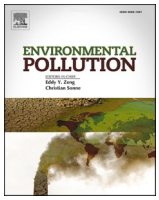
Environmental Pollution 375 (2025) 126310

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol



Air quality in a bus depot and a way of improving it: effect of using air purifiers☆

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ARTICLE INFO

Keywords:
$PM_{2.5}$
Particle number (PN)
Black carbon (BC)
Bus stations
Indoor air quality

ABSTRACT

This study assessed airborne particulate matter and black carbon concentrations and their distribution inside a restricted bus depot over two campaigns. Particles with a diameter <2.5 μm were evenly distributed across the depot, influenced by limited bus activity and the depot's spacious layout with three entrances and one exit, facilitating particle dispersion. Their average baseline concentration was 25.2 μg m^{-3}, 4.6 times higher than outdoor levels, primarily driven by bus emissions and maintenance activities. Number concentrations of particles smaller than 0.3 μm (0.01–0.3 μm) averaged 1.3 × 10^3 particles cm^{-3}, while larger particles (0.3–10 μm) averaged 33 × 10^0 particles cm^{-3}. Black carbon averaged 1.3 μg m^{-3}. Concentration peaks occurred from 23:00–9:00 and 16:00–18:00 due to bus activities, maintenance, and soil resuspension.

The impact of air purifiers on air quality was also investigated focusing on their location, number, and air volume flow for optimal results. APs operating at half air volume flow and placed within 6 m of the measurement equipment achieved reductions of up to 45.2 % for $PM_{2.5}$ and 73.6 % for particles sized 0.3–10 μm. However, air purifiers were much less effective for particles <0.3 μm. Crossed airflows and higher air volume flow decreased effectiveness due to turbulence and particle resuspension. This study underscores the need for optimized air purifiers placement, air volume flow settings, and operational strategies to mitigate air pollution in (semi-)closed transport environments like bus depots, improving air quality and health for passengers and workers.

1. Introduction

Numerous studies have been published about the adverse effects of inhalable traffic-related particulate matter (PM) on human respiratory and cardiovascular health (Anderson et al., 2012; De Marco et al., 2018; Kim et al., 2015; Pope and Dockery, 2006; Riediker et al., 2004; Sicard et al., 2019). Other impacts include its association with type 2 diabetes (GBD 2019 Diabetes and Air Pollution Collaborators, 2022; Liu et al., 2021; Rajagopalan and Brook, 2012), increased blood pressure (Liang et al., 2014; Wu et al., 2024; Zhang et al., 2024), neurological disorders (Fu et al., 2019; Lee et al., 2023; O'Piela et al., 2022; Qin et al., 2025; Shi et al., 2020; Yang et al., 2022), DNA damage (Bräuner et al., 2007; Quezada-Maldonado et al., 2021; Risom et al., 2005; Zhao et al., 2022) and premature mortality in general (Cakaj et al., 2023; Samet et al., 2000; Khaniabadi and Sicard, 2021; Rashidi et al., 2023; Yin et al., 2017). The complexity of the effects of inhalable PM on human health derives from the many factors influencing particle bioreactivity (size, concentration, composition, morphology, etc). For instance, the smaller the particle, the deeper the penetration to the body and the higher its potential toxicity (Stone et al., 2017; Harrison and Yin, 2000; Valavanidis et al., 2008). Given the latter realisation, over the last two decades much attention has been given to particles with an aerodynamic

☆ This paper has been recommended for acceptance by Prof. Pavlos Kassomenos.
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https://doi.org/10.1016/j.envpol.2025.126310
Received 13 February 2025; Received in revised form 15 April 2025; Accepted 24 April 2025
Available online 25 April 2025

diameter <2.5 μm ($PM_{2.5}$), black carbon (BC) and ultrafine particles (UFP, particles with a diameter <0.1 μm) emitted in urban transport microenvironments (TMEs) such as buses, metro trains, and cars (Karanasiou et al., 2014; Kaur et al., 2007; Kumar et al., 2018; Marinello et al., 2023). In general, such studies have revealed that people inhale higher concentrations of $PM_{2.5}$ and UFP during commuting than non-commuting hours (Both et al., 2013), with bus passengers usually being exposed to the highest concentrations (Knibbs and de Dear, 2010; Moreno et al., 2015, 2020; Suárez et al., 2014).

Despite significant attention to PM and BC concentrations in urban TMEs, there are no studies specifically focusing on bus depots and only a few have investigated bus stations (Table S1). Bus depots represent a different environment where buses are parked, engines are cold started, and prolonged idling may occur in addition to maintenance activities where engines also may be turned on. Additionally, workers, staff and passengers often spend a significant amount of time at bus depots and stations, either working or in the case of stations waiting there, raising health concerns. Existing research has primarily focused on bus stations, revealing higher particles' concentrations than surrounding outdoor environments due to activities like idling, accelerating, and braking (Jayaratne et al., 2009; Kinsey et al., 2007). Previous studies report $PM_{2.5}$ average concentrations between 19 and 55 μg m^{-3} (Table S1), although there are huge variations ranging from 15.0 μg m^{-3} (Nogueira et al., 2019) to 222.9 μg m^{-3} (Salama et al., 2017). Fewer studies have reported average BC concentrations, and these once again show considerable variation, from, for example, 5.3 μg m^{-3} (Nogueira et al., 2019) and 24.9 μg m^{-3} (da Silva Junior et al., 2019) to exceptional levels of 63.8 μg m^{-3} (Morales Betancourt et al., 2019) (Table S2). Even fewer studies report average particle number concentrations (PN), with observed ranges $PN_{0.01\text{-}1}$ at 5.0–11.3 × 10^4 particles cm^{-3} (Cheng et al., 2011, 2012), and for $PN_{0.007\text{-}3}$ at 4.5–4.8 × 10^4 particles cm^{-3} (Wang et al., 2011) (Table S3). These average concentrations are considerably higher than those typically found in urban environments which are in the range of a few thousand to approximately 1.0 × 10^4 particles cm^{-3} (Birmili et al., 2016; Morawska et al., 2008; Sun et al., 2019). However, bus depots differ in operational dynamics and require dedicated research.

Based on the above findings, several studies have highlighted the importance of implementing effective ventilation and/or air purifying systems to improve air quality inside (semi-)closed environments (Brehmer et al., 2019; Cheek et al., 2021; Kelly and Fussell, 2019; Zhan et al., 2018). In this context, we deployed air purifiers (APs) as a localized mitigation strategy to enhance air quality in a specific area within the bus depot, rather than as a replacement for full-scale ventilation systems. This study aims to assess the levels, spatial distribution, and temporal variation of $PM_{2.5}$, PN and BC in a major publicly restricted bus depot. Moreover, it evaluates the effectiveness of APs in reducing particulate matter under varying configurations. This work contributes to understanding air quality in (semi-)closed environments, offering insights into practical interventions to enhance occupational health.

2. Methodology

2.1. Study area

The study was carried out at the public-restricted bus depot of AUVASA, located in Valladolid, north-western Spain (an area of approximately 200 km^2, elevation of approximately 700 m and a population of around 302,000 people, https://populationstat.com/spain/valladolid, Fig. S1). Based on the Köppen classification, the climate of Valladolid can be classified as both "hot-summer Mediterranean" and "cold Semi-arid". AUVASA is an urban transport company, operating an extensive transport network covering 545 km and 51 lines that offers 98 % coverage to city's population.

AUVASA bus depot is around 10,000 m^2 in area and in addition to the parking area includes a workshop, washing rooms, a paint shop, and an open-air parking site (Fig. S2). During the air quality measurements, a total of 154 buses were accommodated there consisting of 28 diesel, 46 liquid petroleum gases (LPG), 51 compressed natural gas (CNG), 18 hybrid and 11 electric buses on a daily basis (http://www.auvasa.es/auv_opendata.asp). A total 450 staff members spend at least several hours per working day at the depot with potential exposure to emissions from engine exhaust, brake wear, resuspended dust and emissions from other occupational activities at the depot. The actual number of buses inside AUVASA bus depot depends on the hour and day of the week. Generally, more buses are present there on the weekends than weekdays, with the lowest number of buses at the bus depot being between 07:00 and 14:00, whereas the highest number of buses occurred between 23:00 and 07:00. It is worth noting, with the exception of some buses which were under maintenance, all the buses entered the depot for parking and exited for starting their routes. This means engines were not idling for extensive periods of time as there was no need to pick up passengers. At AUVASA bus depot, regular vehicle maintenance tasks associated with oil changing, air filter cleaning, tire and brake servicing, as well as sheet metal work involving sanding and use of fillers, primers and paints were routinely performed.

2.2. Measurement campaigns

Two air quality measurement campaigns took place in the AUVASA bus depot. The first campaign took place from May 17, 2023 to June 16, 2023, while the second from April 29, 2024 to June 01, 2024. For statistical reasons and to simplify the results, the data from both campaigns were combined for analysis.

In both campaigns, the same protocol was followed. As such, $PM_{2.5}$, PN and BC concentrations were measured before and during the operation of the APs. During the 1st week of each campaign, only continuous baseline measurements (BL, i.e. without using APs) were obtained to establish the usual levels and temporal distribution of the measurement pollutants in the bus depot. After this baseline period, measurements were obtained with the APs operating under different conditions (setups). However, because four main variables related to the APs were tested, BL measurements were made between the previous and following setup to assure the measurements of the following setup were not influenced by the previous one. The four main variables investigated were 1) the air volume flow (AVF), 2) the number of APs, 3) the location of the APs and 4) the distance from an operating AP.

A total of 10 APs were used in the measurements, however mostly four, seven or ten were operating simultaneously, either at the half or maximum level of AVF (1250 or 2500 m^3 h^{-1}). Regarding the APs locations, two configurations were used (Fig. S3). Location "a" is represented by seven APs surrounding the measuring equipment at a distance up to ~5 m, with three additional APs located ~17 m farther away. Two buses could park in between these three APs and the measuring equipment. Regarding location "b" two APs were moved ~12 m farther away than location "a", allowing enough space for buses to pass between these APs and the measuring equipment (APs 6 and 7 in Fig. S3). To investigate how the AP airflow reaches and dilutes particles, the measuring equipment was repositioned 2 m further from the AP air outlet every 15 min while the AP was operating at the maximum AVF (Fig. S4). This experiment was repeated three times (weekdays and same period of time) and the average concentrations of the obtained data were used for the analysis.

To evaluate the impact of APs operation on $PM_{2.5}$, PN and BC levels in a defined space inside the bus depot, and determine how the modified variables (i.e., APs location, number, and AVF) influenced pollutant reductions, data from corresponding time periods during BL and setup conditions for each campaign were compared (Table S4). To examine the impact of a single variable at a time, all other variables were held constant. For example, to isolate the effect of AVF, factors like the location and number of APs were kept unchanged.

