



D3.3. EFFECT ON WORKERS' HEALTH, IMPROVED AIR AND WATER QUALITY STUDIED FOR VARIOUS SETUPS AT CLOSED DEMO-SITE OF A BUS DEPOT

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DoA	The closed environment of the AUVASA bus depot at Valladolid offers the advantage of a public restricted area. This facilitates easier installations with less protective measures and might already be possible with existing air purifiers. In addition, the location will allow more detailed scientific-grade measurements and to test smart control of the air purifier. Location will provide options to set up lab-like conditions for specific braking testing. For at least three different setups of air purifiers, the effect on improving air quality, reducing



the effect of brake emissions will be measured and studied in simulations. Simulation models will be enhanced by comparing with measured data Effect of time-resolved simulations will be evaluated. Emissions of buses when leaving depot and when returning from duty will be measured to assess e.g., temperature effect on brake emissions to the environment.

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LIST OF ABBREVIATIONS

ACRONYM	DESCRIPTION
AP	Air-purifier
AQ	Air Quality
AUVASA	Autobuses Urbanos de Valladolid, S. A.
BC	Black Carbon
BL	baseline measurements
BZ	Breathing zone (Measuring with the same proximity as workers with regards to exposures)
CARTIF	Centro tecnologico CARTIF
CSIC	Consejo Superior de Investigaciones Cientificas (Spanish Research Council)
DM	DiSCmini
EC	Elemental Carbon
FF	Far-field (reference measuring location)
IUTA	Institut für Energie und Umwelttechnik e.V.
LDSA	Lung deposited surface area ($\mu\text{m}^2/\text{cm}^3$)
NF	Near-field (measuring location close to the point of interest)
NFA	Det Nationale Forskningscenter for Arbejdsmiljø (English translation: The National Research Center for Work Environment)
NS	NanoScan particle sizer
OC	Organic Carbon
OPS	Optical Particle Sizer

PM (PM _{2.5} , PM ₄ , PM ₁₀)	Particulate Matter (smaller than 2,5 microns, smaller than 4 microns, smaller than 10 microns)
PNC	Particle number concentration
SMPS	Scanning Mobility Particle Sizer

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
#/cm ³	Number of particles per cubic centimetre
µg/m ³	Micrograms per cubic metre
ng/m ³	Nanograms per cubic metre
µm ² /cm ³	Square micrometres per cubic centimetre

PUBLISHABLE SUMMARY

This deliverable relates to Task 3.4 and involves assessing the impact of retrofitted air purifiers (AP) on air quality (AQ) within an enclosed work environment. The evaluation was conducted by comparing AQ measurements before and during the APs operation. The deliverable has been led by NFA, with contributions from CSIC, M+H, IUTA, CARTIF, and AUVASA.

The assessment focused on AUVASA's main urban bus depot in Valladolid, Spain, which includes a semi-indoor depot area, an enclosed workshop, and an office space. These areas represent typical transport-related micro-environments. To analyse the effect of APs, measurements were conducted within the workshop, acting as the enclosed work environment, and comparisons were made with AQ in the depot area.

The first measurement campaign was conducted in 2023, providing baseline (BL) data for comparison with a second campaign conducted from May 20th to May 31st, 2024. The second campaign included BL measurements until May 28th, followed by the deployment of four AP units in the workshop. The AQ was monitored using a suite of online instruments, including an Optical Particle Sizer (OPS), Scanning Mobility Particle Sizer Nanoscan (SMPS-NS), aethalometers, low-cost sensors, and a DiSCmini (DM), which measured particulate matter concentration and size distribution. Additional data were collected through filter samples for chemical, gravimetric, and elemental/organic carbon (EC/OC) analysis.

The key scientific questions addressed in this deliverable were:

- 1) To what extent can AQ be improved by the implementation of APs in an enclosed environment?
- 2) What positive effect could this have on water quality?

In this deliverable, we report on the AQ inside the AUVASA bus depot in Valladolid, Spain. Our results show that:

- AQ inside the workshop area was similar to AQ measured within the depot area, with both locations susceptible to large variations due to frequent transient peaks in air pollutants.
- During the first campaign, the office area exhibited unexpectedly poor AQ. Although this issue persisted throughout the first campaign, no similar AQ levels were observed in the office during the second campaign.
- Daily AQ in the depot area, as measured by inhalable particle mass, was typically worse at the start of the working day, with a “rush hour” peak, reaching an average of 30 $\mu\text{g}/\text{m}^3$ during the morning shift.
- The introduction of AP increased the effective air-exchange rate from 2-3 times per hour to 4 times per hour.
- The implementation of APs resulted in a 37% reduction in particles smaller than 700 nm and reductions in PM_{2.5}, PM₄, and PM₁₀ of 37%, 46%, and 52%, respectively.
- While a slight reduction in BC was observed, it could not be confirmed due to high variability in measurements.
- The assessment of positive effect on the water quality was limited, as the air within the workshop was not in significant contact with water and therefore not relevant to this study.

- The effective removal factor is dependent on the number of AP-units and further improvement in AQ could be possible with an increased number of units.

The main audience for this deliverable includes not only those working at the bus depot monitoring site but also employees in similar semi-closed, transport-related micro-environments. Our recommendations for follow-up actions within the AeroSolfd project are: 1) report further on the effects of AP use on AQ within enclosed work environments and 2) incorporate data collected from filter samples to better quantify pollution reduction and link improvements to the removal of specific pollutants.



1. INTRODUCTION

1.1.PURPOSE AND TARGET GROUP

The purpose of D3.3 is to evaluate the impact of introducing air purification systems in a closed work environment and assess their effectiveness in improving air quality. By identifying changes in particulate matter concentrations, air-exchange rates, and pollutant reductions, this study aims to quantify the potential benefits of air purification for worker health and overall workplace safety.

The primary target group for this deliverable includes occupational health and safety professionals, facility managers, and decision-makers responsible for maintaining safe working conditions in semi-enclosed or enclosed environments. The findings will also be relevant to researchers and policymakers focusing on strategies for mitigating airborne hazards and improving environmental quality in workplace settings.

1.2.CONTRIBUTIONS OF PARTNERS

Table 1: Contribution of each partner in this deliverable

PARTNER SHORT NAME	CONTRIBUTIONS
NFA	Led the deliverable, conducted the measurement campaign, and prepared the report.
CSIC	Conducted supporting air quality measurements, managed the implementation of air purifiers at the location, and assessed the potential effects on water quality.
M+H	Provided support during the campaign and reviewed the deliverable for quality assurance. Supplied the APs.
CARTIF	Developed and installed low-cost sensors and microprocessors, supported the measurement campaign in the AUVASA bus depot, and managed the electrical installation for various air purifier setups.
IUTA	Reviewed the deliverable for quality assurance.
AUVASA	Provided logistical and technical support during the campaign.

2. OBJECTIVES AND EXPECTED IMPACT

2.1.OBJECTIVES

The primary objective of this deliverable is to evaluate the potential for improving AQ and reducing exposure to airborne pollutants through the implementation of APs in specific enclosed environments, with a focus on a closed demonstration site at a bus depot. By assessing the efficiency of APs within this environment, the study aims to identify effective strategies to improve AQ and mitigate health risks to workers, ultimately improving their health and safety.

2.2.EXPECTED IMPACT

The findings of this study are expected to provide valuable insights into the benefits of APs in reducing airborne particle concentrations, particularly in workplaces with significant localized sources of diverse particulate matter chemical compositions. The results will inform evidence-based policy decisions within the EU, enabling the development of targeted strategies to minimize health risks for workers in enclosed environments. This work has the potential to contribute to improved occupational health standards and environmental quality in various workplaces.

3. DESCRIPTION OF TECHNICAL/SCIENTIFIC ACTIVITIES

A second measurement campaign was conducted at the AUVASA bus depot from May 20th to May 31st, 2024, to assess the effects of APs on workers' health and AQ in a closed demonstration site. This study focused on monitoring AQ with regard to particle concentrations and composition within the AUVASA workshop where workers performed maintenance tasks, both before and during the APs operation. Measurements were performed at four locations: the Far-Field (FF), Near-Field (NF), Breathing Zone (BZ), and an office area. The FF and NF locations were equipped with highly sensitive instruments, allowing for detailed characterization of particle size and composition under two distinct setups.

To establish baseline conditions, AQ measurements were taken from 07:00 on May 21st until 14:30 on May 28th, 2024. Following this baseline period, four APs were installed within the workshop. From May 28th, 2024 at 14:30 until the conclusion of the campaign at 15:00 on May 31st, AQ measurements were carried out with the APs in operation.

3.1.WORK ENVIRONMENT AND MEASUREMENT LOCATIONS

While the entire AUVASA bus depot was used for the work in D3.2, the scope for D3.3 was limited to the workshop area in order to specifically evaluate the effect of APs on AQ within a closed environment.

Figure 1 shows on the left an overhead view of the entire AUVASA area, with a green-highlighted section indicating the workshop, body/paint shop, and offices. A layout of this area is provided on the right, with color-coded markers indicating the locations of the measurement stations.

