was to gather information on each room's geometric characteristics, overall layout, and arrangement of medical appliances. Additionally, details regarding the positioning of heating radiators, dimensions of openings, existing furniture, and information about available electrical sockets were collected and documented. This information was used in strategically planning the optimal placement of monitoring instruments and the portable air purifier unit (Mousavi, Khademi, and Taaffe 2020). Moreover, explicit verbal consent was obtained from the participating patient and/or the doctor in charge during this phase.

In Step Two, all instrument sensors were attached to a tripod at varying heights in a specifically designated empty room provided by the staff for this purpose (see section 2.3). The goal was to simplify the deployment of sensors in the investigated rooms efficiently, with minimal disruption to patients and personnel, while reducing the exposure time for researchers entering the room to minimize the potential infection risk. On Step Three, the monitoring instruments and the portable air purifier unit were transferred to the patient rooms and positioned according to the pre-visit observations in Step One. In Step Four, monitoring took place over a span of two days without turning on the portable air purifier units. Step Five involved a subsequent visit by the research team to retrieve measured data from the sensors, reset sensors for the following monitoring period, and turn on the air purifier units. In the final step, Step Six, a concluding visit was conducted to retrieve all data and take sensors away after disinfecting them. On each visit to the investigated rooms, the prescribed disinfection protocol mandated by the hospital was applied to the instrument tools brought to the room as well as the research team members.

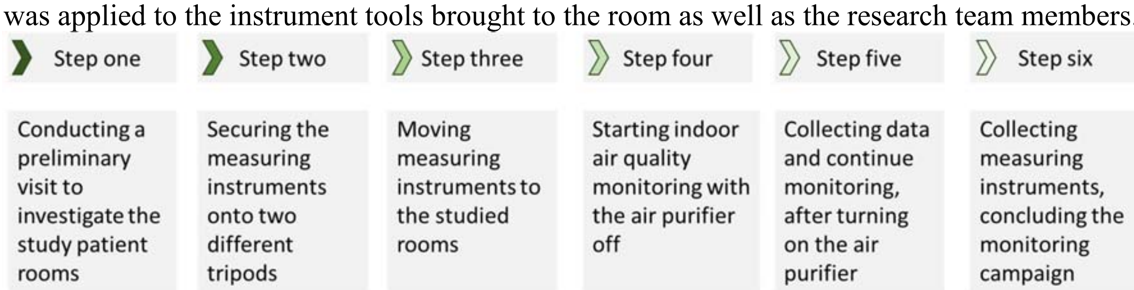


Figure 3: Case study monitoring campaign steps.

2.3 Indoor and outdoor measurements

For the indoor air measurements, sensors were attached to a tripod in each room at a different height (150, 100, and 50 cm). The tripod was positioned near the patient bed, approximately 100 – 150 cm away from the patient's head and 50-100 cm from the adjacent wall (see Figure 4), following the recommendations of Mousavi et al. (2020), and Yun and Licina (2023), for optimal particle exposure capturing. For the $PM_{2.5}$ mass concentration measurement, a miniaturized optical particle counter (OPC-N3 from Alphasense) was attached to the tripod at a height of 150 cm. It operated with a one-second resolution in accordance with the European standard EN 481 and previous studies (Kaur and Kelly 2023). For carbon dioxide (CO_2) concentrations, HOBO data logger MX1102 was attached to the tripod at a height of 150 cm, the MX1102 sensor also measured indoor air temperature (T) and relative humidity (RH%). Two HOBO data loggers MX1101 were attached to the tripod at the height of 100, and 50 cm to measure the air temperature and RH%. The data from all HOBO data loggers were used for building the simulation model and infection risk assessment. The temperature measurement range of the HOBO sensors is from -20 to +70 °C, with an accuracy of ± 0.21 °C. The range for RH% was 1-95 %, with an accuracy of ± 2.0 %, and the range for CO_2 measurement from

0 to 5000 parts per million (ppm), with an accuracy of ± 50 ppm at 25 °C (Onset 2022). The monitoring resolution for all HOBO sensors was set to one-minute based on recommendations from previous in-situ measurement campaigns to capture sudden variations possibly linked to human activities, such as window or door openings (Elsayed et al. 2023). The outdoor instruments including OPC and HOBO MX2301A were positioned on the second-floor balcony on the western side of the isolation department building. Sensors were positioned within a specifically designated outdoor enclosure to protect them from adverse weather conditions (Schery 2001). Patients were located in nearby buildings, but their rooms were at the same height from the ground level as the second floor, where the PM levels were measured.