2.3. Monitoring equipment

2.3.1. Particles mass concentrations

For $PM_{2.5}$ gravimetric sampling, an automatic sequential high-volume sampler (HVS, Model CAV-A/MSb, MCV) equipped with an inlet (PM1025/UNE model, built according to the European Norm: EN 14907) was used. The sampler was equipped with quartz microfiber filters and programmed to sample $PM_{2.5}$ over 24 h (from 00:00 to 00:00) at a sampling flow rate of 30 m^3 h^{-1}. Filters were weighed before and after exposure using a microbalance (Model XP105DR, Mettler Toledo, sensitivity: ±10 μg) and the $PM_{2.5}$ concentration was calculated considering the volume of sampled air. Prior to weighing, the filters were conditioned in a room with controlled temperature (T ≈ 20 °C), and relative humidity (RH ≈ 50 %) for 48 h.

The mass concentrations of $PM_{2.5}$ were also monitored with a real-time light-scattering laser photometer DustTrak DRX (Model 8533, TSI) operating with a time resolution of 300 s (s) and a flow rate of 1 L min^{-1} (5 s time resolution was used for the distance experiment). To ensure proper particle aerodynamic size selection, flow calibration was performed before using DustTrak.

For understanding the spatial distribution of $PM_{2.5}$, 17 Sensirion sensors (SEN54) were distributed at the depot. These sensors, operated continuously with a time resolution of 300 s and a sampling interval of 1 ± 0.03 s. The obtained $PM_{2.5}$ concentrations with DustTrak DRX were corrected against gravimetric $PM_{2.5}$ data obtained with the above-mentioned HVS. This was not done for SEN54, because most of them were installed far away from the HVS.

For comparison purposes, ambient $PM_{2.5}$ data were obtained from the closest official air quality monitoring station (Vega Sicilia, ~0.9 km WNW of the AUVASA building, Fig. S1).

2.3.2. Particle number concentrations

The total particle number concentration (PN) in the size range 0.01–0.3 μm (modal value) was monitored with a DISCmini (Testo), operating with a time resolution of 60 s and a flow rate of 1 L min^{-1} (1 s time resolution was used for the distance experiment). For the data analysis, 300 s average concentrations were used.

Particle number concentrations in the size range 0.3–10 μm were obtained using an Optical Particle Sizer (OPS, TSI Model 3330, TSI Inc., Shoreview, MN, United States) measuring optical particle size distributions across 16 channels from 0.3 to 10 μm, with a 300 s time resolution and a flow rate of 1 L min^{-1} (5 s time resolution was used for the distance experiment). Prior to operation, flow calibration was conducted to ensure accurate size selection and optimal instrument performance.

2.3.3. Black carbon concentrations

Black carbon concentrations were monitored through the operation of a microAeth (Model AE51, AethLabs) aethalometer at a standard flow rate of 0.1 L min^{-1} and a sampling interval of 300 s (10 s time resolution was used for the distance experiment). To ensure measurement accuracy, the filter media were replaced at least twice per week.

2.4. Air purifiers

Air purifiers were designed and manufactured by MANN + HUMMEL GmbH (Ludwigsburg, Germany). These APs are stationary air purification systems, with their filters specifically designed for (semi)-closed environments such as bus, tram, and subway depots/stations, to significantly decrease the concentrations of particles. Each AP weights ~150 kg and its dimensions (height x width x depth) are 1004 mm × 1051 mm x 523 mm (https://shop.mann-hummel.com/media/catalog/Manual-OurAir-SQ2500.pdf). Its maximum operating power consumption is 600 W and it includes 10 adjustable levels of AVF (from 0 to 2500 m^3 h^{-1}). It is worth noting the used APs have two installed UVC light lamps to neutralize pathogens such as bacteria and viruses.

As mentioned before, these APs were deployed to assess their impact on the studied pollutants under different setups within a specific area, rather than to improve overall air quality at AUVASA bus depot. This is the reason the measurement equipment, excluding Sensirion sensors, was installed at fixed location(s) (Figs. S3 and S5). Before the beginning of the campaign, completely new high-efficiency particulate air (HEPA) filters were installed. However, as the HEPA filters were rated with a lifetime of ~ 2 years, the same filters were used for both campaigns. HEPA filters are highly efficient at removing ultrafine particles under standardized conditions, as documented in the literature (e.g., Bennett et al., 2022; Carmona et al., 2022; Dubey et al., 2021).

2.5. Installation point of the equipment

All the measurement equipment and APs was placed ~30 m away from the corner opposite the AUVASA bus depot entrances and exit (Fig. S2). This location was chosen for three main reasons. Firstly, the installation point could be used without obstructing the workers (e.g. not at a location which could limit the movement of buses). Secondly, all the buses entering from the entrance near the south wall (Fig. S2) pass by this point either to park or exit the depot. Thirdly, this point was far away from the entrances and the exit, thus it was not heavily affected by the indoor-outdoor air exchange effects. The online instruments were housed in a protective box (i.e. DustTrak DRX, OPS, microAeth AE51 and DISCmini), next to the HVS and were surrounded by the APs (Fig. S5).

2.6. Statistical methods

To assess the statistical significance of the differences in all comparisons (i.e., between the baseline and setups, as well as among individual setups), non-parametric Mann-Whitney-Wilcoxon tests were performed using the R programming language (www.R-project.org).

3. Results and discussion

3.1. Average baseline concentrations and comparison with other studies

Table S1 compares the average BL weekly $PM_{2.5}$ concentrations in the bus depot (both campaigns combined) with $PM_{2.5}$ concentrations measured in bus stations worldwide. To our knowledge, this is the first study on PM concentrations in a bus depot. Therefore, $PM_{2.5}$ levels in the AUVASA bus depot are compared to those in bus stations worldwide, as both are similar environments. The average weekly $PM_{2.5}$ BL concentration was 25.2 μg m^{-3}, slightly exceeding the EU outdoor air quality limit of 25 μg m^{-3} (Table S4). This indoor $PM_{2.5}$ concentration was approximately 4.6 times higher than the average outdoor $PM_{2.5}$ concentration during the same period (25.2 vs. 5.5 μg m^{-3}; Table S5). The indoor-outdoor $PM_{2.5}$ showed a weak or negligible correlation (i.e. $R1^2 = 0.21$ and $R2^2 = 0.01$) (Fig. S6), indicating that indoor sources, such as bus exhaust, brake dust, maintenance activities, and resuspension, are dominant contributors to the elevated concentrations inside the depot.

The concentrations of $PM_{2.5}$ in bus stations typically range between 15.0 and 222.9 μg m^{-3}, influenced by factors such as bus types and age (Morales Betancourt et al., 2019; Zuurbier et al., 2010), station design and orientation (Moore et al., 2012), meteorological conditions (Galindo et al., 2011; Nhu et al., 2018; Wang et al., 2011), and surrounding land use (Hess et al., 2010). Activities which depend on the time/working shifts (Cheng et al., 2012) such as refueling, maintenance, and bus idling also contribute significantly to particle levels (Jayaratne et al., 2009; Salama et al., 2017).

The observed average $PM_{2.5}$ concentration at the AUVASA bus depot (25.2 μg m^{-3}) is similar to concentrations reported at stations in Brisbane (Australia) (Wang et al., 2011), Chiayi City (Taiwan) (Lee et al., 2017), and Londrina (Brazil) (da Silva Junior et al., 2019), which range between 18 and 33.8 μg m^{-3} by excepting an average value of 50.7 μg m^{-3} observed in the bus station in Chiayi City. However, the majority of

studies report higher $PM_{2.5}$ concentrations, with some exceeding the 100 μg m^{-3} (Table S1) due to diesel bus idling, refueling, and maintenance activities (Morales Betancourt et al., 2019; Salama et al., 2017; Mkoma et al., 2014).

Fewer studies report BC average concentrations in bus stations with most values vary from 2.2 to 12.4 μg m^{-3} (Nogueira et al., 2020) (Table S2). There are cases which report much higher concentrations, such as the study of da Silva Junior et al. (2019) which mentions average BC concentrations up to 24.9 μg m^{-3}. Another study found the extremely high BC average concentration of 63.8 μg m^{-3} (Morales Betancourt et al., 2019). The BC concentration in AUVASA was much lower, at 1.3 μg m^{-3}, which could reflect the lower diesel bus activity at the depot compared to stations with higher BC emissions (Table S2).

The average $PN_{0.01\text{-}0.3}$ BL concentration at the bus depot was 1.3 × 10^3 particles cm^{-3}. Although direct comparisons with PN concentrations measured at bus stations are not possible due to differences in size ranges, the average $PN_{0.01\text{-}1}$ concentrations at bus stations range between 5.0 and 11.3 × 10^4 particles cm^{-3} (Cheng et al., 2011, 2012) while $PN_{0.007\text{-}3}$ concentrations vary between 4.5 and 4.8 × 10^4 particles cm^{-3} (Wang et al., 2011) (Table S3). These concentrations are an order of magnitude higher than those observed in AUVASA. The average BL concentration of $PN_{0.3\text{-}10}$ in the bus depot was 33 × 10^0 particles cm^{-3} (Table S3). To our knowledge, no studies have specifically assessed PN concentrations in this size range in bus stations. However, higher concentrations in bus stations are expected due to the more intense activities related to buses as there are passengers (i.e. more braking, idling and accelerating of buses, Jayaratne et al., 2009).

AUVASA is a public restricted bus depot, thus buses do not need to pass through it to pick-up commuters and this plays a key role on PM concentrations and its diurnal distribution as PM is strongly correlated with the emissions from buses in such environments. In addition, AUVASA bus depot is not located in an area where a great number of vehicles pass (with the exception of AUVASA buses), whereas bus stations are usually located in environments highly affected by transportation. This is also important, as there is not an enormous influence on the air quality in the bus depot from other vehicles and industries nor PM accumulation due to them.

3.2. Daily distribution

Average hourly concentrations of $PM_{2.5}$, BC, and PN (particles with a diameter between 0.01 and 10 μm) for the whole BL week in AUVASA bus depot follow a similar pattern (Fig. 1) with higher concentrations occurring during specific time periods. Two prominent peaks are observed: one at 01:00 and another between 03:00 and 05:00, which result from vehicle maintenance and bus movements. Some buses return after their shift ends (at 01:00), while others prepare for early shifts to transport workers from the industrial estate, idling to warm their engines and departing around 06:00. Maintenance activities include oil changes, cleaning, brake servicing, and sheet metal work involving sanding, fillers, primers, and paints. Another peak is observed between 06:00 and 09:00 coinciding with most buses starting their daily commuting activities, leaving the depot at around 07:00. The maintenance and bus movement activities lead to generally higher particle concentrations during morning time than afternoon (Fig. 1).