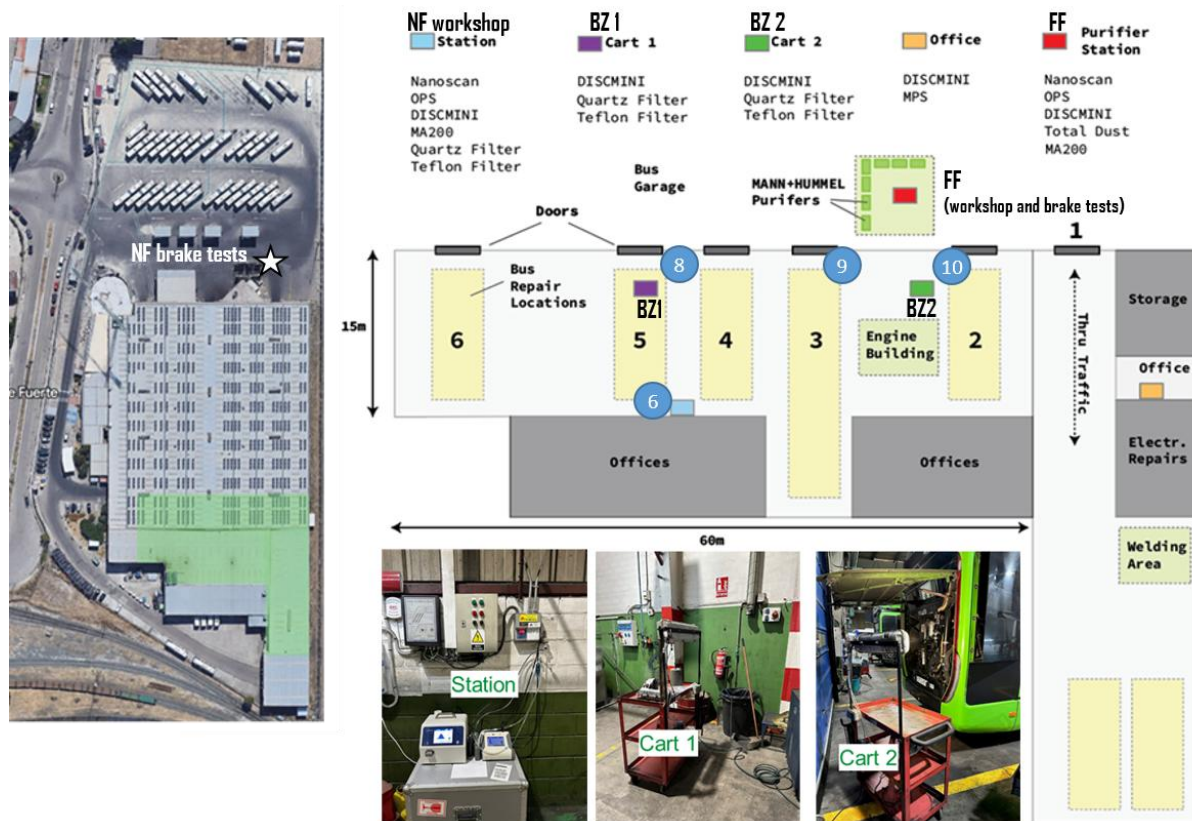


Figure 1: Overview of the workshop and surrounding area, including photos of the near-field station and the two carts representing the locations for breathing zone sampling. The blue circles indicate the positions of the four air purifiers (6, 8, 9, and 10), which were added to the workshop on May 28 at 14:00 (modified from Fonseca et al., submitted).

The workshop has an approximate volume of 8 900 m³ and is capable of accommodating the repair and maintenance of up to five buses simultaneously, though no more than three buses were present at any given time during the campaign. The background air-exchange rate was determined by measuring particle number concentration (PNC) decay rates before the air purifiers were activated, revealing an air-exchange rate of 2-3 times per hour.

3.2.MEASUREMENT STRATEGY

The measurement strategy adopted in this study followed the Tier 3 approach for particle exposure assessment published by the Organisation for Economic Co-operation and Development (OECD, 2015), and EN 17058:2018 (CEN, 2018). It included real-time particle monitoring combined with collection of samples for gravimetric, morphological, and chemical analysis. The goal was to capture statistically representative samples that reflect daily exposure variations. To achieve this, measurements and sampling were repeated at the same locations during maintenance tasks at the workshop. Two different workers were selected to carry personal instruments and samplers during their working activities.

For background discrimination (i.e., particles from sources other than the target process), a spatial approach was adopted by utilizing the FF measurements (Kuhlbusch et al., 2011).

During the workplace measurements, normal work activities were observed, and detailed notes were taken about the different actions being performed. A field measurement form was used to record this information, including details about the measurement series, contextual factors, and worker behaviours.

3.3.PARTICLE MONITORING AND SAMPLING TECHNIQUES

For the purpose of measuring the AQ, several different instruments and sampling equipment were utilized to provide a comprehensive understanding of the environment. The location and types of equipment used are shown in Figure 1 and described in detail below.

At all five locations, continuous measurements of Particle Number Concentration (PNC) were conducted in the range of 10^3 - 10^6 #/cm³ using the Miniature diffusion size classifier (DiSCmini, DM); Testo SE and Co. KGaA, Lenzkirch, Germany). This instrument reports PNC for particles ranging from 10-700 nm and identifies the dominant particle mode between 10-300 nm (Fierz et al., 2011).

At both the NF and FF locations, additional particle sizing instruments were deployed to measure the size distribution of particles, offering better accuracy than the DiSCmini. The instruments used included the NanoScan (NS; TSI NanoScan model 3091, TSI Inc., Shoreview, MN, USA), which measures particle mobility size distributions for particles from 10 to 420 nm in 13 size bins (Fonseca et al., 2016; Tritscher et al., 2013) and Optical Particle Sizers (OPS; TSI model 3330, TSI Inc., Shoreview, MN, USA) to measure the optical particle size distributions in 16 channels from 300 nm to 10 μ m (Baron & Willeke, 2001; McMurry, 2002; TSI, 2012). These instruments allowed for the derivation of size-specific PM_x (Particle Mass Concentration values, measured at a 50% cut-off point at x μ m), helping to assess the impact of the AP on size fractions that are relevant for human health and risk assessments.

In addition, real-time aethalometers (microAeth[®] model MA200, Aethlabs) were used to measure the BC concentrations. These instruments are small mobile BC aerosol monitors. They also report the fraction of biomass BC and fossil fuel BC, to aid source apportionment.

Each measuring location was also equipped with a temperature and relative humidity sensor (LITE5032, Fourtec).

For the DM, particles were sampled through transparent conductive Tygon[™] tubing (Saint Gobain Performance Plastics, Courbevoie, France) (Asbach et al., 2016), while electrically conductive silicone sampling lines were used for the other instruments.

The mobility and optical particle number size distributions measured by the NS and OPS were combined to form a wide size-range $dN/d\text{Log}(D_p)$ particle number size distribution for both NF and FF measurements. To make this combination it was assumed that a particle mobility and optical diameter were equivalent even though optical diameter may differ from mobility diameter depending on the particle shape, refractive index, and size (Pandis, 2004).

The results from these real-time measurements were indicative of the tasks and processes that resulted in high particles release. The time resolution for all instruments was set to five seconds, with

the exception of NS, which had a minimum one-minute resolution. During data processing, the values were converted to five-minute averages, as the five seconds resolution was used to have sufficient resolution to discern the events during the concurrent brake-testing experiments.

In addition to continuous measurements, the following samples were collected:

- Respirable particles (d_{50} cut size of 4 μm) for gravimetric and inorganic chemical analysis, collected using Fluoropore™ (Millipore, Billerica, MA, USA) membrane filters (25-mm PTFE with a 1.0- μm pore size), mounted in SKC cassettes and connected to portable sampling pumps (Apex2, Casella Inc., Bedford, United Kingdom) or AirCheck Touch (SKC Limited, Dorset, United Kingdom), previously calibrated at 2.5 L/min.
- Total suspended particles for EC/OC analysis, collected using Quartz filters mounted in Millipore cassettes and connected to portable sampling pumps (Apex2, Casella Inc., Bedford, United Kingdom) or AirCheck Touch (SKC Limited, Dorset, United Kingdom), operating at 1.9 L/min. EC and OC were quantified using a thermal-optical method (EUSAAR2 protocol) with transmission-based charring correction. EC was determined from the front filter, while OC was calculated by subtracting the back filter content from the front, to correct for the adsorption of semi-volatile organic compounds (SVOCs) under the assumption of equal adsorption on both filters.
- Grids for nano Particles using a naneos Partector for electrostatic deposition of particles, followed by further particle characterization using Scanning Electron Microscopy (SEM).
- Mini Particle Sampler (MPS) for collecting particles onto microscope grids for further particle characterization using SEM.

Note: Particle mass concentrations were gravimetrically determined by pre- and post-weighing the filters collected using an electronic microbalance (Mettler Toledo Model XP6) with $\pm 1 \mu\text{g}$ sensitivity, located in a climate-controlled weighing room (relative humidity (RH) = 50%, $T = 22 \text{ }^\circ\text{C}$). Three blind filters were stored to be used as laboratory blanks, correcting for handling and environmental factors.