Prior to the measurement campaign, a comprehensive testing procedure was executed at the Technical Research Centre of Finland (www.vttresearch.com). The testing phase aimed to establish a baseline for sensor performance, enabling robust comparisons throughout the study (Clements and Duvall 2022). The PM sensors' performance was assessed using a reference instrument (Fidas® Frog from Palas), while the HOBO sensors' performance was evaluated against TESTO 605I from TESTO.

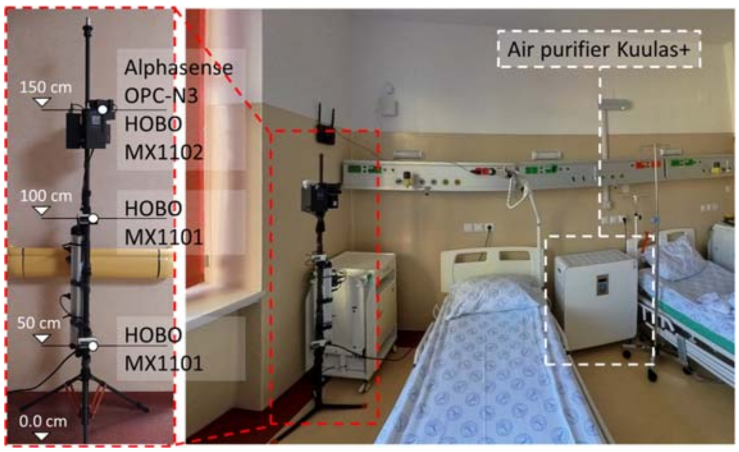


Figure 4: Indoor sensors and air purifier placement-Isolation room.

2.4 Air purifier intervention and infection risk assessment

Portable air purifier (Kuulas+) with a Clean Air Delivery Rate (CADR) of 320m^3/h was installed in the two investigated rooms. The air purifier was placed next to the patient bed and was operating at 60% power, providing CADR of 192m^3/h. Each individual unit is outfitted with three distinct filters. The initial filter, a coarse filter, serves to eliminate sizable dust particles, thereby averting the potential obstruction of the subsequent active carbon filter. The active carbon filter is designed to mitigate odours, as well as reduce the concentration of chemical and gaseous compounds in the air. Lastly, a HEPA filter is incorporated, demonstrating efficacy in the removal of 99.97% of dust and pollen particles with a size exceeding 0.3 µm (ISEC n.d.).

Wells-Riley model was used for the calculation of the probability of infection transmission (Lastovets et al., 2023). This model has been extensively used in studies of indoor air quality and ventilation design, and it is applicable to influenza and COVID-19, using quanta emission rates as an indicator of infection doses that affect infection transmission probabilities (Noakes and Sleigh 2008). The analysis focused on scenarios devoid of facial masks, with emission rates ranging from 2 to 10 quanta per hour per person. These simulations considered a setting with one infectious and one susceptible individual consistently present. The study further explored the effect of incorporating an air purifier (ISEC Kuulas) in naturally ventilated conditions. This comprehensive approach allowed for evaluating different ventilation and air purification strategies in reducing infection risks within hospital settings.

3 RESULTS AND DISCUSSION

3.1 Indoor and outdoor particulate matter

Figure 5 a represents the monitored indoor and outdoor $PM_{2.5}$ concentration as a 30-minute average for the investigated rooms. Throughout the monitoring period (i.e., 5 days), both before and after turning on the air purifier unit, the indoor $PM_{2.5}$ mass concentration in the ICU room remained lower than the outdoor concentration and was within the WHO global air quality guidelines (i.e., a 24-hour average concentration of 15 µg/m^3) (WHO 2021). After turning on the air purifier unit in the ICU, the $PM_{2.5}$ concentration decreased, reaching the lowest value of 1.0 µg/m3. On the other hand, in the isolation room and before turning on the air purifier unit, the $PM_{2.5}$ mass concentration was close to the WHO guidelines, with some spikes in concentration in the afternoon and evening, reaching 30-minute average concentrations of up to 87 µg/m^3. After turning on the air purifier, the indoor $PM_{2.5}$ concentration in the isolation room was below the recommended concentration of 15 µg/m3. However, two short spikes were noticed in concentration on the 16th of February, reaching 30-minute average concentrations of up to 26 µg/m3. The reason behind these spikes was not further investigated; however, it might be caused by the cleaning protocol conducted by staff preparing the room for the next patient, which includes using cleaning products and opening the window. Both factors could have an influence on the indoor $PM_{2.5}$ concentration, as concluded from previous studies (Chamseddine and El-Fadel 2015). On the same day (i.e., the 16th of February), two spikes were observed in the isolation room, which could be caused by window opening or human activities. However, with the absence of the outdoor $PM_{2.5}$ concentration at the time of these spikes, it was not possible to correlate these spikes to the outdoor $PM_{2.5}$ concentration. Nevertheless, the daily check on the instrument revealed that data loss remains a problem within situ monitoring (Ministry for the Environment 2009), and it is one of the limitations of this study.

