Atmospheric Pollution Research 14 (2023) 101680

Contents lists available at ScienceDirect

Atmospheric Pollution Research

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

A methodology to assess a mobile urban street cleaning activity

Andrea Brunelli [a,*], Silvia Breda [b], Petra Scanferla [b], Loris Calgaro [a], Antonio Marcomini [a], Elena Badetti [a,**]

[a] DAIS - Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Via Torino 155, 30170, Venice, Italy
[b] Fondazione Università Ca' Foscari Venezia, Venice, Italy

ARTICLE INFO

Keywords:
Urban street cleaning
Leaf blower
Mobile sampling
Human exposure
Dust wave effect

ABSTRACT

An experimental methodology to assess the human exposure of a street cleaning service, performed by a worker handling a leaf blower followed by a water-flushing sweeper, was developed. The sampling campaign was achieved by considering data from road dust, personal air sampling and portable particulate matter detector. The experimental design allowed to obtain qualitative and quantitative information on the chemical composition of road dust, the size and chemical composition of potentially inhalable particles suspended during the street cleaning activity, as well as the duration of the particles' suspension effect. The methodology employed showed: i) the compliance with the occupational exposure threshold values for the total inhalable dust and with the occupational exposure limit values according to national and international regulatory approaches for polycyclic aromatic hydrocarbons (PAH) and inorganic elements; ii) a good agreement of the metals concentrations from the road dust (i.e., calcium, magnesium, potassium, iron, aluminium and sodium) with those from the material collected by the personal air sampler, highlighting the negligible effect of the investigated sweeping activity compared to the material already present on the road; iii) a similar pattern of inorganic elements within the three different monitoring areas; iv) a "dust wave" effect detected by the particle counter lasting no more than 2 min. Thus, such information suggested that performing the urban sweeping activity in the early mornings, when there is a general low PM_{10}-$PM_{2.5}$ average concentration, low traffic intensity, and the almost absence of passers-by, lead to a low probability of citizens' exposure.

1. Introduction

Outdoor and indoor air pollution are environmental risk factors that have been linked to several health conditions including cardiovascular illness, stroke, respiratory disease, and cancer, leading to approximately 7 million deaths globally in 2016 (WHO, 2021). The European Environmental Agency (EEA) has estimated that, in Italy, more than 50 thousand premature deaths in 2014 may be attributable to long-term exposure to particulate matter (PM, either in solid or liquid state) suspended in the atmosphere with different average aerodynamic diameter (i.e., $\phi \leq 10$ μm (PM_{10}), $\phi \leq 2.5$ μm ($PM_{2.5}$) and $\phi \leq 1$ μm (PM_1)). Furthermore, the EEA also reported more than 17 thousand deaths could be related to NO_2 exposure and roughly 3 thousand to O_3 (ISPRA, 2017). Road traffic is one of the main sources which contributes to outdoor air pollution, which includes both exhaust emissions from combustion processes and non-exhaust sources, such as the wear of tires, suspensions, brakes (pads and discs), road surface and the re-suspension of road dust (RD) (Valotto et al., 2015).

The literature indicates that non-exhaust particles from road transport can be as hazardous as exhaust PM, depending on particle mass, size, and surface chemistry (Padoan and Amato, 2018). The nature and composition of RD is expected to vary widely mostly based on local climate, geology, population, and traffic density (Amato et al., 2016). For example, during the cold season, maintenance sand or road salt are a source of primary granular material and can contribute to RD through mechanical abrasion of the road surface.

Given this context, a comprehensive management of urban pollution should focus not only on exhaust emissions, which are the main focus of most regulatory and control measures, worldwide, but also on non-exhaust emissions, which are largely unregulated. The Organization

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.
* Corresponding author.
** Corresponding author.
E-mail addresses: andrea.brunelli@unive.it (A. Brunelli), elena.badetti@unive.it (E. Badetti).

https://doi.org/10.1016/j.apr.2023.101680
Received 13 September 2022; Received in revised form 6 February 2023; Accepted 6 February 2023
Available online 7 February 2023

for Economic Co-operation and Development (OECD) recently stated that non-exhaust emissions are expected to be responsible for the vast majority of PM emissions from road traffic in future years, considering the increases in the demand for urban passenger travel, which is projected to more than double by 2050 (OECD, 2020).