4. RESULTS AND DISCUSSION

4.1. INSTRUMENTS INTERCOMPARISON

Before background measurements could begin, all instruments were placed at the FF location from 16:00 on May 20th until 07:00 on May 21st, 2024. This setup allowed for simultaneous measurement of the same air sample, facilitating comparison and inter-calibration between the instruments.

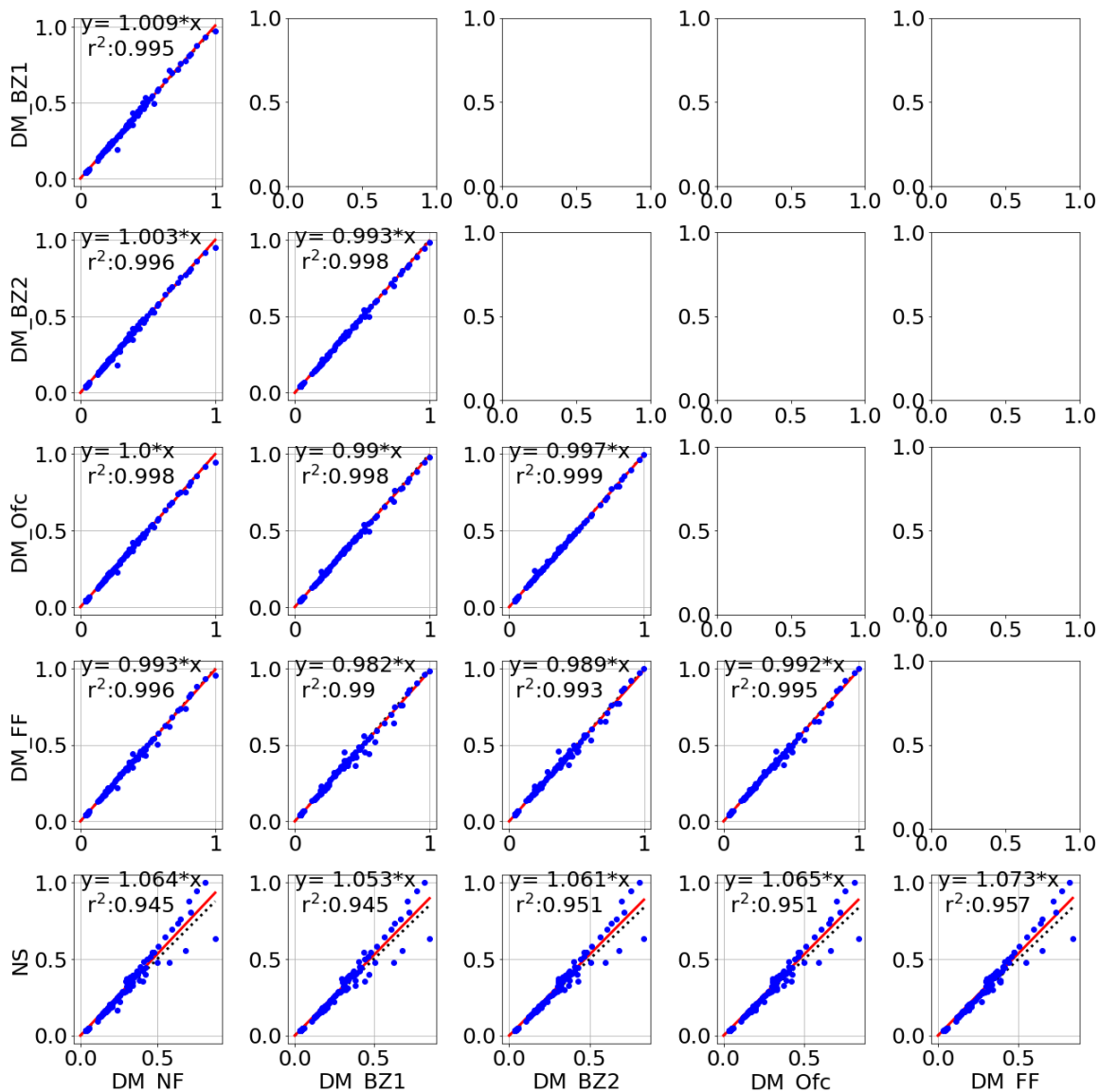


Figure 2: Correlation plots between DM units and NS, with relative axis (Source: Fonseca et al., submitted).

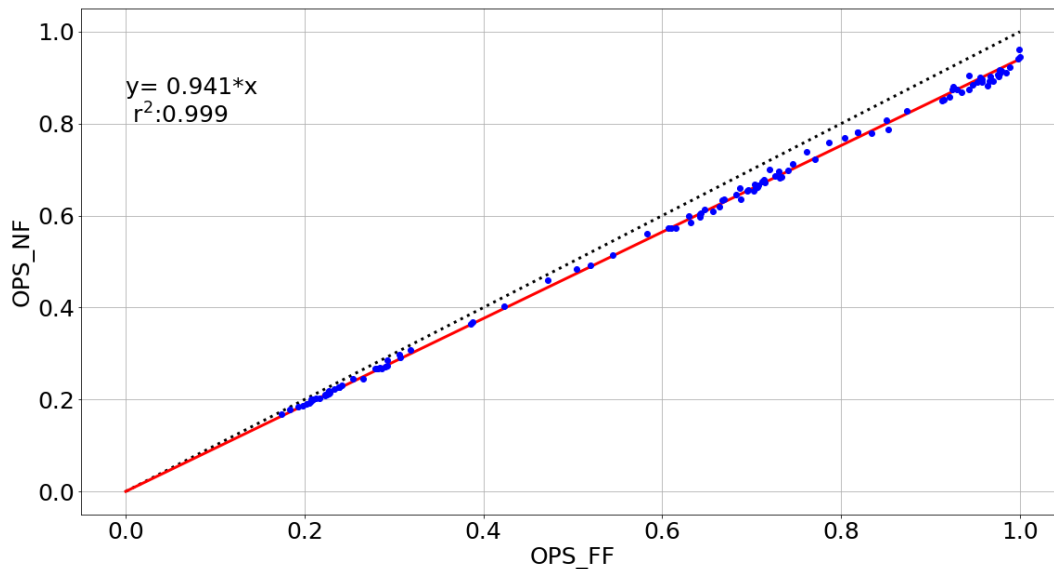


Figure 3: Correlation plot between OPS NF and FF, with relative axis (Source: Fonseca et al., submitted).

Figure 2 and Figure 3 show the calibration period results for the PNC measuring instruments (DM, NS and OPS), demonstrating a satisfactorily high level of agreement between them. Ideally, this calibration period would have been followed by another similar period at the end of the campaign to assess potential instrumental drift. However, due to logistical constraints, this was not possible. As a result, the data analysis proceeded under the assumption that any drift in the instruments' performance was negligible.

4.2. BACKGROUND MEASUREMENTS

To evaluate the impact of the APs, it was essential to measure background AQ levels. Background measurements, obtained using DM units, were conducted during two campaigns: the first in 2023 and the second from May 20th to May 31st, 2024. These measurements are presented in Figure 4, enabling a comparison of baseline AQ conditions between the two periods.