One smaller peak can be seen between 15:00 and 18:00 due to limited buses movements and servicing/maintenance of their wheels. Around 16:00, approximately 20 drivers return to the depot to "book" their parking lot. When this is done, they start idling their engines 5–10 min to warm up, they exit the depot and they either go to the bus wash or to the filling station (if not to both of them) and they return to the already "booked" parking lot where they park until the next shift. This

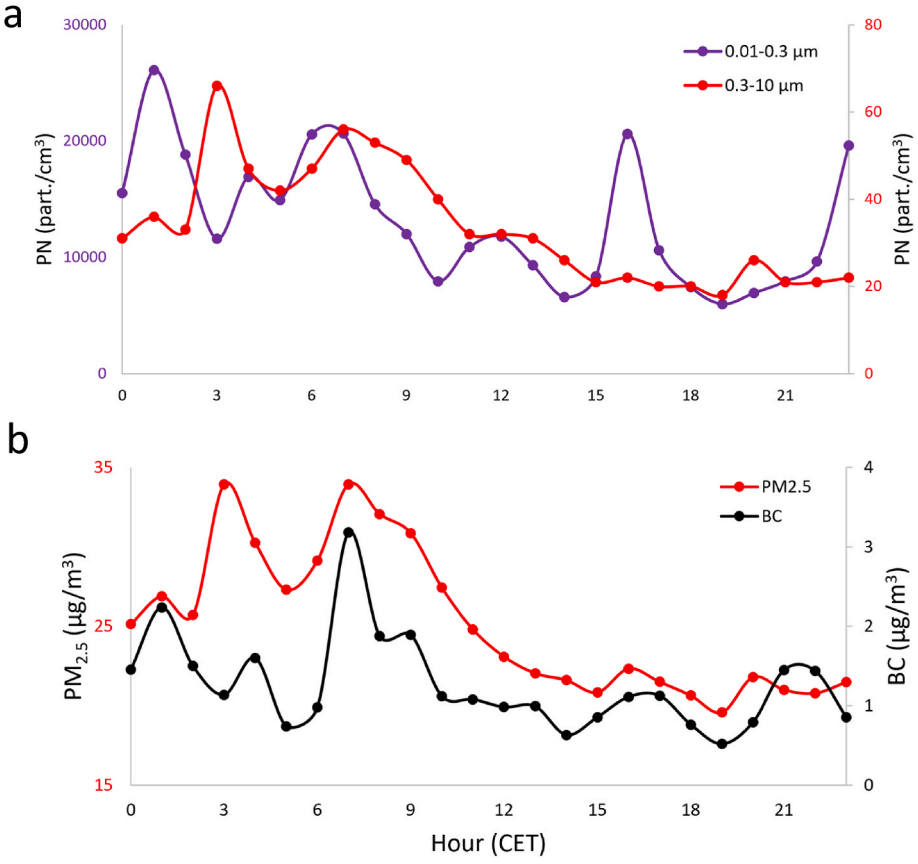

Fig. 1. Average hourly number and mass concentrations of a) particles with a diameter between 0.01 and 10 μm and b) PM2. 5 and BC for the whole BL week in AUVASA bus depot (both campaigns combined).

process of moving buses, excluding the maintenance of the wheels, also occurs between 19:00 and 21:00. Consequently, the elevated peak of $PN_{0.01\text{-}0.3}$ compared to other particles between 15:00 and 18:00 is likely due to wheel maintenance.

Lastly, the increased levels of particles at 23:00 are also a result of bus movement, as the buses complete their last daily shift and return at the depot between 22:30 p.m. and 01:00 to park, with most arriving between 22:45 and 23:45.

Higher PM levels from bus movements align with findings from other studies, which report peak particle concentrations during periods of high bus activity, such as morning and afternoon rush hours (Cheng et al., 2012; Wang et al., 2011).

Overall, it is evident that PM levels at the bus depot are primarily influenced by maintenance activities, moving buses and resuspension which take place between specific ranges of time with generally higher levels occurring between 23:00 and 09:00 than afternoon.

The described daily pattern is consistent across different days. While some day-to-day fluctuations occurred due to depot-specific operational variations, the overall pattern remained stable.

3.3. Spatial distribution of $PM_{2.5}$

The spatial distribution of median $PM_{2.5}$ BL concentrations for both campaigns combined in the bus depot can be seen in Fig. S2. The $PM_{2.5}$ concentrations do not vary greatly thus with the exception of data from one sensor which was located very close to one of the entrances and recorded a value of 2 μg m^{-3}, $PM_{2.5}$ values ranged between 4 and 5.6 μg m^{-3}. This $PM_{2.5}$ distribution within the bus depot, was expected for two main reasons. Firstly, the bus depot is large (13,200 m^2) with three entrances and one exit, and consequently particles are easily dispersed by advection, diffusion and deposition. Secondly, it is a public restricted bus depot with limited bus operations occurring at specific times. Bus stations, typically experience more intense and localized activities, such as braking, idling, and accelerating, concentrated in specific areas like platforms or parking zones instead of waiting areas.

Some studies assessed the PM spatial distribution in bus stations and generally observed higher PM levels in areas with frequent and intense operation of buses. One of these studies found 2 times higher $PM_{2.5}$ concentrations on the bus platform compared to the waiting room surrounded by the platform of the same floor, supporting this was the result of the emissions from diesel buses (Cheng et al., 2012). Another study which among others compared $PM_{2.5}$ concentrations in different areas of several bus stations, reported much higher $PM_{2.5}$ concentrations in the parking and garage than the waiting room (Salama et al., 2017). The authors believe the idling diesel buses and their refueling played a key role to these higher concentrations.

In addition to the aforementioned reasons about the homogeneous $PM_{2.5}$ distribution, the median $PM_{2.5}$ values were reported in Fig. S2, which means that even if the measuring equipment was installed relatively close to the workshop (i.e.~ 10 m away from its door), it is unlikely the $PM_{2.5}$ values were influenced by maintenance or even from the movement of buses which take place between specific time periods.

These findings indicate that the location of the measuring equipment for this study was representative of the overall $PM_{2.5}$ distribution in the depot, as no much higher or lower values were recorded at the measurement site compared to other areas.

3.4. Air purifiers

3.4.1. Air volume flow

Fig. 2 demonstrates the impact of AVF of the APs on $PM_{2.5}$, PN, and BC concentrations. The figure was generated using data collected over the same period for each campaign, which were then combined (Table S4). To isolate the effect of AVF, other variables such as the location and number of APs were kept constant. As shown in Fig. 2, ten APs operated at either half or maximum AVF, represented by the red and blue boxplots respectively. The grey boxplots on the left indicate the weekly BL levels for both campaigns combined.

A reduction on $PM_{2.5}$ concentrations and particles with diameters between 0.3 and 10 μm ($PN_{0.3\text{-}10}$) was observed during the APs operation. However, for smaller particles, (0.01–0.3 μm, $PN_{0.01\text{-}0.3}$, Fig. 2d), the APs had a less pronounced impact. This can be attributed to different deposition mechanisms governing particle retention in both air purifiers and the respiratory system. Particles <100 nm deposit predominantly

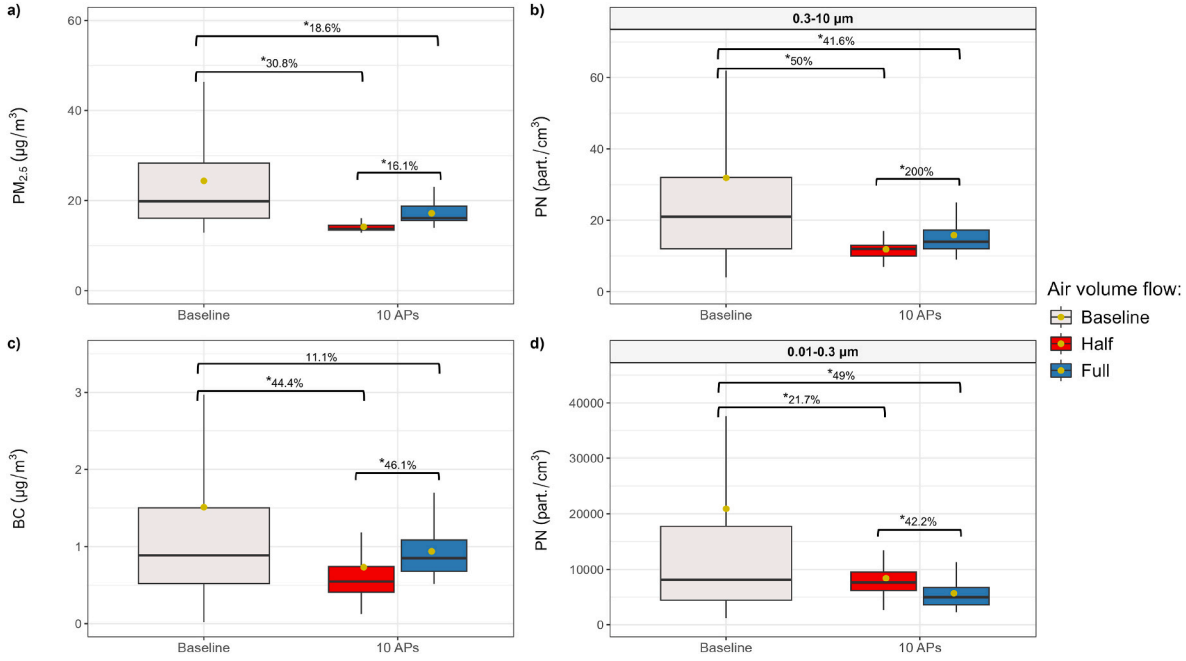

Fig. 2. Effect of air purifiers' (APs) air volume flow (AVF) on pollutants' concentrations. The percentages above boxplots represent the percentage differences between median concentrations. The asterisks indicate statistically significant differences, while the yellow dots represent average concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

via diffusion, making them difficult to remove via mechanical filtration and potentially more hazardous. Particles ~0.3 μm are often in the filtration efficiency limit for both respiratory systems and APs, as they are too small for impaction/capture but too large for diffusion-based deposition (Malloy et al., 2021). Particles >0.3 μm tend to deposit via impaction and sedimentation, making them easier to capture in both lung tissues and air filters (Cheng, 2014).

It should also be stressed out that the two installed UVC lamps, which are highly effective at neutralizing pathogens (Palma et al., 2024; Pereira et al., 2023), may have also contributed to the formation of UFP. Graeffe et al. (2023) observed that when UVC lights were turned on, high concentrations of small particles formed, with 2.5 nm particle formation rates reaching 250 particles $cm^{-3}s^{-1}$ (median). The total particle concentrations from <1000 particles cm^{-3} were increased to 4.5×10^4–1.6×10^5 particles cm^{-3}, depending on irradiation time and ozone (O_3) levels. Once the lamps were turned off, particle concentrations rapidly decayed. Notably, particle mass concentrations remained unchanged, as these newly formed particles did not grow beyond 30 nm. Similarly, Sørensen et al. (2024) observed UFP production through increased O_3 levels. Park and Rim (2024) further observed that independently on the lamp position, the concentrations of O_3 in the breathing zone increase by 4–6 ppb after an hour of operation while O_3 levels near the lamp itself exceeded 25 ppb. O_3 production from UVC lamps should not be overlooked, as it can trigger oxidation reactions with VOCs, leading to secondary aerosol formation and increased UFP concentrations (Luo et al., 2021; Wu et al., 2017). This effect is more pronounced at full speed, where higher air exchange increases the rate of photochemical reactions and oxidation processes.

In relation to the reduced $PM_{2.5}$ and $PN_{0.3\text{-}10}$ concentrations, interestingly, higher reduction was observed when the APs functioned at half AVF compared to maximum AVF. These differences were statistically significant in all comparisons (i.e., $p \leq 0.005$, BL vs. setups and setup vs. setup) (Table 1). The less effective reduction in particle concentrations observed when operating the APs on full AVF was probably a result of particle resuspension. Previous studies, have demonstrated that elevated airflow speeds can increase particle resuspension by 2.4–2.9 times (Kim et al., 2021), particularly for larger particles (1–20 μm) (Mukai et al., 2009). In the AUVASA depot, this effect appears to outweigh the benefits of increased airflow at maximum AVF, resulting in less effective reductions in $PM_{2.5}$ and $PN_{0.3\text{-}10}$ concentrations.