Policies and investments supporting cleaner transport, energy-efficient homes, power generation, industry, and better municipal waste management would reduce key sources of outdoor air pollution (WHO, 2018). These actions are urgently needed considering the rapid growth of megacity populations and that roughly 68% of the global population is expected to live in urban areas by 2050 (United Nations, 2018). In this sense, along with prevention actions (e.g., paving unpaved lots, covering truck loads, incentivizing sustainable mobility, and boosting public transports), mitigation strategies to reduce the resuspension of RD from urban roads should also be included in the air pollution management plans for urban areas.

Street cleaning activities are usually accomplished worldwide for both human health and environmental protections (e.g., for air quality and stormwater management) as well as for aesthetic purposes. In the past, these activities were performed manually, using a broom, a shovel, and a wheelie bin. Nowadays, the most common cleaning tools are mechanical brooms, vacuum sweepers, leaf blowers, and regenerative air sweepers, allowing to obtain clean streets with higher efficiency and to overcome numerous street obstacles such as bollards, trees, or cars (Calvillo et al., 2015). As already reported in the literature (Horwatich and Bannerman, 2009; Pitt et al., 2005), pollution retention capacity of pavements, which highly depends on surface materials, pavement structures, laying slope and rainfall intensity, decreases with increasing days since the last draining event. Therefore, when the storage capability of the street surface decreases, PM is more easily resuspended and dispersed, increasing the risk for human health. However, it has been reported that this street cleaning approach could also generate exhaust emissions, resuspension RD, and high noise levels (Air Resources Board, 2000; Fitz and Bumiller, 2000), becoming an issue for both employees and citizens encountering street cleaning (van Kampen et al., 2020). Recently, many efforts have been devoted to preventing the resuspension of PM in the atmosphere during this process. A report of the AIRUSE-LIFE + project (AIRUSE, 2013) includes a list of studies from 1990 to 2012 that investigated air quality efficiency of sweeping, washing and combinations of both approaches. In general, based on this literature analysis, the authors suggested that the best approach for both sediment removal from the streets and PM reduction would be a combination of sweeping and water flushing, to be performed in the early morning hours (5–6 AM). The authors of the AIRUSE-LIFE + report also suggested that the positive results obtained by the sweeping-water flushing combo could be ascribed to the surface wetting that inhibits resuspension, rather than to the actual removal of particles. This indicates that the effectiveness of the street cleaning service highly depends on local parameters (meteoclimatic conditions, traffic dynamics and intensity, street surface, mixing layer height etc.).

For these reasons and due to the lack of a standard methodological approach suitable to assess the potential adverse effects from street cleaning activities directly on air quality and human health, data supporting the identification of best practices to properly manage cities hygiene are still scarce.

In this context, this work aims at estimating the potential exposure to mechanised road sweeping activities – which consists in a motor water-flushing sweeper and electric leaf blower - on potential pedestrians passing nearby the sweeping service. The study was designed to investigate the worst-case scenario in terms of human exposure, by simulating at least 60 min exposure of a person in close contact with the leaf blower and the water-flushing sweeper and without personal protective equipment (PPE). To achieve this goal, an *ad hoc* monitoring sampling campaign has been designed to collect information about i) the particles potentially resuspendable due to cleaning activities ii) the particles potentially inhalable by the operator using the blower and by citizens close to the cleaning activities, in terms of chemical composition and particle size; and iii) the duration of the particles' suspension effect generated by the cleaning activity investigated. The main novelty of this work lies in performing an outdoor air monitoring campaign by following a mobile urban street cleaning service. This required to combine different sampling approaches and to find the optimal conditions to collect a sufficient amount of sample in a shorter time than stationary air monitoring samplers.