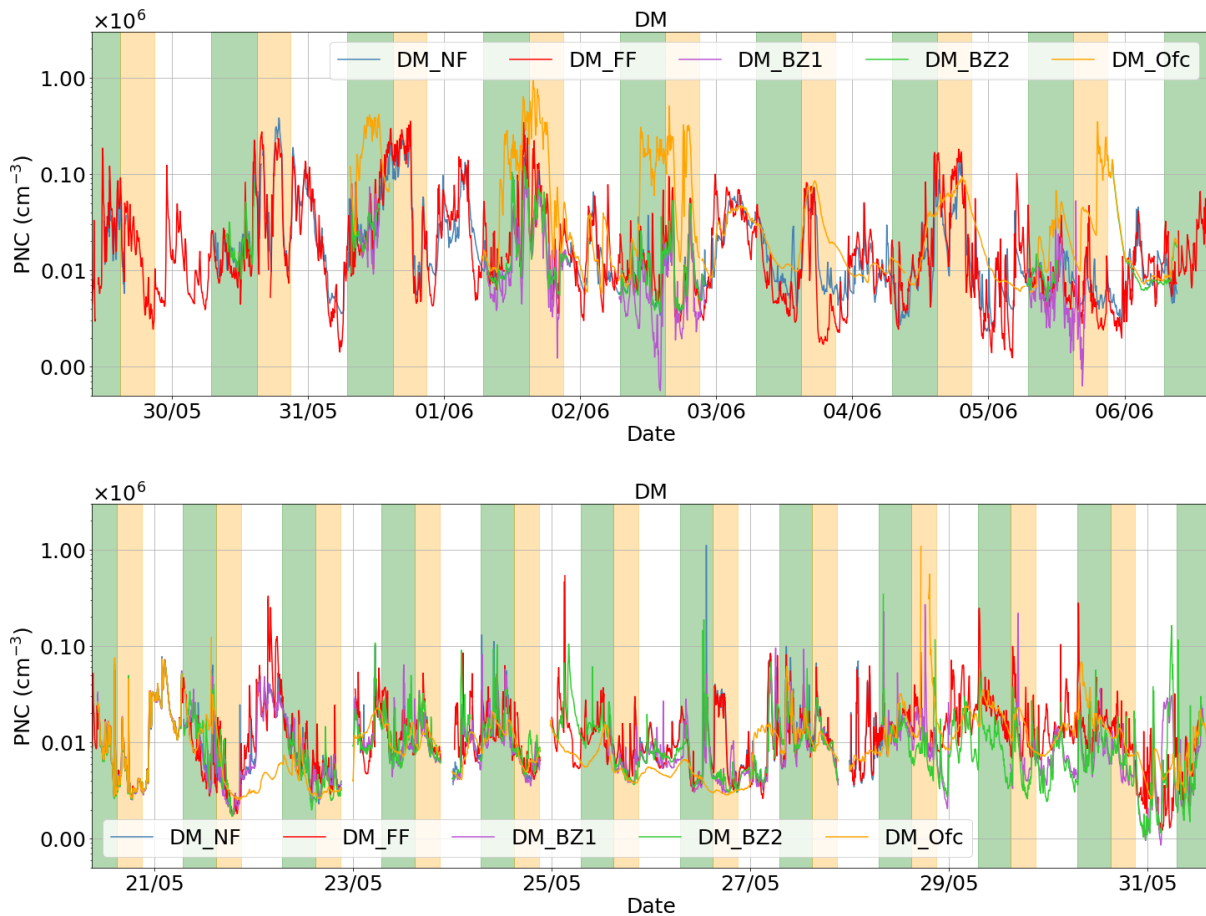


Figure 4: DiSCmini PNC data from the five locations throughout the 1st campaign (top figure) and 2nd campaign (bottom figure). The morning shift (green) and afternoon shift (yellow) are highlighted, enabling association of concentrations with specific activities (Source: modified from Fonseca et al., submitted).

Overall, a systematic variation in PNC was observed over time, with general peaks in PNC corresponding to the fluctuation in vehicle density as buses exited and returned to the depot and workshop, particularly associated with the morning and afternoon shifts. Activity is noticeable during the morning shift, with PNC levels rising around 12:00-13:00 and again around 16:00 when the afternoon shift began. Both campaigns show low levels during the latter part of the afternoon shift, correlating with a decrease in bus density in the workshop. Levels rise again as buses return to the depot around 22:00.

Comparing the daily averages for both campaigns (as shown in Figure 5), the two campaigns exhibit agreement on lung deposited surface area (LDSA) levels between 21:00 and 07:00. However, the first campaign saw substantial particle release between 12:00 and 19:00 exceeding $50 \mu\text{m}^2/\text{cm}^3$, a trend not observed during the second campaign. The office, expected to be representative of the work-area background with minimal particle emission sources, experienced unexpectedly high particle exposure during the first campaign, particularly in the offices adjacent to the electro-repair stations (Figure 4). This high PNC in the office was found to contribute to increased LDSA levels later observed in the workshop, accompanied by a noticeable odour and visible fog (Figure 5). The timing of the increase suggests that the source of the particles was likely associated with specific work activities. However,

due to the lack of a detailed work log for activities outside of the main workshop area, we were unable to attribute the particle source to any particular task carried out during the first campaign.

To better understand the potential source of this unexpected particle release, a DM was again allocated to the office during the second campaign (2024). However, no similar signs of a significant particle source were observed in 2024. The disappearance of the source between the campaigns left us unable to identify the origin. While PNC measurements in the office greatly exceeded those in the workshop during the first campaign, the office recorded the lowest PNC among all measured locations during the second campaign. Consequently, the AQ measurements from the office during the second campaign can generally be used as a reference for the cleanest AQ in comparison to the workshop. However, for the purpose of assessing AQ improvement, the FF location will be used as the reference point, as the office was only equipped with a DM.

Gravimetric PM₄ concentrations at the NF were elevated across both campaigns, reaching up to 38.5 µg/m³, particularly during high-emission tasks such as grinding and sanding. However, concentrations measured in the BZ were frequently higher than those at the NF, with a peak average of 549 µg/m³ recorded during the second campaign. This discrepancy highlights the limitation of NF measurements in capturing actual worker exposure and underscores the importance of personal exposure monitoring. Relying solely on ambient or area-based measurements may significantly underestimate exposure levels in task-intensive occupational environments (Brostrøm et al., 2025).

PM₁₀ levels recorded by the OPS units for the second campaign show higher average levels (22.6 µg/m³) compared to the first campaign (17.8 µg/m³). For both campaigns, similar daily trends were observed, with repeated peaks around 04:00 and at the start of the morning shift at 07:00 (see example of Figure 6). Additionally, a general increase post-midnight is observed which drops at around 2:00 and a daily-elevated level at 21.9 and 30.2 µg/m³ during the morning shift for the first and second campaign, respectively.

In both campaigns, while background levels were comparatively low relative to other locations, local emission events in the workshop caused significant increases in particle concentrations, at times exceeding 100 µg/m³, with particles lingering for about half an hour. As with the DM data, a clear relationship was observed between particle levels in the workshop and at the FF location.

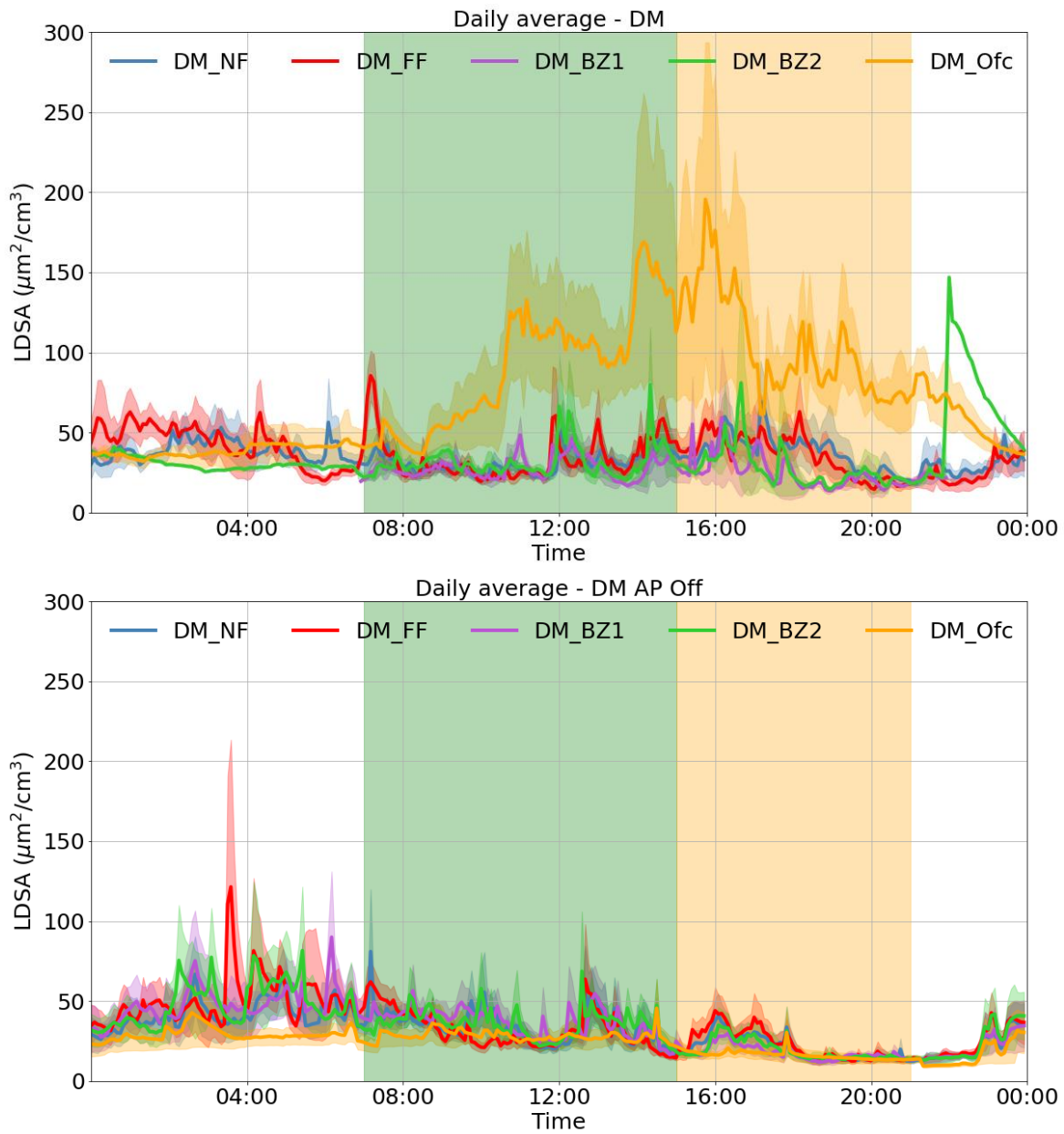


Figure 5: Daily average LDSA in $\mu\text{m}^2/\text{cm}^3$ as measured by DM, across the different days from the five locations throughout the 1st campaign (top plot) and 2nd campaign (bottom plot). The morning shift (green) and afternoon shift (yellow) are highlighted.