In contrast, smaller particles with diameters between 0.01 and 0.3 μm (Fig. 2d), exhibited greater reductions at maximum AVF than at half AVF. This trend likely stems from the dilution effect created by stronger airflows, as APs seem to be less effective at capturing ultrafine particles and much more effective on reducing the concentrations of larger particles (0.3–10 μm).

In the case of BC, the APs had a similar effect to that observed for $PM_{2.5}$, although, BC concentrations remain consistently low because activities such as idling, accelerating, and braking are not frequent in the bus depot (e.g., the average BC BL concentration during the measuring campaigns was 1.3 μg m^{-3}, Table S2).

Resuspension is something which cannot be overlooked, especially in environments such as bus depots and stations where PM originating from bus exhaust and non-exhaust emissions, maintenance activities, and resuspension will be passively deposited on surfaces throughout the facility. Based on these findings, by using the APs at half instead of maximum AVF, not only reduces the mass and number concentrations of particles between 0.3 and 10 μm more effectively but also results in lower energy consumption. To further validate these findings, an additional experiment was conducted to specifically investigate how the number of the APs influences particles' concentrations.

3.4.2. Number

To assess the importance of the number of the APs, other variables, such as their location and AVF, were held constant. Four APs (red boxplots, Fig. 3) and ten APs (blue boxplots) operating at the maximum AVF were compared (the grey boxplots on the left represent the weekly BL levels for both campaigns combined).

With the exception of $PN_{0.01\text{-}0.3}$ and BC (Fig. 3c and d), the concentrations' reduction with four APs operating showed little ($PM_{2.5}$) to no difference ($PN_{0.01\text{-}0.3}$) compared to the reduction observed with ten APs on. However, $PM_{2.5}$ demonstrated statistically significant differences ($p < 0.001$), suggesting that using more APs could significantly enhance $PM_{2.5}$ reduction, even if these differences are not so high (i.e., from a $PM_{2.5}$ median of 15 to 13.9 μg m^{-3}, Table 2). The relatively small difference in $PM_{2.5}$ concentrations between four and ten APs also suggests that particle resuspension may have contributed, as all the APs were operating at the maximum AVF. For smaller particles (<0.3 μm), lower concentrations were observed with 10 APs and this difference was statistically significant ($p < 0.001$). BC concentrations remained relatively stable. However, no definitive conclusions can be drawn for BC due to its low concentrations.

The finding that using more APs can be more effective for PM reduction aligns with the study of Lowther et al. (2020) who compared the effects of a single AP with the effects of multiple APs on air quality in a multi-room residence, although the AVF of their APs was much lower than in our study. Given that their measurements were taken in a residential environment with lower AVF APs, PM resuspension would likely be less of a concern. The location of the APs might have also played a role in these results as is discussed in the next section.

Table 1
Summary statistics of $PM_{2.5}$, BC and PN concentrations observed in AUVASA bus depot during the AVF experiment. The column at the right demonstrates the significant difference between the setups which were made.

Air volume flow	Setup	n	Avg.	Median	SD	Range (min.-max.)	Wilcoxon rank-sum test (p value)	
$PM_{2.5}$ (μg m^{-3})								
BL	BL	1293	24.4	19.8	15.7	12.9–287.8	BL vs Half	<0.001
Half	10 APs	168	14.2	13.7	1.3	12.9–19.8	BL vs Full	<0.001
Full	10 APs	168	17.2	16.1	2.3	13.9–24	Half vs Full	<0.001
BC (μg m^{-3})								
BL	BL	1259	1.5	0.9	1.6	0.02–14.8	BL vs Half	<0.001
Half	10 APs	169	0.7	0.5	0.7	0.1–5	BL vs Full	0.46
Full	10 APs	132	0.9	0.8	0.3	0.5–2.1	Half vs Full	<0.001
PN (particles with a diameter between 0.3 and 10 μm)								
BL	BL	1459	32	24	53	4–1065	BL vs Half	<0.001
Half	10 APs	169	12	12	3	7–29	BL vs Full	<0.001
Full	10 APs	168	16	14	5	9–33	Half vs Full	<0.001
PN (particles with a diameter between 0.01 and 0.3 μm)								
BL	BL	1433	20915	9763	33145	1164–509751	BL vs Half	<0.001
Half	10 APs	169	8431	7639	3870	2662–32499	BL vs Full	<0.001
Full	10 APs	167	5684	4974	3038	2296–23715	Half vs Full	<0.005

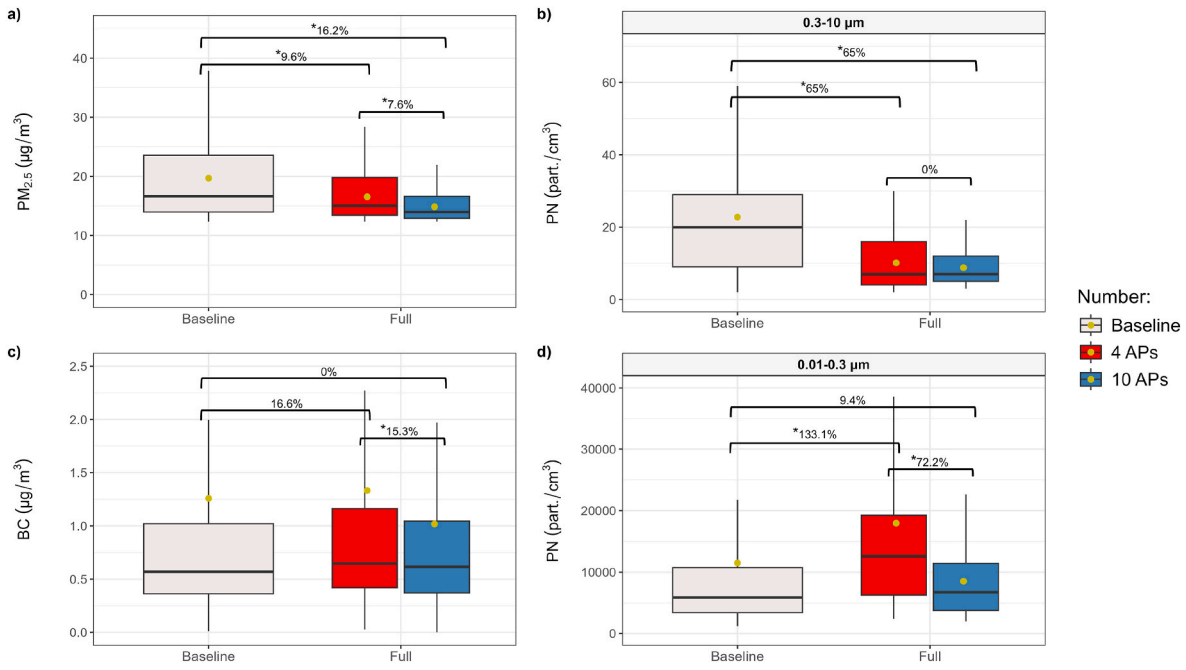

Fig. 3. Effect of air purifiers' (APs) number on pollutants' concentrations. The percentages above boxplots represent the percentage differences between median concentrations. The asterisks indicate statistically significant differences, while the yellow dots represent average concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Summary statistics of $PM_{2.5}$, BC and PN concentrations observed in AUVASA bus depot during the number experiment. The column at the right demonstrates the significant difference between the setups which were made.

Number	Setup	n	Avg.	Median	SD	Range (min.-max.)	Wilcoxon rank-sum test (p value)	
$PM_{2.5}$ (μg m^{-3})								
BL	BL	5412	19.7	16.6	11.1	12.3–287.8	BL vs 4 APs	<0.001
4 APs	Full	388	16.5	15	5	12.3–79.2	BL vs 10 APs	<0.001
10 APs	Full	388	14.8	13.9	2.5	12.3–26.2	4 vs 10 APs	<0.001
BC (μg m^{-3})								
BL	BL	5204	1.2	0.6	1.8	0.01–26.5	BL vs 4 APs	0.006
4 APs	Full	388	1.3	0.7	1.6	0.02–20.8	BL vs 10 APs	0.157
10 APs	Full	577	1.01	0.6	2.1	0.001–40.3	4 vs 10 APs	<0.001
PN (particles with a diameter between 0.3 and 10 μm)								
BL	BL	3521	23	20	36	2–1065	BL vs 4 APs	<0.001
4 APs	Full	387	10	7	8	2–58	BL vs 10 APs	<0.001
10 APs	Full	387	9	7	5	3–40	4 vs 10 APs	1
PN (particles with a diameter between 0.01 and 0.3 μm)								
BL	BL	3654	11490	6148	24458	1164–509751	BL vs 4 APs	<0.001
4 APs	Full	249	17961	14335	16256	2386–116077	BL vs 10 APs	0.837
10 APs	Full	262	8510	6730	6396	1963–39714	4 vs 10 APs	<0.001

3.4.3. Location

Seven APs were running in two different locations to investigate the effect on air pollutant concentrations, while the other variables were held constant (i.e. the AVF and number of the APs). The $PM_{2.5}$ concentrations and $PN_{0.3\text{-}10}$ decreased greatly during the usage of the APs (Fig. 4). Interestingly, this reduction was much higher when two APs were moved ~12 m further away (location b, Fig. S3) than when the same two APs were installed at <5 m away from the measuring equipment (location a). It is worth noting that in all the comparisons made (BL vs setups and setups vs setups), the differences were statistically significant ($p \leq 0.001$, Table 3). For particles ranging from 0.01 to 0.3 μm, although higher concentrations were observed at location a) compared to location b), no definitive conclusions can be drawn (Fig. 4d). As with previous findings, BC did not follow the same trend as $PM_{2.5}$, likely due to its low concentrations (e.g. a BL median of 0.6 μg m^{-3}, Table 3).

The generally lower concentrations of particles observed at location b compared to location a is something which was not really expected. This may have occurred due to the crossed ejection of purified air, which can lead to turbulence and therefore increased particles' resuspension, as suggested by Mukai et al. (2009). Another study supports the idea that upward or horizontal ejection of APs (at 45° and 0°) can lead to higher and faster PM reduction levels than downward ejection (−45°), due to higher distribution of purified air (Jin et al., 2016). According to the abovementioned study, the ejection slope should be considered in APs design. The slope of the ejected purified air was horizontal in this study.

Additionally, Park et al. (2020) suggested that APs should be positioned in areas with high PM concentrations or follow occupants' movement, ensuring purified air is directed towards them. However, according to our findings the crossed airflows can favor the resuspension scenario especially at high AVF. Novoselac and Siegel (2009) also emphasized the importance of APs positioning, noting that APs near PM sources are more effective than those placed downstream or upstream. The authors believe the proper installation of the APs can lead up to a factor of 2.5 change in overall PM removal.