To further investigate the impact of the utilisation of air purifiers on indoor $PM_{2.5}$ concentrations, the I/O $PM_{2.5}$ ratio was calculated both before and after using the air purifiers. A notable median reduction in the I/O ratio of 78% and 93% was observed in the ICU and isolation room, respectively (see Figure 5 b). Despite using the same air purifier model and applying same power settings, various factors may have contributed to different $PM_{2.5}$ reduction values in the two rooms, such as room orientation, infiltration rate, and volume (Chen et al. 2022). High levels of PM concentration in the air, especially fine particles like $PM_{2.5}$, contains toxic and harmful substances as well as pathogenic microorganisms such as bacteria and viruses, which can induce and aggravate human respiratory diseases, thereby affecting the probability of contracting an airborne infection (Abdin and Mahmoud, 2024).The demonstrated decrease in $PM_{2.5}$ underscores the potential benefits of employing portable air purifiers equipped with HEPA filters for mitigating PM concentration in hospital patient rooms. This approach has the potential to reduce the risk of airborne pathogen infections, as further detailed in section 3.3.

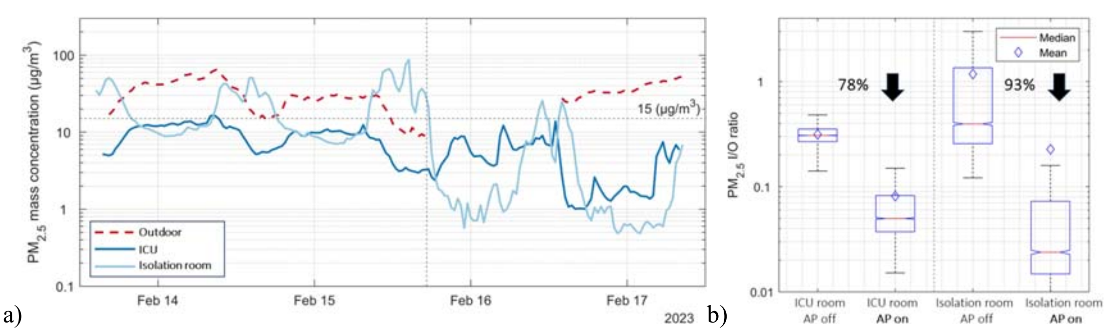


Figure 5: a) $PM_{2.5}$ mass concentration time series. The vertical dotted line represents the time when air purifiers were turned on and the horizontal dotted line marks the WHO guideline value of 15 µg/m^3 (24-hour average), b) $PM_{2.5}$ mass concentration indoor to outdoor ratios - ICU, and isolation room.

3.2 Indoor air temperature and CO_2 concentration

Both the ICU and isolation room featured traditional natural ventilation. As previously mentioned, the windows in each room were manually opened by hospital staff for fifteen minutes every two hours. In the ICU room (78.7m^3), there was a variation in indoor air temperature at different heights, indicating heat stratification, with an average difference of 1.5 $^\circ$C. The average recorded indoor air temperature in the ICU room was 23.4°C, while the maximum recorded outdoor air temperature was 9 $^\circ$C, and the minimum recorded outdoor air temperature -3 $^\circ$C. Conversely, in the isolation room (42m^3), the indoor air temperature exhibited greater stability with less heat stratification phenomenon with an average recorded indoor air temperature of 22 $^\circ$C (see Figure 6). However, both rooms were equipped with a wall-mounted radiator for heating, technical information about the temperature set point and heating schedule was not available.

Regarding CO_2 concentration, for 64% and 67% of the monitoring time for the isolation room and the ICU room respectively, the CO_2 levels remained below the recommended threshold value of 800 ppm by the World Health Organization (WHO) and the REHVA guidelines (REHVA 2021; WHO 2021). However, there were spikes in the CO_2 concentration in both rooms, the spikes lasted for longer periods in the isolation room than in the ICU room (see Figure 6). Several factors could have contributed to the elevated CO_2 levels in the isolation room, including orientation, room volume, and human activities. The lowest CO_2 concentrations in both rooms occurred during the day (afternoon and evening), while elevated concentrations were observed from midnight until morning. This could be attributed to less frequent window opening during the night. However, it was not possible to monitor window opening during the campaign, hindering confirmation of this potential causation.