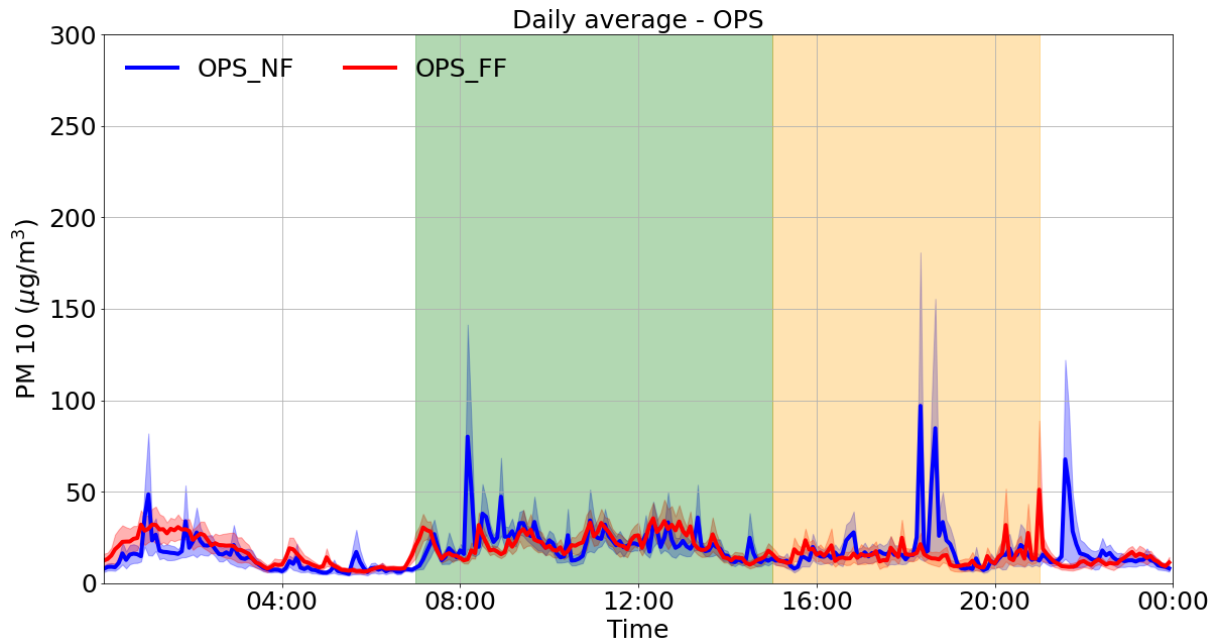


Figure 6: Daily average PM_{10} levels for the two OPS units at NF (blue) and FF (red) throughout the 1st campaign. The morning shift (green) and afternoon shift (yellow) are highlighted.

4.3.DETERMINING THE EFFECT OF AIR PURIFIERS

With the introduction of four APs within the workshop, we observed a reduction in the decay time of observed emission events. This reduction corresponded to an increase in the air exchange rate, from 2-3 times per hour before the APs were turned on, to 4 times per hour after their activation.

Due to significant daily variation in the timing and size of local emission events during the shifts, it became apparent that the best approach was to compare measurements within the workshop to simultaneous measurements at the FF location. This approach was justified by the close correlation between particle levels measured at the workshop and FF, as described above.

As shown in Figure 7, the total PNC as measured by NS and DM at NF and FF were in agreement (close to a ratio of 1) before the APs were turned on. The FF typically showed a slightly higher PNC, as expected, due to the broader particle size range measured. With the AP activated, the correlation decreases, as the FF sees relatively more particles than at NF. It is however problematic to assign this effect to a decrease in NF concentrations, as comparison between the locations before and after turning on the AP, shows that the PNC measured at NF are identical, while the FF values increased between the two periods. Additionally the NS data spans two days during with the AP on, limiting the comparisons.

For a more representative comparison, we focus on the DM data, as shown in Figure 8. The median PNC levels at different locations (NF, FF, BZ1, BZ2, and the office) were in close agreement for background levels before the APs were turned on. However, with the APs operating, a reduction in PNC was observed within the workshop, particularly relative to FF and office locations.

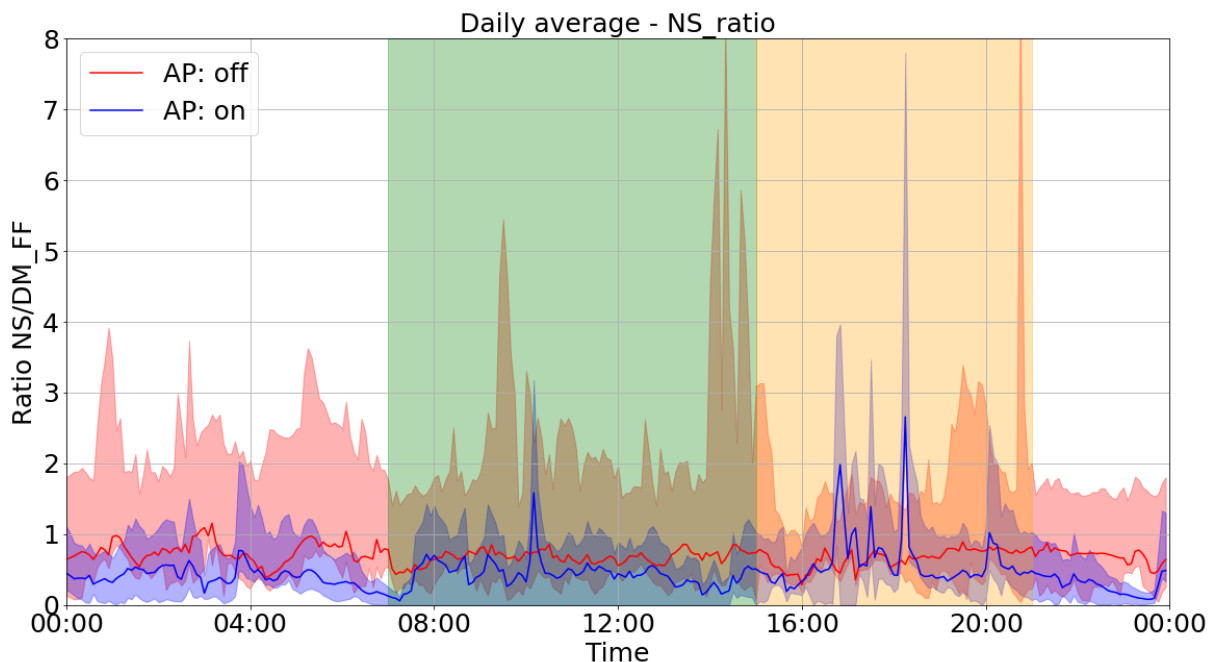


Figure 7: Median ratio between measured total particle number at NF (NS) and FF (DM). The red line represents the ratio before the APs were turned on, while the blue line represents the ratio during the period with the APs activated. The morning shift (green) and afternoon shift (yellow) have been highlighted.

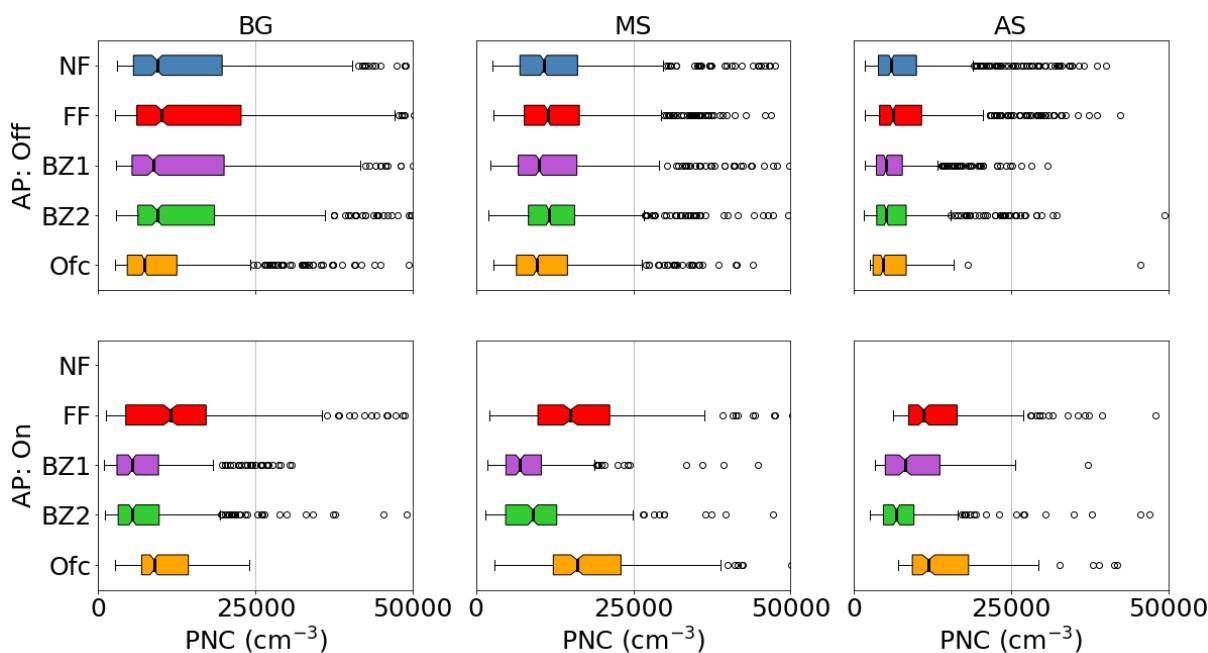


Figure 8: Plot of the effect of air purifiers on particles smaller than $0.7 \mu\text{m}$. The top row represents the median PNC during the period with APs off, while the second row shows the median PNC during the period with APs on. The plots display the 1st, 2nd, and 3rd quartiles for the three shifts at the five locations (Source: modified from Fonseca et al., submitted).