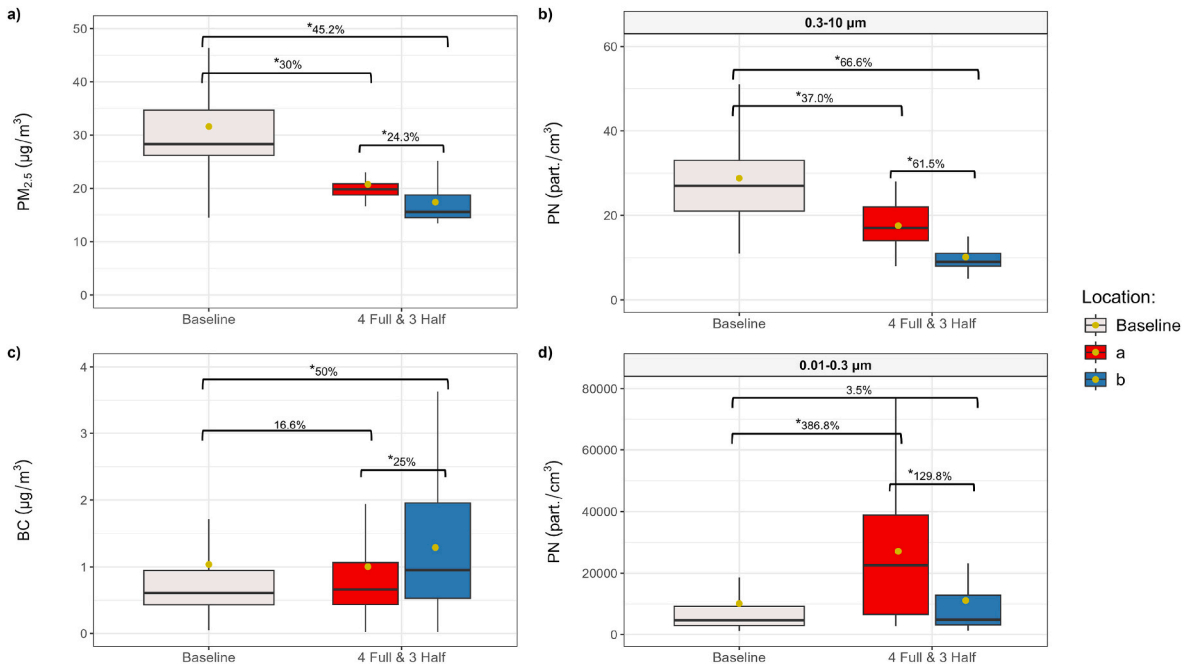

Fig. 4. Effect of air purifiers' (APs) locations on pollutants' concentrations. The percentages above boxplots represent the percentage differences between median concentrations. The asterisks indicate statistically significant differences, while the yellow dots represent average concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Summary statistics of $PM_{2.5}$, BC and PN concentrations observed in AUVASA bus depot during the location experiment. The column at the right demonstrates the significant difference between the setups which were made.

Location	Setup	n	Avg.	Median	SD	Range (min.-max.)	Wilcoxon rank-sum test (p value)	
$PM_{2.5}$ (µg m^{-3})								
BL	BL	2812	31.6	28.3	9.9	14.5–148.2	BL vs a	<0.001
a	4 Full & 3 Half	202	20.7	19.8	4.5	15.5–47.4	BL vs b	<0.001
b	4 Full & 3 Half	201	17.4	15.5	4.4	13.4–38.9	a vs b	<0.001
BC (µg m^{-3})								
BL	BL	2648	1	0.6	1.4	0.05–23.6	BL vs a	1
a	4 Full & 3 Half	203	1	0.7	1.3	0.02–9.6	BL vs b	<0.001
b	4 Full & 3 Half	202	1.3	0.9	0.9	0.02–4.1	a vs b	<0.005
PN (particles with a diameter between 0.3 and 10 µm)								
BL	BL	1202	29	27	10	11–114	BL vs a	<0.001
a	4 Full & 3 Half	69	18	17	5	8–28	BL vs b	<0.001
b	4 Full & 3 Half	69	10	9	4	1–22	a vs b	<0.001
PN (particles with a diameter between 0.01 and 0.3 µm)								
BL	BL	2828	10118	4684	26323	1108–509751	BL vs a	<0.001
a	4 Full & 3 Half	202	27098	22806	21770	2782–96893	BL vs b	0.21
b	4 Full & 3 Half	202	11146	4849	12928	1280–52500	a vs b	<0.001

By combining the information from other studies with the findings of this study, we suggest that best practices for installing APs in transport microenvironments, such as bus depots, should focus on locating the zones where PM levels show the highest concentrations. The ejection orientation of the APs should be upward (e.g. 45°) or horizontal (e.g. 0°) for higher and faster removal of PM and never downward (e.g. −45°), as the latter causes more recirculation and less distribution of the purified air. Moreover, APs should not be positioned too far away from pollutant sources and the purified air should be directed straight at the subjects. Crossed airflow should be avoided to reduce turbulence and consequently PM resuspension.

3.4.4. Distance

The effect of the distance between an AP at the maximum AVF and the measuring equipment on $PM_{2.5}$, PN, and BC concentrations is shown in Fig. 5. Following the same principle, the aforementioned variables were held constant to assess the importance of the distance from the AP. A comprehensive description of this experiment was done before (2.2 Measurement campaigns).

As expected, the closer to the AP, the higher the reduction of particles' concentrations as shorter distances result in stronger airflow influence and particle dilution (Galindo et al., 2011; Nhu et al., 2018). This effect was also observed for the smaller particles (0.01–0.3 µm), despite the relatively minor influence of APs filters on them, and also BC, indicating that airflow alone can influence their dispersion. Statistically significant differences were found between the concentrations of these smaller particles when the equipment was moved from 2 m up to 6 m ($p < 0.001$, Table 4). Nevertheless, no statistical difference was found between their concentrations when the equipment was moved from 6 m to 8 m ($p = 0.09$).

Although these findings may seem to contradict the location experiment (where PM concentrations decreased more when the two APs were farther apart), they emphasize the strong influence of APs with high AVF on resuspension. When considering AVF alone (Fig. 2), the

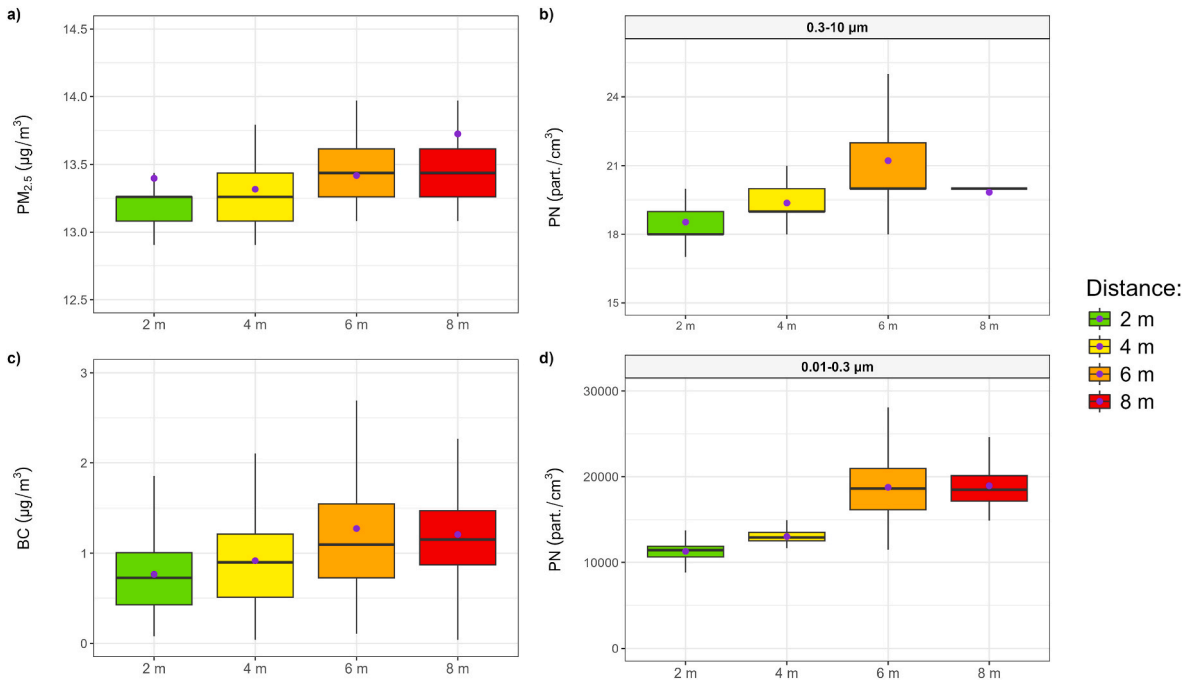

Fig. 5. Effect of air purifier's (AP) distance on pollutants' concentrations. The purple dots represent the average concentrations from three weekday repetitions conducted at the same time. The AP was directly blowing purified air on the measuring equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Summary statistics of $PM_{2.5}$, BC and PN concentrations observed in AUVASA bus depot during the distance experiment. The column at the right demonstrates the significant difference between the setups which were made.

Distance	Setup	n	Avg.	Median	SD	Range (min.-max.)	Wilcoxon rank-sum test (p value)	
$PM_{2.5}$ (µg m^{-3})								
2 m	1 Full	181	13.4	13.2	1.39	12.9–30.3	2 vs 4 m	0.07
4 m	1 Full	180	13.3	13.2	0.3	12.9–15	4 vs 6 m	<0.001
6 m	1 Full	180	13.4	13.4	0.3	13–14.8	6 vs 8 m	<0.001
8 m	1 Full	180	13.7	13.4	1.7	13–35.3	2 vs 8 m	<0.001
BC (µg m^{-3})								
2 m	1 Full	91	0.7	0.7	0.4	0–2.1	2 vs 4 m	0.08
4 m	1 Full	90	0.9	0.9	0.4	0–2.1	4 vs 6 m	<0.001
6 m	1 Full	90	1.2	1.1	0.7	0.1–5.1	6 vs 8 m	1
8 m	1 Full	91	1.2	1.1	0.4	0–2.5	2 vs 8 m	<0.001
PN (particles with a diameter between 0.3 and 10 µm)								
2 m	1 Full	181	19	18	1	17–21	2 vs 4 m	<0.001
4 m	1 Full	180	19	19	1	136–161	4 vs 6 m	<0.001
6 m	1 Full	180	21	20	2	18–31	6 vs 8 m	<0.001
8 m	1 Full	180	20	20	1	19–22	2 vs 8 m	<0.001
PN (particles with a diameter between 0.01 and 0.3 µm)								
2 m	1 Full	901	11319	11468	989	8233–22105	2 vs 4 m	<0.001
4 m	1 Full	900	13046	12940	666	11694–15473	4 vs 6 m	<0.001
6 m	1 Full	900	18761	18631	4649	11533–30600	6 vs 8 m	0.09
8 m	1 Full	901	18950	18576	2665	14904–33548	2 vs 8 m	<0.001

smaller particles showed an opposite trend from the rest, likely because most larger particles were trapped by the AP filters. Moreover, regarding the effect of location (Fig. 4) the smaller particles followed the same trend as the rest of the particles. This showcases at the location experiment when the two APs were moved away, their concentrations decreased due to the reduction of crossed airflows and consequently decreased turbulence and resuspension which obviously affected the smaller particles as well.