2. Materials and methods

2.1. Sampling strategy

2.1.1. Sampling area identification

This study was carried out within the county of Treviso, the 14th most densely populated county in Italy with more than 875 thousand inhabitants. It is located within the Veneto region, in the eastern part of the Po Valley, a zone where European air-quality limit values are often exceeded, mainly due to a combination of anthropogenic stressors (e.g., vehicular traffic, industrial activities, power plants, and heating), and orographic and meteorological factors. The Alpine mountain range influences indeed the wind regime, by which the intensity is generally low, making this area of high atmospheric stability. Under these conditions, and especially during the cold season, thermal inversion occurs, and the temperature of the atmospheric layer increases with the altitude, thus preventing the dispersion of pollutants in the vertical layer of the atmosphere (Raffaelli et al., 2020).

The sampling area of the monitoring campaign carried out in this study had been identified after collecting and analysing air quality (both PM_{10} and $PM_{2.5}$ trends) and meteorological data (mean temperature, rain, relative humidity, wind speed, and global radiation), provided by the local environmental protection agency (Veneto Agency for the Prevention and Protection of the Environment, ARPAV), as well as census data (population density) of four different macro-areas within the Veneto region (North-East of Italy) (Fig. S1) from January 2016 to May 2019. The monitoring station classification according to the Italian legislation (D.lgs, 2010) and the corresponding GPS coordinates are reported in the Supporting Information. Among the four macro-areas highlighted in Fig. S1, based on air quality data available from ARPAV (PM_{10} and $PM_{2.5}$ concentrations over the entire period investigated and hourly PM_{10} values for both working days and holidays, in Figures S2-S3-S4-S5, respe ctively), along with the information on the population density (Urbistat, 2019), and on the presence of sensitive areas (i.e., middle and high schools, universities, hospitals, public transports stops and terminals with high frequency of pedestrians), three different sampling sites with a greater likelihood of human exposure to resuspended PM by street cleaning activities were identified within the historical city centre of Treviso (Area 1 in Fig. S1). The location of the sampling sites is displayed in Fig. 1.

2.1.2. Equipment for street cleaning activity

The street cleaning activity was performed by using a battery powered manual leaf blower (Pellenc Airion 2 model), combined with a mechanical water-flushing sweeper (Euro 6, Dulevo 5000 model). The action of the leaf blower is to channel the dust from the asphalt sidewalks and roads towards the mechanical water-flushing sweeper, equipped with a suction/filtering system with a total waste container capacity of 5 m^3 (category N3 refers to vehicles intended for the carriage of goods with a maximum mass exceeding 12 tons). According to the technical data of the company, this vehicle is equipped with a filtering system capable of retaining above 99% of the PM with a diameter in the 1–10 μm range.