From the data presented in Table 2, we can observe that the ratio between BZ1/BZ2 and FF for background measurements was around $89\% \pm 7\%$ before the APs were turned on. However, this ratio

decreased to $56\% \pm 11\%$ with the APs active, indicating an average reduction of $37\% \pm 13\%$ in the PNC of particles smaller than 700 nm.

Table 2: Median total PNC values as measured by DM for the second campaign. The columns represent shifts, locations, and values for the period with the AP off and on, including the median value, the first and third quartiles (Q1/Q3), and the ratio between location/FF for each shift. Nan indicates unavailable data; MS: morning shift; AS: afternoon shift; Ofc: office. (Source: Fonseca et al., submitted).

PNC BY DM		AP: OFF			AP: ON		
Shift	Location	Median ($10^3/\text{cm}^3$)	Q1/Q3 ($10^3/\text{cm}^3$)	Location/F F (%)	Median ($10^3/\text{cm}^3$)	Q1 / Q3 ($10^3/\text{cm}^3$)	Location /FF (%)
BG	FF	10.1	-4.0/+13	-	11.4	-7.1/+5.7	
	NF	9.3	-3.7/+10	93%	nan	nan	nan
	BZ1	8.7	-3.3/+11	86%	5.4	-2.4/+4.2	47%
	BZ2	9.3	-3/+9.1	92%	5.4	-2.3/+4.2	48%
	Ofc	7.3	-2.7/+5.1	73%	8.8	-1.9/+5.5	77%
MS	FF	11.4	-3.7/+5.1	-	15.0	-5.2/+6.2	
	NF	10.8	-3.8/+5.4	95%	nan	nan	nan
	BZ1	10.1	-3.3/+6.0	88%	7.0	-2.2/+3.4	47%
	BZ2	11.6	-3.2/+4.1	102%	9.0	-4.3/+3.8	60%
	Ofc	9.6	-3.2/+4.9	84%	16.1	-3.8/+7.0	107%
AS	FF	6.3	-2.1/+4.6	-	11.2	-2.4/+5.3	
	NF	6.0	-2.1/+4.0	96%	nan	nan	nan
	BZ1	5.1	-1.5/+2.7	81%	8.2	-3.1/+5.6	73%
	BZ2	5.2	-1.5/+3.2	83%	6.8	-2.1/+2.8	61%
	Ofc	4.7	-1.6/+3.7	75%	11.9	-2.6/+6.4	107%

Similarly, we can compare the values for LDSA, as shown in Table 3. The ratio for BZ1 and BZ2 compared to FF is around $102\% \pm 7\%$, while the AP ratio is $61\% \pm 12\%$. This gives us an average reduction in LDSA of $41\% \pm 12\%$ when the AP is on.

Table 3: Median LDSA values as measured by DM for the second campaign. The columns represent shifts, locations, and values for the period with the AP off and on, including the median value, the first and third quartiles (Q1/Q3), and the ratio between location/FF for each shift. Nan indicates unavailable data; MS: morning shift; AS: afternoon shift; Ofc: office. (Source:Fonseca et al., submitted).

LDSA BY DM		AP: OFF			AP: ON		
Shift	Location	Median ($\mu\text{m}^2/\text{cm}^3$)	Q1/Q3 ($\mu\text{m}^2/\text{cm}^3$)	Location/ FF (%)	Median ($\mu\text{m}^2/\text{cm}^3$)	Q1 / Q3 ($\mu\text{m}^2/\text{cm}^3$)	Locatio n/FF (%)
BG	FF	25.6	-9.3/+28		30.1	-20.5/+14	
	NF	24.0	-8.5/+27	94%	nan	nan	nan
	BZ1	25.5	-9.5/+33	99%	15.6	-7.0/+8.1	52%
	BZ2	26.6	-10/+25	104%	14.5	-5.6/+10	48%
	Ofc	18.6	-5.9/+13	73%	23.3	-7.2/+12	77%
MS	FF	27.0	-8.1/+11		35.9	-12/+20	
	NF	27.0	-9.0/+14	100%	nan	nan	nan
	BZ1	28.7	-9.4/+16	106%	19.1	-5.0/+10	53%
	BZ2	30.5	-8.8/+12	113%	24.1	-10.4/+12	67%
	Ofc	22.4	-7.6/+13	83%	39.4	-12/+25	110%
AS	FF	14.7	-4.4/+10		29.5	-7.0/+16	
	NF	14.3	-4.0/+8.5	97%	nan	nan	nan
	BZ1	13.7	-3.1/+7.5	93%	23.4	-8.5/+17	79%
	BZ2	14.2	-3.6/+8.3	96%	19.0	-5.4/+8	64%
	Ofc	12.3	-3.8/+10	84%	30.2	-4.5/+10	102%

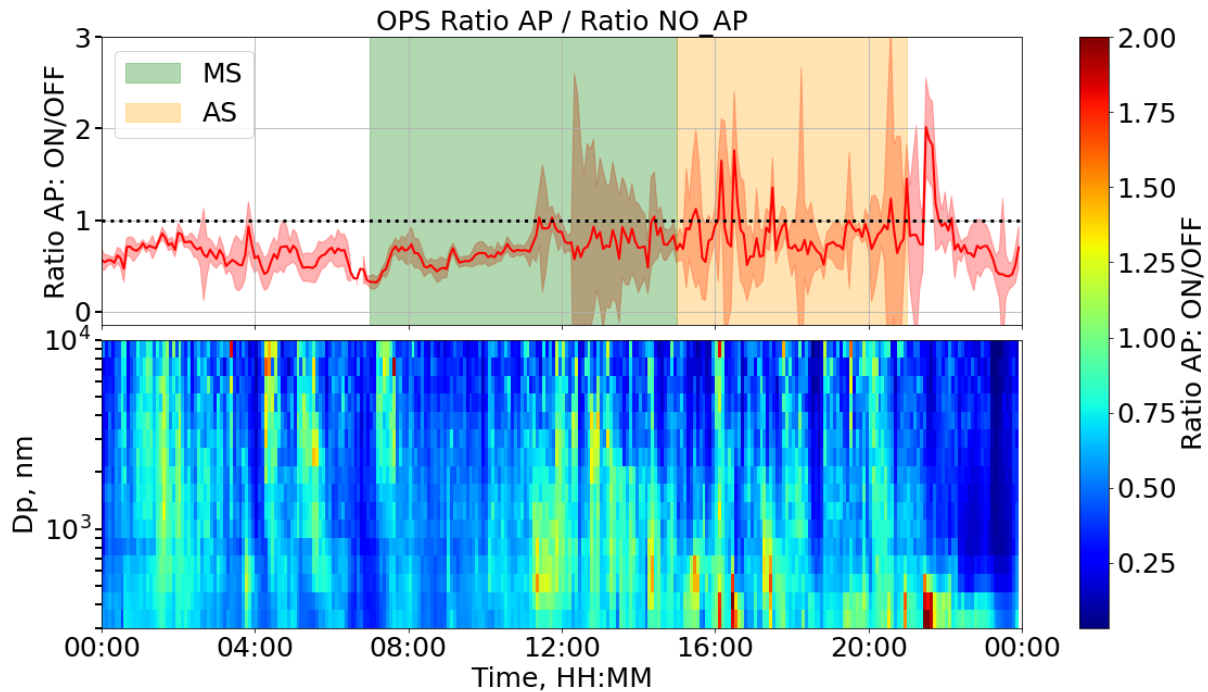


Figure 9: Plot showing the ratio of time with and without air purifiers for the ratios between NF and FF OPS. The total ratio is shown in the top graph, with a highlight at 1 to indicate the degree of removal. The morning shift (green) and afternoon shift (yellow) are highlighted.