Overall, significant reductions in particle concentrations were observed up to 6 m (usually $p < 0.001$, Table 4). Particles with diameter between 0.3 and 10 µm also showed statistically significant differences at their concentrations by moving the equipment from 6 m to 8 m. This was also observed for $PM_{2.5}$ (Table 4).

Based on these findings, the APs should be ideally placed within 6 m of the target area blowing purified air directly on the subjects. However, it should be noted that if the AP was running at its half AVF instead of its full AVF, different results would be expected based on what is already discussed. In other words, lower concentrations of particles due to their lower resuspension and an overall significant reduction on particles' concentrations at a lower distance (e.g. up to 4 m instead of 6 m) owing to the lower airflow influence and particle dilution.

3.5. Limitations

This study has several limitations. Firstly, both measurement campaigns were conducted in May and June, which limits our understanding

of the potential seasonal variability in air quality. As a result, the study does not fully capture the effects of seasonality, like the lower PM levels that are often observed during winter due to increased precipitation. Furthermore, as discussed earlier, resuspension plays a critical role in how APs affect PM concentrations, and it is influenced by the cleanliness of the floors, but also meteorological factors such as the temperature and relative humidity (Qian et al., 2008; Yuan et al., 2023). To further understand these dynamics, future research could explore the impact on floor cleanliness and the efficacy of APs during the winter months in the same study area.

Another limitation is the placement of the APs within the bus depot. Due to operational concerns, the purifiers could not be positioned freely, as their placement had to avoid interfering with the workers of the depot. Nonetheless, the measurement point was not randomly selected; it was chosen based on specific criteria as explained before. We also emphasize that the air exchange rate (AER) at which the APs were operating in the large bus depot was very low, and that our study was limited to experimenting with local changes in air quality rather than attempting to use enough machines to clean the entire depot air volume.

Additionally, simultaneous measurements at multiple locations within the depot by using the same instruments were not possible, due to limitations in the number of instruments. While the comparisons made during the study were robust and followed several key principles, such as using BL data from the first week with the same time range as the setups, the inclusion of parallel measurements using identical instruments would have further strengthened the reliability of these comparisons.

Finally, it is crucial to examine how the APs influence the chemical composition of PM which is strongly related to human health implications. This study focused on $PM_{2.5}$, PN and BC concentrations, but future research should investigate the effect of the APs on particles' chemical characteristics.

4. Conclusions

This study evaluated the levels and temporal distribution of $PM_{2.5}$, PN, and BC in a major public restricted bus depot, compared them with bus stations worldwide, and investigated the impact of APs on its air quality. The effects of different APs variables (such as the AVF, number, location and distance) were examined to determine the optimal configuration for the highest PM reduction with the minimum energy consumption. The key conclusions of this study are:

- The average BL $PM_{2.5}$ concentration in the bus depot was 25.2 μg m^{-3}, about 4.6 times higher than outdoor levels (5.5 μg m^{-3}), highlighting the dominance of indoor PM sources, such as bus exhausts, brakes, maintenance activities, and resuspension.
- The average BL BC concentration was 1.3 μg m^{-3}, which is lower than typical concentrations in bus stations, consistent with the restricted nature of the depot where buses are not continuously moving and idling inside the depot. BC emissions primarily originate from the buses' exhausts in this type of environment, thus the lower concentrations compared to those in bus stations were expected.
- The average BL concentration of number of particles between 0.01 and 0.3 μm was 1.3×10^3 particles cm^{-3}, while for particles between 0.3 and 10 μm it was 33×10^0 particles cm^{-3}.
- Daily patterns showed particle concentrations peaking during night time (23:00 to 9:00) and additional evening spikes (e.g. 16:00 to 18:00), corresponding with the movement of buses and maintenance activities. Such temporal variations reflect the depot's operational dynamics and the influence of activity-based particles' generation.
- The distribution of median $PM_{2.5}$ levels was homogeneous across the depot, despite its large area (around 10,000 m^2), which is ascribed to the active mixing supported by traffic entering via three entrances and one exit.
- The use of APs significantly reduced the concentrations of $PM_{2.5}$ and particle numbers in the 0.3–10 μm size range, although their impact on BC was unclear due to the low concentrations of BC. Smaller particles (<0.3 μm) were reduced indirectly via dilution effects from purified air streams.
- The effectiveness of APs was influenced by their positioning, number of units, and AVF. Optimizing these factors can lead to significant improvements in air quality. More APs, operating at half AVF, placed within 6 m from the subject without crossing airflows, could provide the optimum results. Avoiding crossed airflows at this distance can minimize turbulence and resuspension risk.
- Particle resuspension, especially in (semi-)closed environments, plays a key role for the APs with high AVF such as the ones used in this study, where indoor PM sources are dominant and particles can be deposited on the floor (e.g. bus depots and stations).
- APs do not seem to capture effectively particles below 50 nm, this could explain why BC concentrations remained stable. Further investigation into airflow dynamics and filter efficiency for UFPs would help clarify these findings.
- Although HEPA filters are highly efficient at removing ultrafine particles under standardized conditions, the observed increase in 0.01–0.3 μm particles particularly at full AVF suggests that other processes, such as secondary aerosol formation, may have reduced the APs' removal capacity to capture UFPs. The possible contribution of UV-induced ozone and secondary ultrafine particle formation should be taken as a potential drawback of some AP technologies and we strongly recommend that future deployments carefully evaluate such risks.

Ensuring good air quality in (semi-)closed environments such as bus depots and stations, is crucial for occupational health and air quality management. The use of efficient APs, operated at the optimal air volume flow (AVF) and placement offers a promising, cost-effective solution to reduce PM concentrations and therefore health risks associated with particulate inhalation. However, APs should be considered as a local and/or complementary mitigation strategy rather than a replacement for ventilation, with their effectiveness enhanced when combined with improved ventilation systems. This study provides practical, energy-efficient solutions for reducing airborne particle concentrations, thereby improving occupational health, aligning with urban air quality policies and promoting cost-effective pollution mitigation strategies. Despite extensive research on air pollution in public transport systems, bus depots remain an overlooked microenvironment. This study offers data-driven insights on AP efficiency and optimization of its operation. Findings from this study provide a scientific basis for improving air quality in transport systems, helping policymakers develop targeted regulations for AP implementation in bus depots and similar environments. The study also presents an alternative to large-scale HVAC retrofits, making air quality improvements more accessible and cost-effective for transit operators.

CRediT authorship contribution statement

S. Agathokleous: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K. Kedwell:** Writing – review & editing, Methodology, Conceptualization. **C. Casado:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization. **C. Asbach:** Writing – review & editing, Funding acquisition, Conceptualization. **A.S. Fonseca:** Writing – review & editing, Writing – original draft, Visualization, Resources, Data curation. **J.B. Liisberg:** Writing – review & editing, Visualization, Resources, Formal analysis. **S.B. Jensen:** Writing – review & editing, Resources. **K.A. Jensen:** Writing – review & editing, Resources, Funding acquisition. **J.A. Rodríguez:** Resources. **A. Karanasiou:** Writing – review & editing, Supervision. **M. Lehmann:** Writing – review & editing,

Resources, Methodology, Funding acquisition, Conceptualization. **T. Moreno:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Funding

The present research is being carried out within the project AeroSolfd, Horizon Europe project supported by the European Commission under grant agreement No. 101056661. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. Swiss participant(s) in the AeroSolfd project are co-funded by the Swiss State Secretariat for Education, Research and Innovation (SERI).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stefanos Agathokleous reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors want to thank Ayuntamiento de Valladolid (AVa) for the collaboration and support provided throughout the measurement campaigns.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126310.

Data availability

Data will be made available on request.

References

Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. J. Med. Toxicol. 8, 166–175. https://doi.org/10.1007/s13181-011-0203-1.

Bennett, D.H., Moran, R.E., Krakowiak, P., Tancredi, D.J., Kenyon, N.J., Williams, J., Fisk, W., 2022. Reductions in particulate matter concentrations resulting from air filtration: a randomized sham-controlled crossover study. Indoor Air 32 (2), e12982. https://doi.org/10.1111/ina.12982.

Birmili, W., Weinhold, K., Rasch, F., Sonntag, A., Sun, J., Merkel, M., Wiedensohler, A., Bastian, S., Schladitz, A., Löschau, G., Cyrys, J., Pitz, M., Gu, J., Kusch, T., Flentje, H., Quass, U., Kaminski, H., Kuhlbusch, T.A.J., Meinhardt, F., Schwerin, A., Bath, O., Ries, L., Wirtz, K., Fiebig, M., 2016. Long-term observations of tropospheric particle number size distributions and equivalent Black carbon mass concentrations in the German ultrafine aerosol network (GUAN). Earth Syst. Sci. Data 8, 355–382. https://doi.org/10.5194/essd-8-355-2016.

Both, A.F., Westerdahl, D., Fruin, S., Haryanto, B., Marshall, J.D., 2013. Exposure to carbon monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: effect of commute mode. Sci. Total Environ. 443, 965–972. https://doi.org/10.1016/j.scitotenv.2012.10.082.

Bräuner, E.V., Forchhammer, L., Möller, P., Simonsen, J., Glasius, M., Wåhlin, P., Raaschou-Nielsen, O., Loft, S., 2007. Exposure to ultrafine particles from ambient air and oxidative stress-induced DNA damage. Environ. Health Perspect. 115, 1177–1182. https://doi.org/10.1289/ehp.9984.

Brehmer, C., Norris, C., Barkjohn, K.K., Bergin, M.H., Zhang, J., Cui, X., Zhang, Y., Black, M., Li, Z., 2019. The impact of household air cleaners on the chemical composition and children's exposure to $PM_{2.5}$ metal sources in suburban Shanghai. Environ. Pollut. 253, 190–198.

Cakaj, A., Lisiak-Zielinska, M., Khaniabadi, Y.O., Sicard, P., 2023. Premature deaths related to urban air pollution in Poland. Atmos. Environ. 301, 119723. https://doi.org/10.1016/j.atmosenv.2023.119723.

Carmona, N., Seto, E., Gould, T.R., Rasyid, E., Shirai, J.H., Cummings, B.J., Hayward, L., Larson, T.V., Austin, E., 2022. Indoor air quality intervention in schools: effectiveness of a portable HEPA filter deployment in five schools impacted by roadway and aircraft pollution sources. Atmosphere 13 (10), 1623. https://doi.org/10.3390/atmos13101623.

Cheek, E., Guercio, V., Shrubsole, C., Dimitroulopoulou, S., 2021. Portable air purification: review of impacts on indoor air quality and health. Sci. Total Environ. 766, 142585. https://doi.org/10.1016/j.scitotenv.2020.142585.

Cheng, Y.S., 2014. Mechanisms of pharmaceutical aerosol deposition in the respiratory tract. In: AAPS PharmSciTech. Springer New York LLC, pp. 630–640. https://doi.org/10.1208/s12249-014-0092-0.