2.2. Sampling methodology

The approach used to investigate the human exposure to inhalable

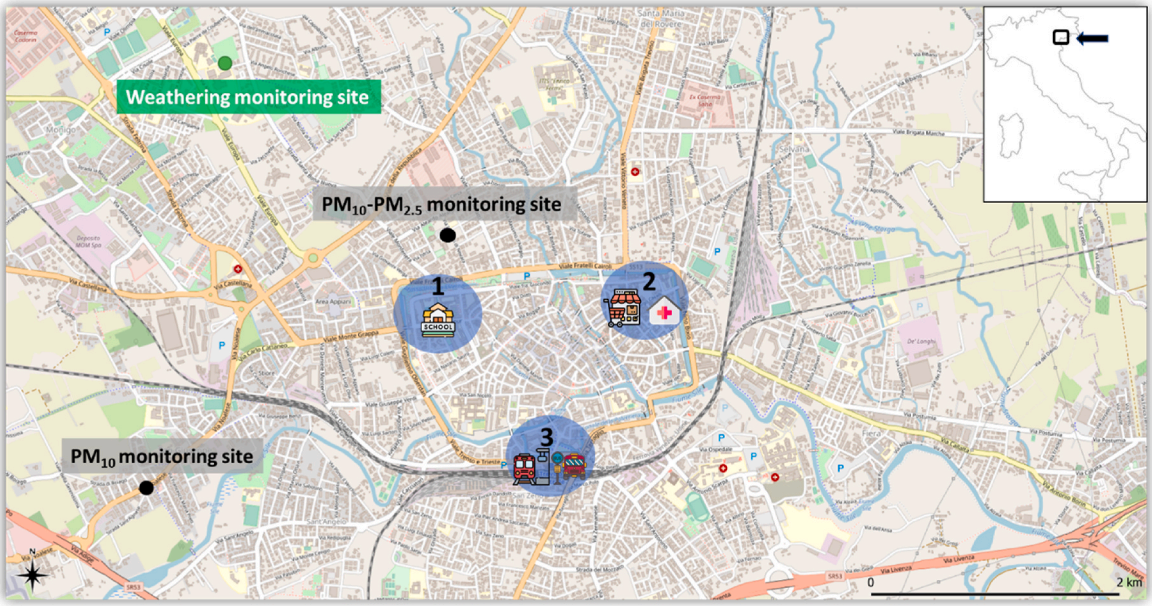

Fig. 1. Sampling areas (in blue) within the Treviso city centre: site 1 (near both middle and high schools), site 2 (near the local market and a local clinic), and site 3 (near the railway and the bus stations). The weather monitoring sampling site and the 2 p.m.$_{10}$-$PM_{2.5}$ monitoring sites are displayed in green and black, respectively.

PM and PAHs during the street cleaning activity by the combination of leaf blower and water-flushing sweeper is schematized in Fig. 2 and displayed in Fig. S6. First, road dust was sampled from asphalt sidewalks and roads at 5:00 a.m. along the route of the cleaning service but before the beginning of the activity, when the lower vehicular traffic flow usually occurs (Fig. 2A). The aim of this sampling was to gather information on the chemical composition of the material potentially resuspendable by the service that is known to be site-specific (Amato et al., 2016). Afterwards, inhalable PM and PAHs were collected by means of personal air samplers for 60 min before the service as background (Fig. 2B), and for 60 min during the cleaning activity (Fig. 2-C1). In addition, the applied methodology included the characterization of the resuspended airborne particles size range and its re-deposition time by a scanning mobility particle sizer (Fig. 2-C2). The details of each step are reported below.

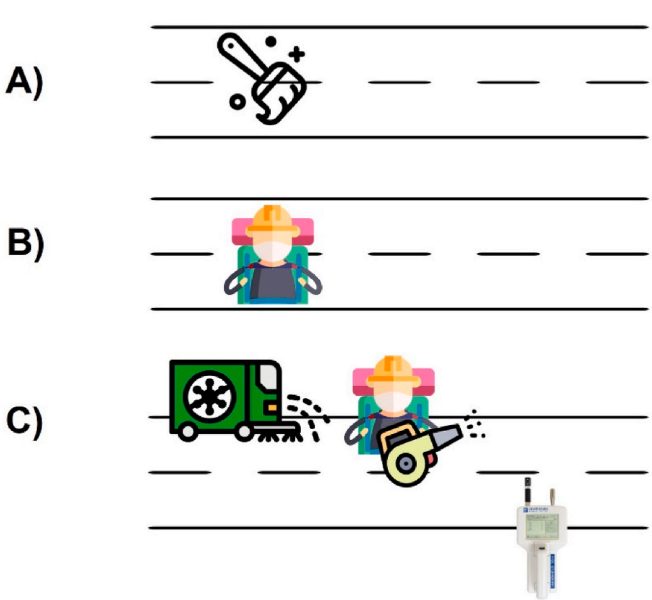

Fig. 2. Schematic representation of the sampling methodology used: A) road dust sampling before the cleaning activity; B) personal air sampling before the cleaning activity; C) air sampling by the portable particulate matter detector before, during and after the cleaning activity.

Regarding monitoring seasonality selection, due to the global pandemic of coronavirus disease 2019 (COVID-19), the sampling campaign was carried out over summer, autumn, and winter, across 2020 and 2021, as reported in Table S1, by performing three different samplings for each of the sites displayed in Fig. 1. The sampling days were identified by assuring three boundary conditions: i) dry conditions (no heavy precipitation phenomena) at least three days before the sampling; ii) temperatures in line with the seasonal averages of the previous two years; iii) no exceptional wind events before and during the sampling (according to ARPAV, Table S2).