Prior to the AP being activated, the measurements at FF and NF are nearly identical. However, once the AP is turned on, there is a noticeable reduction in the NF compared to the FF. Further investigation, comparing the NF/FF ratio with and without the AP, reveals a daily average, as shown in Figure 9. This comparison includes the total PNC and the heat map of ratios for different particle size bins. The majority of the values are below one, indicating removal of particles, although unaccounted emission events during the AP operation result in a median ratio above one in some cases.

Table 4: Median PM_x values as measured by the OPS for the second campaign. The columns represent shifts, locations, and PM values for the period with the AP off and on, including the median value, the first and third quartiles (Q1/Q3), and the ratio between NF/FF for each shift. Nan indicates unavailable data; MS: morning shift; AS: afternoon shift. (Source: Fonseca et al., submitted).

		$PM_{2.5}$			PM_4			PM_{10}		
Shift	Location	Median ($\mu\text{g}/\text{m}^3$)	Q1 / Q3 ($\mu\text{g}/\text{m}^3$)	NF/FF (%)	Median ($\mu\text{g}/\text{m}^3$)	Q1 / Q3 ($\mu\text{g}/\text{m}^3$)	NF/FF (%)	Median ($\mu\text{g}/\text{m}^3$)	Q1 / Q3 ($\mu\text{g}/\text{m}^3$)	NF/FF (%)
AP: Off										
BG	FF	2.8	-0.8/+0.7	98%	5.3	-1.5/+2	94%	13	-5/+7	100%
	NF	2.7	-0.5/+1.1		5.0	-1.3/+3		13	-5/+10	
MS	FF	2.9	-0.8/+0.9	100%	5.9	-1.7/+2	98%	18	-6/+10	112%
	NF	2.9	-0.7/+0.9		5.7	-1.4/+2		20	-6/+11	

AS	FF	1.6	-0.3/+0.6	97%	3.0	-0.8/+1.7	92%	9.2	-3/+9	99%
	NF	1.5	-0.3/+0.6		2.7	-0.8/+1.7		9.14	-4/+6	
AP: On										
BG	FF	2.5	-0.9/+0.7	46%	4.9	-1.4/+2	46%	15	-5/+9	50%
	NF	1.1	-0.3/+0.8		2.2	-0.7/+1.8		7.2	-3/+6	
MS	FF	3.3	-0.6/+0.8	65%	6.9	-1.8/+3	57%	22	-7/+14	54%
	NF	2.1	-0.7/+0.4		4.0	-1.3/+1.2		12	-4/+5	
AS	FF	1.8	-0.5/+1	61%	4.3	-1.2/+2	51%	16	-6/+9	43%
	NF	1.1	-0.2/+0.7		2.2	-0.6/+1.2		7.0	-2/+5	

Table 4 illustrates the data, where it is clear that $PM_{2.5}$, PM_{4} , and PM_{10} experience a mass reduction of 37%, 46%, and 52%, respectively, during working shift hours. This reduction suggests a beneficial impact on worker health by lowering exposure to harmful particulate matter. Decreasing the concentration of fine particles can reduce respiratory risks, including asthma, bronchitis, and cardiovascular diseases, by preventing the deeper penetration of particles into the lungs and bloodstream (Pope & Dockery, 2006; Schraufnagel, 2020; Xing et al., 2016). Additionally, reduced exposure to PM_{4} and PM_{10} can mitigate respiratory irritation and inflammation, lowering the risk of chronic lung diseases and even lung cancer (Kyung & Jeong, 2020; Marín-Palma et al., 2024). Long-term reductions in particulate exposure have been linked to improved cardiovascular health and fewer sick days, ultimately increasing worker productivity (Mak et al., 2024). While the health benefits are considerable, the overall effectiveness of the reduction will depend on whether the remaining exposure levels remain within safe limits, as outlined by occupational exposure guidelines.

The final aspect of the OPS data involves calculating the removal efficiency based on size-bin ratios. **Fehler! Verweisquelle konnte nicht gefunden werden.** The minimum removal efficiency (26%) occurs in the 300-500 nm range, with values increasing from 40% at 1 μm to 50% at 10 μm . This finding aligns well with the results from the DM units for particles below 700 nm, where the average removal efficiency was approximately 37%.

4.4. BLACK CARBON MEASUREMENTS

BC is a critical component for assessing health risks, making its measurement essential. Using aethalometers, we analysed BC levels in different areas.

BC concentrations in the workshop (NF) were consistently higher than those in the depot area (FF) across most of the day, with mean values reaching 2.0 $\mu g/m^3$ during the morning shift. These levels are indicative of diesel engine-related emissions, particularly from tasks involving combustion engines. However, occasional BC peaks at FF exceeded those at NF, suggesting episodic external sources, such as the arrival and prolonged idling of diesel buses near the FF zone.

During the period with the AP activated, a potential reduction in BC levels is observed during the first three hours of the morning shift. Median daily BC concentrations decreased from 1.3 \pm 0.5 $\mu g/m^3$ to 0.9 \pm 0.3 $\mu g/m^3$ at NF, and from 0.8 \pm 0.3 $\mu g/m^3$ to 0.7 \pm 0.3 $\mu g/m^3$ at FF. This represents an estimated reduction of ~22% at NF. This reduction in BC was relatively small compared to those observed for PNC

and PM, indicating that APs may be less efficient at removing combustion-related UFPs. However, this effect falls within the range of natural daily variability and is further obfuscated by suspected malfunction of the NF aethalometer, introducing significant uncertainty into the measurements.

4.5. EC/OC ANALYSIS

To further evaluate the impact of APs on combustion-related aerosols, OC and EC concentrations were determined from the collected filters. Before AP activation, OC concentrations reached $26.7 \pm 1.3 \mu\text{g}/\text{m}^3$ in the BZ and $31.9 \pm 1.6 \mu\text{g}/\text{m}^3$ at the FF. EC concentrations were $5.4 \pm 0.8 \mu\text{g}/\text{m}^3$ in the BZ and $6.6 \pm 1.0 \mu\text{g}/\text{m}^3$ at the FF. Following AP activation, OC remained relatively stable in the BZ ($28.0 \pm 1.4 \mu\text{g}/\text{m}^3$), while EC concentrations decreased to $1.9 \pm 1.6 \mu\text{g}/\text{m}^3$ in the BZ and $4.2 \pm 0.7 \mu\text{g}/\text{m}^3$ at the FF, representing an approximate 56% reduction in the BZ.

In occupational exposure monitoring, EC and BC are both used as indicators of diesel particle emissions but reflect different measurement techniques. EC was determined via filter-based sampling, which captures a broader particle size range, whereas BC was measured using aethalometers equipped with a $\text{PM}_{2.5}$ cyclone, excluding larger particles, partly explaining differences in response to AP operation.

These findings suggest that APs were more effective at reducing EC, and thus combustion-derived particulates, especially near emission sources. In contrast, OC levels remained largely unaffected, likely due to ongoing emissions of semi-volatile organic compounds (SVOCs) and continuous activity within the workshop. Overall, this highlights the partial effectiveness of APs in mitigating occupational exposure to carbonaceous aerosols, with efficiency influenced by both particle composition and spatial proximity to sources.

4.6. WATER QUALITY

The effect of air pollution on water quality has been a matter of concern for decades as the deposition of air pollutants, most notably particulate matter, is a leading source of aqueous contamination. Current estimates identify water stress as already affecting 20% of Europe's territory and 30% of the population every year, and well over half of surface water bodies are failing to achieve an acceptable (i.e. at least "good") ecological status, figures that are likely to increase in the future due to climate change (EEA, 2024). The most common contaminant pressure on surface waters is that linked to pollution from diffuse atmospheric sources (52%: Figure 10).

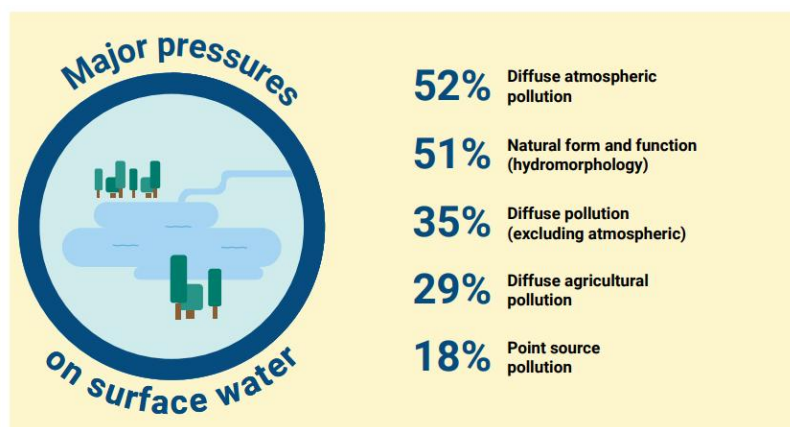


Figure 10: Major pressures on surface water quality. Source: European Environment Agency 2024. Europe's state of water 2024: The need for improved water resilience. EEA Report 07/2024.