Cheng, Y.H., Chang, H.P., Hsieh, C.J., 2011. Short-term exposure to PM_{10}, $PM_{2.5}$, ultrafine particles and CO_2 for passengers at an intercity bus terminal. Atmos. Environ. 45, 2034–2042. https://doi.org/10.1016/j.atmosenv.2011.01.061.

Cheng, Y.H., Chang, H.P., Yan, J.W., 2012. Temporal variations in airborne particulate matter levels at an indoor bus terminal and exposure implications for terminal workers. Aerosol Air Qual. Res. 12, 30–38. https://doi.org/10.4209/aaqr.2011.06.0085.

da Silva Junior, C.R., Lemos, B.R.L., Pinto, J.P., Amador, I.R., Solci, M.C., 2019. Black carbon associated to $PM_{1.0}$ and $PM_{2.5}$: mass variation due to combustion of biodiesel/diesel blends (B5, B6, B7 and B8). J. Braz. Chem. Soc. 30, 786–792. https://doi.org/10.21577/0103-5053.20180209.

De Marco, A., Amoatey, P., Khaniabadi, Y.O., Sicard, P., Hopke, P.K., 2018. Mortality and morbidity for cardiopulmonary diseases attributed to $PM_{2.5}$ exposure in the metropolis of Rome, Italy. Eur. J. Intern. Med. 57, 49–57. https://doi.org/10.1016/j.ejim.2018.07.027.

Dubey, S., Rohra, H., Taneja, A., 2021. Assessing effectiveness of air purifiers (HEPA) for controlling indoor particulate pollution. Heliyon 7 (9), e07976. https://doi.org/10.1016/j.heliyon.2021.e07976.

Fu, P., Guo, X., Cheung, F.M.H., Yung, K.K.L., 2019. The association between $PM_{2.5}$ exposure and neurological disorders: a systematic review and meta-analysis. Sci. Total Environ. 655, 1240–1248. https://doi.org/10.1016/j.scitotenv.2018.11.218.

Galindo, N., Varea, M., Gil-Moltó, J., Yubero, E., Nicolás, J., 2011. The influence of meteorology on particulate matter concentrations at an urban Mediterranean location. Water Air Soil Pollut. 215, 365–372. https://doi.org/10.1007/s11270-010-0484-z.

GBD 2019 Diabetes and Air Pollution Collaborators, 2022. Estimates, trends, and drivers of the global burden of type 2 diabetes attributable to $PM_{2.5}$ air pollution, 1990-2019: an analysis of data from the global burden of disease study 2019. Lancet Planet. Health 6, 586–600. Available at: www.thelancet.com/planetary-health.

Graeffe, F., Luo, Y., Guo, Y., Ehn, M., 2023. Unwanted indoor air quality effects from using ultraviolet C lamps for disinfection. Environ. Sci. Technol. Lett. 10 (2), 172–178. https://doi.org/10.1021/acs.estlett.2c00807.

Harrison, R.M., Yin, J., 2000. Particulate matter in the atmosphere: which particle properties are important for its effects on health? Sci. Total Environ. 249, 85–101. https://doi.org/10.1016/S0048-9697(99)00513-6.

Hess, D.B., Ray, P.D., Stinson, A.E., Park, J.Y., 2010. Determinants of exposure to fine particulate matter ($PM_{2.5}$) for waiting passengers at bus stops. Atmos. Environ. 44, 5174–5182. https://doi.org/10.1016/j.atmosenv.2010.08.046.

Jayaratne, E.R., Wang, L., Heuff, D., Morawska, L., Ferreira, L., 2009. Increase in particle number emissions from motor vehicles due to interruption of steady traffic flow. Transp. Res. D Transp. Environ. 14, 521–526. https://doi.org/10.1016/j.trd.2009.07.007.

Jin, X., Yang, L., Du, X., Yang, Y., 2016. Particle transport characteristics in indoor environment with an air cleaner. Indoor Built Environ. 25, 987–996. https://doi.org/10.1177/1420326X15592253.

Karanasiou, A., Viana, M., Querol, X., Moreno, T., de Leeuw, F., 2014. Assessment of personal exposure to particulate air pollution during commuting in European cities-Recommendations and policy implications. Sci. Total Environ. 490, 785–797. https://doi.org/10.1016/j.scitotenv.2014.05.036.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmos. Environ. 41, 4781–4810. https://doi.org/10.1016/j.atmosenv.2007.02.002.

Kelly, F.J., Fussell, J.C., 2019. Improving indoor air quality, health and performance within environments where people live, travel, learn and work. Atmos. Environ. 200, 90–109. https://doi.org/10.1016/j.atmosenv.2018.11.058.

Khaniabadi, Y.O., Sicard, P., 2021. A 10-year assessment of ambient fine particles and related health endpoints in a large Mediterranean city. Chemosphere 278, 130502. https://doi.org/10.1016/j.chemosphere.2021.130502.

Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143. https://doi.org/10.1016/j.envint.2014.10.005.

Kim, M.Y., Jung, Y.G., Park, J.C., Yang, Y.K., 2021. The impact of airflow and air purification on the resuspension and removal of deposited particulate matter. J. Build. Eng. 41, 102367. https://doi.org/10.1016/j.jobe.2021.102367.

Kinsey, J.S., Williams, D.C., Dong, Y., Logan, R., 2007. Characterization of fine particle and gaseous emissions during school bus idling. Environ. Sci. Technol. 41, 4972–4979. https://doi.org/10.1021/es0625024.

Knibbs, L.D., de Dear, R.J., 2010. Exposure to ultrafine particles and $PM_{2.5}$ in four Sydney transport modes. Atmos. Environ. 44, 3224–3227. https://doi.org/10.1016/j.atmosenv.2010.05.026.

Kumar, P., Patton, A.P., Durant, J.L., Frey, H.C., 2018. A review of factors impacting exposure to $PM_{2.5}$, ultrafine particles and black carbon in Asian transport microenvironments. Atmos. Environ. 187, 301–316. https://doi.org/10.1016/j.atmosenv.2018.05.046.

Lee, Y.Y., Lin, S.L., Aniza, R., Yuan, C.S., 2017. Reduction of atmospheric $PM_{2.5}$ level by restricting the idling operation of buses in a busy station. Aerosol Air Qual. Res. 17, 2424–2437. https://doi.org/10.4209/aaqr.2017.09.0301.

Lee, J., Weerasinghe-Mudiyanselage, P.D.E., Kim, B., Sohi, K., Kim, J.S., Moon, C., 2023. Particulate matter exposure and neurodegenerative diseases: a comprehensive update on toxicity and mechanisms. Ecotoxicology and Environmental Safety. Academic Press. https://doi.org/10.1016/j.ecoenv.2023.115565.

Liang, R., Zhang, B., Zhao, X., Ruan, Y., Lian, H., Fan, Z., 2014. Effect of exposure to $PM_{2.5}$ on blood pressure: a systematic review and meta-analysis. J. Hypertens. 32, 2130–2141. https://doi.org/10.1097/HJH.0000000000000342.

Liu, C., Wang, B., Liu, S., Li, S., Zhang, K., Luo, B., Yang, A., 2021. Type 2 diabetes attributable to PM2.5: a global burden study from 1990 to 2019. Environ. Int. 156. https://doi.org/10.1016/j.envint.2021.106725.

Lowther, S.D., Deng, W., Fang, Z., Booker, D., Whyatt, D.J., Wild, O., Wang, X., Jones, K. C., 2020. How efficiently can HEPA purifiers remove priority fine and ultrafine particles from indoor air ? 144. https://doi.org/10.1016/j.envint.2020.106001.

Luo, H., Chen, J., Li, G., Taicheng, A., 2021. Formation kinetics and mechanisms of ozone and secondary organic aerosols from photochemical oxidation of different aromatic hydrocarbons: dependence on NOx and organic substituents. Atmos. Chem. Phys. 21 (10), 7567–7578. https://doi.org/10.5194/acp-21-7567-2021.

Malloy, J., Quintana, A., Jensen, C.J., Liu, K., 2021. Efficient and robust metallic nanowire foams for deep submicrometer particulate filtration. Nano Lett. 21 (7), 2968–2974. https://doi.org/10.1021/acs.nanolett.1c00050.

Marinello, S., Lolli, F., Coruzzolo, A.M., Gamberini, R., 2023. Exposure to air pollution in transport microenvironments. Sustainability 15, 1–32. https://doi.org/10.3390/su151511958.

Mkoma, S.L., Da Rocha, G.O., Regis, A.C.D., Domingos, J.S.S., Santos, J.V.S., De Andrade, S.J., Carvalho, L.S., De Andrade, J.B., 2014. Major ions in $PM_{2.5}$ and PM_{10} released from buses: the use of diesel/biodiesel fuels under real conditions. Fuel 115, 109–117. https://doi.org/10.1016/j.fuel.2013.06.044.

Moore, A., Figliozzi, M., Monsere, C.M., 2012. Air quality at bus stops empirical analysis of exposure to particulate matter at bus stop shelters. Transp. Res. Board 5, 76–86. https://doi.org/10.3141/2270-10.

Morales Betancourt, R., Galvis, B., Rincón-Riveros, J.M., Rincón-Caro, M.A., Rodriguez-Valencia, A., Sarmiento, O.L., 2019. Personal exposure to air pollutants in a bus rapid transit system: impact of fleet age and emission standard. Atmos. Environ. 202, 117–127. https://doi.org/10.1016/j.atmosenv.2019.01.026.

Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U., Ling, X., 2008. Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure. Atmos. Environ. 42, 8113–8138. https://doi.org/10.1016/j.atmosenv.2008.07.050.

Moreno, T., Reche, C., Rivas, I., Cruz Minguillón, M., Martins, V., Vargas, C., Buonanno, G., Parga, J., Pandolfi, M., Brines, M., Ealo, M., Sofia Fonseca, A., Amato, F., Sosa, G., Capdevila, M., de Miguel, E., Querol, X., Gibbons, W., 2015. Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. Environ. Res. 142, 495–510. https://doi.org/10.1016/j.envres.2015.07.022.

Moreno, T., Reche, C., Ahn, K.H., Eun, H.R., Kim, W.Y., Kim, H.S., Fernández-Iriarte, A., Amato, F., Querol, X., 2020. Using miniaturised scanning mobility particle sizers to observe size distribution patterns of quasi-ultrafine aerosols inhaled during city commuting. Environ. Res. 191. https://doi.org/10.1016/j.envres.2020.109978.

Mukai, C., Siegel, J.A., Novoselac, A., 2009. Impact of airflow characteristics on particle resuspension from indoor surfaces. Aerosol. Sci. Technol. 43, 1022–1032. https://doi.org/10.1080/02786820903131073.

Nhu, Ngoc, Le, T., Minjeong, K., Hoang Bui, K.V., Park, D., Lee, Young-Chul, 2018. Particulate matter exposure of passengers at bus stations: a review. Environ. Res. Pub. Health 15. https://doi.org/10.3390/ijerph15122886.

Nogueira, T., Dominutti, P.A., Vieira-Filho, M., Fornaro, A., de Fatima Andrade, M., 2019. Evaluating atmospheric pollutants from urban buses under real-world conditions: implications of the main public transport mode in São Paulo, Brazil. Atmosphere 10. https://doi.org/10.3390/atmos10030108.