2.2.1. Road dust

Road dust samples (at least 5 g, over a defined surface area of 0.04 m^2 at each sampling) were collected before the street cleaning activity by a plastic brush and transferred to polytetrafluoroethylene (PTFE) bottles for storage. After collection, the samples were sieved through 200 mesh to remove coarse materials (e.g., organic waste, cigarette butts, leaves and plastic) and then ground in an agate mortar and stored in PTFE bottles before analysis. Samples mineralization was performed by microwave acid digestion, according to the EPA 3051 A method (U.S. EPA, 2007). Briefly, 250 mg of sample (previously ground and homogenised) were weighed directly into Teflon containers and a mixture of 9 mL of HNO_3 and 3 mL of HCl was added. A Milestone ETHOS One microwave laboratory unit was used for the samples' digestion. The temperature was ramped to 180 °C within 6 min and then kept constant for 5 min. After cooling to room temperature, the samples were diluted with ultrapure water for chemical analysis. To evaluate the possible environmental contamination, three blank samples (9 mL of HNO_3 and 3 mL of HCl) were also prepared. After road dust samples digestion, the contents of Aluminium (Al), Arsenic (As), Barium (Ba), Beryllium (Be), Boron (B), Cadmium (Cd), Calcium (Ca), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Nickel (Ni), Potassium (P), Lead (Pb), Antimuonium (Sb), Selenium (Se), Tin (Sn), Thallium (Tl), Vanadium (V) and Zinc (Zn) was determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, 7900 Agilent Technologies, USA). The Limit of Quantification (LOQ, mg/g, dry weight) calculated were:

0.109 for Al, 0.018 for As and Cd, 0.239 for Ca, 0.109 for Co, 0.131 for Cr, 0.046 for Cu, 0.783 for Fe, 0.565 for K, 0.051 for Mg, 0.119 for Mn, 0.118 for Mo, 0.360 for Na, 0.010 for Ni, 0.019 for Pb, 0.801 for Sn, 0.041 for V and 0.065 for Zn.

2.2.2. Personal air sampling

SENSIDYNE personal air samplers (GILIAN AIR PLUS, USA) were equipped with cellulose esters filters (25 mm diameter and 0.8 µm pores, Millipore®, Merck) for metals and with XAD-2 tubes (Aquaria Srl, Italy) for organics, the latter compliant with NIOSH, OSHA and EPA regulations. The samplers were calibrated at a flow of 2 L/min with Institute of Occupational Medicine (IOM) type selectors. Filter masses were obtained by gravimetric determination after pre-conditioning at constant temperature (20 ± 5 °C) and humidity (RH 50 ± 5%) for at least 48 h. The personal air sampling was carried out over at least 60 min near the breathing zone of the employee, as depicted in Fig. S7, also showing the exact placement of the inlet.

The samples collected were characterised by means of electron microscopy to gather insights on the physical structure of the inhalable PM and by spectroscopy and chromatography techniques to investigate their chemical composition.

After the sampling procedure, the size, shape, and morphology of the airborne particulate collected and the elemental analysis was carried out by employing a Scanning Electron Microscopy (SEM, FEI Nova 600i NanoLab Dual Beam), coupled with Energy Dispersive X-ray Spectroscopy (EDX, XFlash 6|30, Bruker Nano, Germany). The analysis of the particle size distribution was performed by ImageJ 1.50i software, and at least 500 particles were included in the processing to ensure statistical robustness of the size distribution estimation. Before any analysis, the samples were metallized by means of an air plasma, depositing a film of gold (Au) with a thickness of a few nanometres in order to make the surface of the samples conductive. The images were collected at variable magnifications with a voltage of 10 KeV.

Inorganic elements content of the particulate obtained from air personal samplers was quantified by microwave acid digestion with 5% aqua regia (1 HNO_3:3 HCl) solution (NIOSH, 2003) and ICP-MS analysis (7900 Agilent Technologies, USA) following the same procedure as RD analysis.

PAHs sampled through XAD-2 tubes were extracted by 2 mL carbon disulfide in 5 mL vials with ultrasonication, as reported by (Wei et al., 2007), and analysed by gas chromatography with a flame ionisation detector (Gas Chromatography-Flame Ionisation Detector, GC-FID) (NIOSH, 1994). The sum of the following polycyclic aromatic hydrocarbons (PAHs) was quantified: benzo(a)pyrene, naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo (k + j) fluoranthene, benzo(e)pyrene, benzo(a)pyrene, perylene, indeno pyrene, dibenzo (ah)anthracene, benzo (ghe)perylene, dibenzo (al)pyrene, dibenzo (ae)pyrene, dibenzo (ai)pyrene and dibenzo (ah)pyrene. Benzo(a)pyrene was used as a standard the entire class of PAHs (Moldoveanu, 2019).