Therefore, there is a clear overall need to reduce the use of potential harmful contaminants to improve the quality status of water and thus minimise the danger to people and the environment. It should also be considered that once in the aquatic environment, previously airborne pollutants can be difficult to remove and will be transported downstream and into the coastal and marine environment. Although many case studies exist regarding the general of pollutants on air quality, no study could be identified that explicitly addresses how a reduction in air pollutants might lead to the improvement of local water quality.

From a broad perspective air pollutants with a substantial effect on water quality include trace metals, nutrients, toxic organic compounds, and airborne acids. More specifically the pollutants causing the most damage to chemical status in surface waters are mercury and brominated flame retardants (BFRs) (each responsible for 49% of surface waters failing to reach an acceptable category of cleanliness), followed by polycyclic aromatic hydrocarbons (PAHs), and more recently polyfluoroalkyl substances (PFAS), which are harmful to human health and are being found to be widespread wherever they have been investigated. In addition, a large range of other metals, biocides, plastics and pharmaceuticals, can be found in urban wastewater and urban run-off. Given the ongoing impact of climate change on European weather patterns, managing the impact of more frequent heavy rainfall on stormwater overflows and polluted run-off from urban areas will become increasingly necessary.

Given this need to address any potential impact of air pollutant release on local wastewater quality, we have considered this as a part of our study of the AUVASA bus depot where AeroSolfd AQ measurements were carried out. The bus depot may be taken as broadly typical of such premises where buses are serviced and parked after the daily operation, including as it does several facility areas that cover the maintenance tasks needed to operate a fleet of buses. Thus, the main elements of AUVASA bus depot include:

- parking bays for buses
- washing rooms
- body/paint shop
- open-air parking
- entry and exit

Auvasa Bus Depot

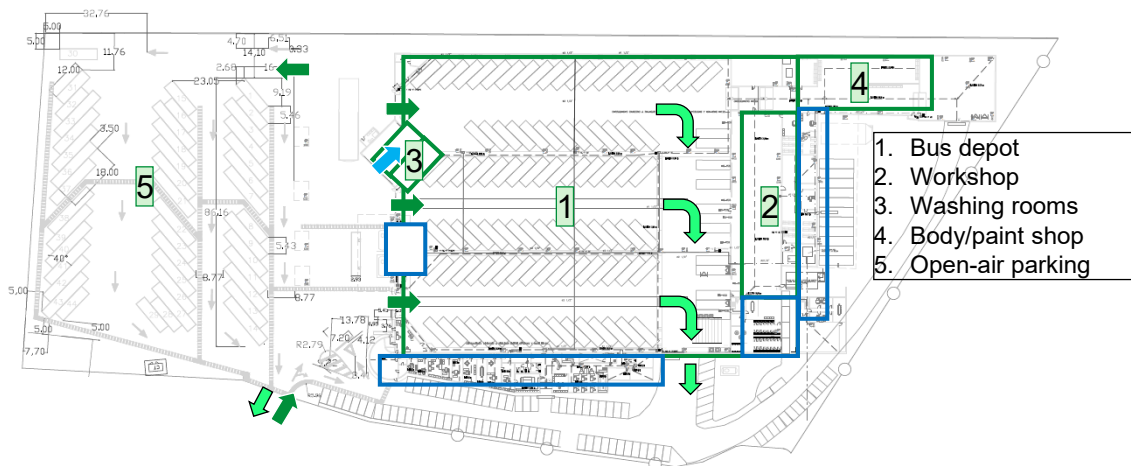


Figure 11: AUVASA bus depot layout. Air quality measurements were conducted inside the bus depot parking area (number 1).

Within this workshop transport microenvironment there is very limited use of water inside the covered bus depot parking area (number 1 in Figure 11). Any direct influence of the improvements on air quality identified during the different setups developed within AeroSolfd on the local water quality is therefore likely to be minimal. Based on the tasks performed in the depot, the only area where significant amounts of water are used is the washing rooms (number 3 in Figure 11) where buses are cleaned. Such areas within bus depots are commonly characterised by a general lack of water management protocols leading to poorly controlled wastewater generation and discharge (Corazza & Robinson, 2024). However, in the case of the AUVASA bus depot, the washing rooms do not leach water into the main parking area where the air measurements were done (number 1 in Figure 11) and therefore are not relevant to our AQ study.

5. DEVIATIONS FROM THE PLAN

The original plan was to equip the NF and FF measurement locations with identical instruments to enable a comprehensive comparison. However, upon initiating the measurements, it was discovered that one of the two NS was non-operational. Despite efforts to restore functionality, the issue could not be resolved. Consequently, the single available NS was allocated to the NF site. As a result, particle number size distribution data below 300 nm could only be collected at NF by one NS. This restricted NF and FF comparisons for this size range, although total PNC data below 700 nm were still available at FF from the DiSCmini, allowing for partial comparisons.

Further challenges arose during the AP activated, when both the DiSCmini and NanoScan at NF experienced technical issues. Consequently, data for sub-300 nm particles during this period were limited to two valid measurement days. Although this narrowed the dataset for one particle fraction, filter samplers and key instruments such as the OPS and additional DMs remained fully operational across all locations, ensuring robust multi-metric coverage during this critical period. These

instruments captured PNC and mass-based PM metrics across a wide size range, supporting a reliable assessment of AP performance.

Another technical deviation was identified post-campaign during data quality checks of the NF aethalometer. The instrument failed to reliably detect low BC concentrations and was unable to differentiate size-resolved BC fractions, likely due to a hardware malfunction. This adds uncertainty to the BC data at NF, particularly under low-emission conditions. However, this issue does not compromise the study's conclusions, as BC trends were supported by well-functioning aethalometers at FF and complemented by filter-based EC/OC analysis.

Lastly, an internal miscommunication within NFA, related to the finalization of legal agreements for data sharing, caused a delay in transferring datasets between relevant groups, pushing the data analysis timeline back to mid-November 2024.

In summary, while minor deviations occurred due to equipment failure and logistical delays, the overall integrity of the dataset and validity of the conclusions remain intact, owing to redundant measurements, complementary data sources, and comprehensive cross-validation across instruments and particle metrics.

6. LINKS WITH OTHER WPS

The assessment of the air purifiers performance contributes directly to WP4 on the following deliverables:

- D4.2: Database for LCA and Sustainability Assessment (M34)
- D4.4: LCA assessment for each product line (M35)
- D4.5: Overall sustainability assessment (M36)

The findings provide critical input for evaluating the environmental and sustainability impacts of implemented measures.

7. CONCLUSIONS AND RECOMMENDATIONS

This deliverable addresses Task 3.4 and evaluates the impact of retrofitted APs on workers' health, AQ improvements, and potential water quality effects within the AUVASA bus depot in Valladolid, Spain. By comparing AQ measurements before and during the deployment of APs during two campaigns, the study demonstrates the significant potential of APs to reduce particulate matter levels and improve the indoor environment in semi-enclosed work settings. The findings underscore the importance of enhanced air purification for worker health while identifying areas for further research. Although the study also explored possible links between air and water quality improvements, the latter was deemed less relevant for the closed demo-site. Future actions are recommended to expand AP evaluation and apply the findings to similar transport-related environments.

Key findings include:



- AQ inside the workshop was comparable to the depot area and similar to results from the first campaign. Both areas were subject to frequent transient peaks in air pollutants, likely influenced by workshop activities.
- During the first campaign, unexpectedly poor AQ was observed in the office, a location expected to have the best AQ. However, this issue was not detected during the second campaign, suggesting improvements in this space.
- Daily AQ as measured by PM₁₀ was usually worse at the start of the working day soon after 07:00, when a “rush hour” peak was common, and reached an average level of 30 µg/m³ lasting the morning shift and can be lower than average during the night/early morning, as the release of particle mass is mostly associated with workshop activity.
- As the optimal running conditions for the AP was determined in previous work, four AP was placed within the workshop and turned on for four days. This increased the effective air-exchange rate from 2-3 times per hour to 4 times per hour.
- The effect of introducing the AP was an observed drop of 37% for particles below 700 nm, and reduction in PM_{2.5}, 4 and 10 of 37, 46 and 52 %.
- No effect on BC could be discerned from the variation measured. However, complementary filter-based EC/OC analysis revealed a notable decrease in EC up to 56% in the breathing zone, following AP activation. This indicates that APs were effective at reducing combustion-related particles, particularly in proximity to emission sources. In contrast, OC levels remained stable, likely due to ongoing SVOC emissions from workshop processes.
- The assessment of positive effect on the water quality was limited as the air within the workshop was not in significant contact with water, and therefore not relevant to this study.
- The effective removal factor is dependent on the number of AP-units and further improvement in AQ could be possible with an increased number of units.

It is recommended to continue evaluating the long-term efficiency of APsto better quantify pollution reduction and link improvements to specific pollutants. Further investigation into the scalability of AP deployment in other semi-enclosed work environments is essential to replicate and validate the findings. Additionally, exploring supplementary strategies to mitigate transient pollutant peaks, particularly during high-activity periods in workshops, will enhance the overall effectiveness of these interventions.

The findings of this deliverable offer a valuable framework for improving AQ and protect workers' health in similar occupational settings.

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