Nogueira, T., Kumar, P., Nardocci, A., de Fatima Andrade, M., 2020. Public health implications of particulate matter inside bus terminals in Sao Paulo, Brazil. Sci. Total Environ. 711, 135064. https://doi.org/10.1016/j.scitotenv.2019.135064.

Novoselac, A., Siegel, J.A., 2009. Impact of placement of portable air cleaning devices in multizone residential environments. Build. Environ. 44, 2348–2356. https://doi.org/10.1016/j.buildenv.2009.03.023.

O'Piela, D., Durisek, G., Escobar, Y., Mackos, A., Wold, L., 2022. Particulate matter and Alzheimer's disease: an intimate connection. Trends in Molecular Medicine. Elsevier Ltd, pp. 770–780. https://doi.org/10.1016/j.molmed.2022.06.004.

Palma, F., Baldelli, G., Amagliani, G., Aliano, M.P., Magnani, M., Brandi, G., Schiavano, G.F., 2024. Assessment of a new UV-C light-emitting diode–based technology for air sanitization in indoor sports environments. Indoor Built Environ. 33 (2), 237–249. https://doi.org/10.1177/1420326X231193597.

Park, S., Rim, D., 2024. Human exposure to air contaminants under the far-UVC system operation in an office: effects of lamp position and ventilation condition. Sci. Rep. 14 (1), 24465. https://doi.org/10.1038/s41598-024-75245-z.

Park, H., Park, S., Seo, J., 2020. Evaluation on air purifier's performance in reducing the concentration of fine particulate matter for occupants according to its operation methods. Int. J. Environ. Res. Publ. Health 17, 1–14. https://doi.org/10.3390/ijerph17155561.

Pereira, A.R., Braga, D.F.O., Vassal, M., Gomes, B., Simões, M., 2023. Ultraviolet C irradiation: a promising approach for the disinfection of public spaces? Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2023.163007. Elsevier B.V.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manage. Assoc. 56, 709–742. https://doi.org/10.1080/10473289.2006.10464485.

Qian, J., Ferro, A.R., Fowler, K.R., 2008. Estimating the resuspension rate and residence time of indoor particles. J. Air Waste Manage. Assoc. 58, 502–516. https://doi.org/10.3155/1047-3289.58.4.502.

Qin, S., Zeng, Q., Zeng, H., Meng, W., Wu, Q., Lv, Y., Dai, J., Dong, G., Zeng, X., 2025. 'Novel perspective on particulate matter and Alzheimer's disease: insights from adverse outcome pathway framework'. In: Environmental Pollution. Elsevier Ltd. https://doi.org/10.1016/j.envpol.2024.125601.

Quezada-Maldonado, E., Sánchez-Pérez, Y., Chirino, Y., García-Cuellar, C., 2021. Airborne particulate matter induces oxidative damage, DNA adduct formation and alterations in DNA repair pathways. In: Environmental Pollution. Elsevier Ltd. https://doi.org/10.1016/j.envpol.2021.117313.

Rajagopalan, S., Brook, R.D., 2012. Air pollution and type 2 diabetes: mechanistic insights. Diabetes 61, 3037–3045. https://doi.org/10.2337/db12-0190.

Rashidi, R., Khaniabadi, Y.O., Sicard, P., De Marco, A., Anbari, K., 2023. Ambient $PM_{2.5}$ and O_3 pollution and health impacts in Iranian megacity. Stoch. Environ. Res. Risk Assess. 37, 175–184. https://doi.org/10.1007/s00477-022-02286-z.

Riediker, M., Devlin, R.B., Griggs, T.R., Herbst, M.C., Bromberg, P.A., Williams, R.W., Cascio, W.E., 2004. Cardiovascular effects in patrol officers are associated with fine particulate matter from brake wear and engine emissions. Part. Fibre Toxicol. 1, 1–10. https://doi.org/10.1186/1743-8977-1-2.

Risom, L., Møller, P., Loft, S., 2005. Oxidative stress-induced DNA damage by particulate air pollution. Mutat. Res. Fund Mol. Mech. Mutagen 592, 119–137. https://doi.org/10.1016/j.mrfmmm.2005.06.012.

Salama, K.F., Alhajri, R.F., Al-Anazi, A.A., 2017. Assessment of air quality in bus terminal stations in eastern province, Kingdom of Saudi Arabia. Int. J COmmunity Med. Public Health 4, 1413–1418. https://doi.org/10.18203/2394-6040.ijcmph20171748.

Samet, Jonathan M., Dominici, Francesca, Curriero, Frank C., Coursac, Ivan, Zeger, Scott L., 2000. Fine PARTICULATE AIR POLLUTION AND MORTALITY IN 20 U.S. CITIES, 1987-1994. J. Med. 343, 1742–1749. https://doi.org/10.1056/NEJM200012143432401.

Shi, L., Wu, X., Danesh Yazdi, M., Braun, D., Abu Awad, Y., Wei, Y., Liu, P., Di, Q., Wang, Y., Schwartz, J., Dominici, F., Kioumourtzoglou, M., Zanobetti, A., 2020. Long-term effects of PM2.5 on neurological disorders in the American medicare population: a longitudinal cohort study. Lancet Planet. Health 4 (12), e557–e565. https://doi.org/10.1016/S2542-5196(20)30227-8.

Sicard, P., Khaniabadi, Y.O., Perez, S., Gualtieri, M., De Marco, A., 2019. Effect of O_3, PM_{10} and $PM_{2.5}$ on cardiovascular and respiratory diseases in cities of France, Iran and Italy. Environ. Sci. Pollut. Control Ser. 26, 32645–32665. https://doi.org/10.1007/s11356-019-06445-8.

Sørensen, S.B., Dalby, F.R., Olsen, S.K., Kristensen, K., 2024. Influence of germicidal UV (222 nm) lamps on ozone, ultrafine particles, and volatile organic compounds in indoor office spaces. Environ. Sci. Technol. 58 (45), 20073–20080. https://doi.org/10.1021/acs.est.4c03903.

Stone, V., Miller, R., Clift, M., Elder, A., Mills, N., Møller, P., Schins, R., Vogel, U., Kreyling, W., Jensen, K., Kuhlbusch, T., Schwarze, P., Hoet, P., Pietroiusti, A., Vizcaya-Ruiz, A., Baeza-Squiban, A., Teixeira, J., Tran, C., Cassee, F., 2017. 'Nanomaterials versus ambient ultrafine particles: an opportunity to exchange toxicology knowledge', environmental health perspectives. Public Health Service US Dept. Health Human Services. https://doi.org/10.1289/EHP424.

Suárez, L., Mesías, S., Iglesias, V., Silva, C., Cáceres, D.D., Ruiz-Rudolph, P., 2014. Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 16, 1309–1317. https://doi.org/10.1039/c3em00648d.

Sun, J., Birmili, W., Hermann, M., Tuch, T., Weinhold, K., Spindler, G., Schladitz, A., Bastian, S., Löschau, G., Cyrys, J., Gu, J., Flentje, H., Briel, B., Asbach, C., Kaminski, H., Ries, L., Sohmer, R., Gerwig, H., Wirtz, K., Meinhardt, F., Schwerin, A., Bath, O., Ma, N., Wiedensohler, A., 2019. Variability of black carbon mass concentrations, sub-micrometer particle number concentrations and size distributions: results of the German ultrafine aerosol network ranging from city street to high alpine locations. Atmos. Environ. 202, 256–268. https://doi.org/10.1016/j.atmosenv.2018.12.029.

Valavanidis, A., Fiotakis, K., Vlachogianni, T., 2008. Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. J. Environ. Sci. Health C Environ. Carcinog. Ecotoxicol. Rev. 26, 339–362. https://doi.org/10.1080/10590500802494538.

Wang, L., Morawska, L., Jayaratne, E.R., Mengersen, K., Heuff, D., 2011. Characteristics of airborne particles and the factors affecting them at bus stations. Atmos. Environ. 45, 611–620. https://doi.org/10.1016/j.atmosenv.2010.10.036.

Wu, W., Zhao, B., Wang, S., Hao, J., 2017. Ozone and secondary organic aerosol formation potential from anthropogenic volatile organic compounds emissions in China. J. Environ. Sci. (China) 53, 224–237. https://doi.org/10.1016/j.jes.2016.03.025.

Wu, R., Kang, N., Zhang, C., Song, Y., Liao, W., Hong, Y., Hou, J., Zhang, K., Tian, H., Lin, H., Wang, C., 2024. Long-term exposure to $PM_{2.5}$ and its components is associated with elevated blood pressure and hypertension prevalence: evidence from rural adults. J. Adv. Res. 60, 173–181. https://doi.org/10.1016/j.jare.2023.07.012.

Yang, L., Wan, W., Yu, C., Xuan, C., Zheng, P., Yan, J., 2022. Associations between $PM_{2.5}$ exposure and Alzheimer's disease prevalence among elderly in eastern China. Environ. Health: A Global Access Sci. Sour. 21 (1). https://doi.org/10.1186/s12940-022-00937-w.

Yin, P., He, G., Fan, Maoyong, Chiu, K.Y., Fan, Maorong, Liu, C., Xue, A., Liu, T., Pan, Y., Mu, Q., Zhou, M., 2017. Particulate air pollution and mortality in 38 of China's largest cities: time series analysis. Br. Med. J. 356, 1–12. https://doi.org/10.1136/bmj.j667.

Yuan, F., Yao, R., Yu, W., Sadrizadeh, S., Awbi, H., Kumar, P., 2023. Dynamic characteristics of particulate matter resuspension due to human activities in indoor environments: a comprehensive review. J. Build. Eng. 79, 107914. https://doi.org/10.1016/j.jobe.2023.107914.

Zhan, Y., Johnson, K., Norris, C., Shafer, M.M., Bergin, M.H., Zhang, Y., Zhang, J., Schauer, J.J., 2018. The influence of air cleaners on indoor particulate matter components and oxidative potential in residential households in Beijing. Sci. Total Environ. 626, 507–518. https://doi.org/10.1016/j.scitotenv.2018.01.024.

Zhang, L., Ke, X., Liu, S., You, J., Wang, X., Li, N., Yin, C., Zhang, Y., Bai, Y., Wang, M., Zheng, S., 2024. A longitudinal study on the effect of $PM_{2.5}$ components on blood pressure in the hypertensive patients from 2011 to 2019. Ecotoxicol. Environ. Saf. 285. https://doi.org/10.1016/j.ecoenv.2024.117054.

Zhao, L., Zhang, M., Bai, L., Zhao, Y., Cai, Z., Yung, K., Dong, C., Li, R., 2022. Real-world $PM_{2.5}$ exposure induces pathological injury and DNA damage associated with miRNAs and DNA methylation alteration in rat lungs. Environ. Sci. Pollut. Control Ser. 29 (19), 28788–28803. https://doi.org/10.1007/s11356-021-17779-7.

Zuurbier, M., Hoek, G., Oldenwening, M., Lenters, V., Meliefste, K., van den Hazel, P., Brunekreef, B., 2010. Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. Environ. Health Perspect. 118, 783–789. https://doi.org/10.1289/ehp.0901622.