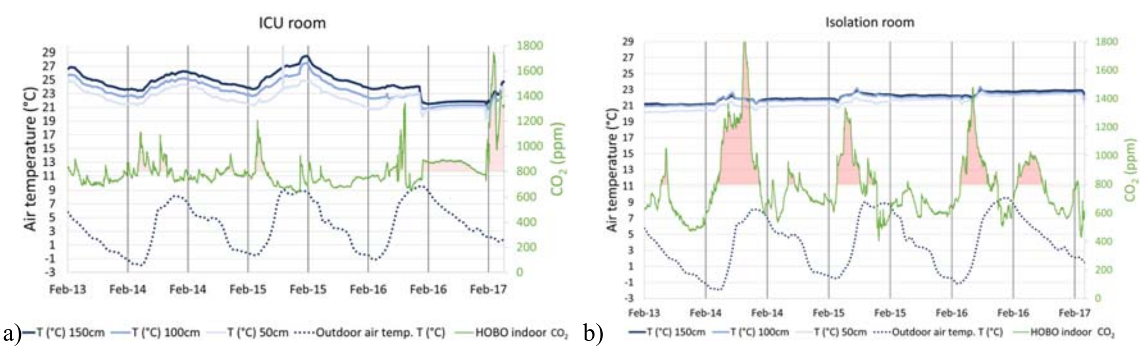
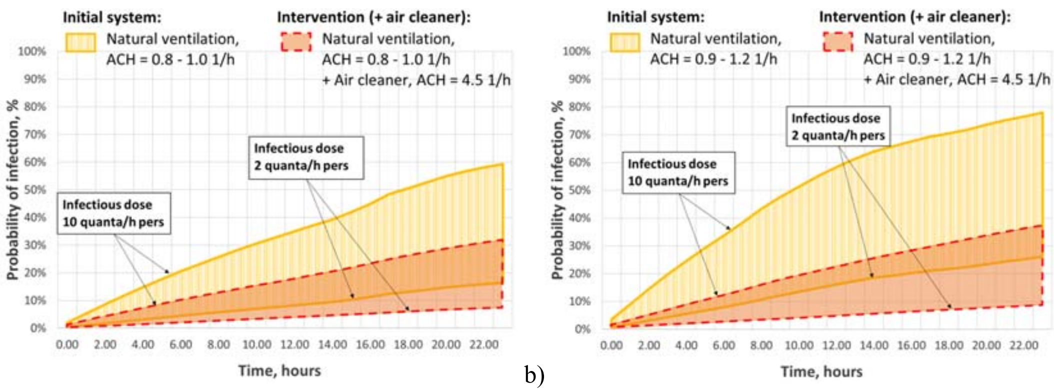


Figure 6: Indoor & outdoor air temperature and indoor CO_2 concentration; a) ICU room, b) Isolation room.

3.3 Air purifier intervention and infection risk assessment

Figure 7 shows how infection rates increase over time in both ICU and Isolation room using natural ventilation, air purifiers, and different infectious dose rates. For both scenarios, the ICU room (Figure 7 a) and the isolation room (Figure 7 b), the probability of infection is calculated from zero and increases rapidly within the first few hours, showing the rapid spread of infection in an enclosed space. Predictably, with natural ventilation alone the infection probability is the highest. The slope of the increase is steeper in the Isolation room, due to it having approximately half the volume compared to the ICU room, which allows for faster accumulation of infectious aerosols. In the studied cases, air purifiers almost halves infection estimated infection probability and can be efficient even in scenarios with high quanta emission rates.



a) b)

Figure 7: Infection risk probability within a day of exposure with and without air cleaners in a) ICU room, b) Isolation room.

4 CONCLUSIONS

The study investigated some aspects of indoor environmental quality (IEQ) and the potential benefits of using portable air purifiers in a naturally ventilated hospital building. By measuring Particulate Matter ($PM_{2.5}$) concentration before and after the use of the portable air purifier, a reduction in $PM_{2.5}$ I/O ratios of 78% to 93% were observed in the two investigated hospital rooms, an Intensive Care Unit (ICU) room, and an isolation patient room, respectively. Regarding indoor air temperature, the average recorded indoor air temperature in the ICU room was 23.4°C, and 22°C in the isolation room, while the average outdoor air temperature was -3°C. The temperature was more stable in the isolation room (42m³), with less heat stratification phenomenon. However, in the ICU room (78.7m³), there was a variation in indoor air temperature at different heights, with an average difference of 1.5°C every 50cm between (50cm-150cm). The CO_2 concentrations in the isolation room and the ICU room remained below the World Health Organization (WHO) recommended value of 800 parts per million (ppm) for 64% and 67% of the monitoring time (five days), respectively. Different room volumes could have contributed to the lower CO_2 concentrations in the ICU room compared to the isolation room, among other possible factors such as occupant behaviour and window opening. The infection risk assessment revels that using portable air purifiers with HEPA filters in hospitals can significantly reduce the risk of airborne infections. The air purifiers can complement natural ventilation, lower the immediate risk of infection, and enhance indoor air quality, creating safer environments for patients and healthcare workers.

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