2.2.3. Resuspended airborne particles

A Handheld Particle Counter portable spectrometer (3016 IAQ, Lighthouse Inc., USA) was located at 1 m height and at around 3 m distance from the leaf blower - on the opposite side of the street and in the direction of the dust conveyed by the blower - to test the potential exposure of pedestrians (Fig. S6). A preliminary study was performed to select the best position of the particle counter with respect to the cleaning activity, bearing in mind that the leaf blower has to be stopped when a pedestrian pass on the same sidewalk of the worker.

The particle size of the airborne particles was sampled continuously with a measurement frequency of 2s, starting 5 min before (t_0), during (t_1) and ending 5 min after the street cleaning activity (t_2), with at least 5 independent measurements for each sampling day. The size classes that can be detected by this instrument are 0.3, 0.5, 1, 3, 5, and 10 µm. However, taking into account the instrumental accuracy declared by the company of the portable spectrometer (counting efficiency: 50% at 0.3 µm and 100% for particles >0.45 µm), the values corresponding to the 0.3 µm size class were not considered in this study.

3. Results

In this study, a methodological approach was developed and applied for assessing the human exposure to mechanised road sweeping activities with a motor water-flushing sweeper and electric leaf blower. In the following section an analysis of the data used to choose sampling timing and locations is presented, followed by the characterization of the particles and chemicals collected by personal air sampling device, and of the resuspended airborne particles concentration profiles by particle counter.

According to the meteorological data collected from the weather station selected (Fig. 1) and summarized in Table S2, the sampling campaign was performed, verifying that the boundary conditions listed in materials and methods were fulfilled. Indeed: i) no intense precipitation phenomena at least three days before the sampling occurred; ii) temperatures were in line with the seasonal averages of the previous two years (Table S3); iii) no exceptional wind events before and during the sampling were observed.

3.1. Road dust

As a screening of the potentially resuspendable material chemical composition, elements present in the road dust were determined by ICP-MS analysis for the different sites and seasons investigated are shown in Fig. 3. According to previous works in the Veneto Region in Italy (Valotto et al., 2018, 2019), the main elements identified in the road dust were Ca, Mg, Fe, K, Al, and Na, which are usually ascribable to soil erosion. From these results, neither a pattern linked to seasonality nor to a specific sampling station emerged, showing, for each element, the concentration values of the same order of magnitude across the three sites investigated.

3.2. Personal air sampling

3.2.1. Particles size, shape, and elemental composition

Preliminary information on the particles size collected onto the personal air sampling filters has been provided by means of scanning electron microscopy. In detail, the size distribution data obtained are shown in Fig. 4 as boxplots and were statistically analysed by the non-parametric Kruskal-Wallis test (p-values in Table S4). This test is usually applied to non-normal distributions to determine whether any of the differences between the medians of two distributions are statistically significant (Ostertagová et al., 2014). Since all the p-values were always higher than the significance level (denoted as α, equal to 0.05), it can be stated that the differences between the medians of the blanks and the samples were not statistically significant. It is worth to notice that despite the medians are similar, a certain variability of particle size distributions was observed, as expected for a sample of resuspended dust from an urban street of a densely populated city such as the historic centre of Treviso.

Furthermore, SEM-EDX analysis supported the particles size characterization and allowed to gather further information on the chemical composition of the particles collected (typical SEM-EDX spectra are displayed in Fig. S8), the latter highlighting the presence of very similar elements between the blanks and the samples, among which calcium, magnesium, potassium, iron, aluminium and sodium, which have been usually ascribable to soil erosion (Valotto et al., 2018, 2019).

The overall characterization data are collated in Table S4, including sampling season, location and date of samples, particle size and qualitative elemental composition by SEM-EDX, and p-values of the Kruskal-Wallis statistical test.

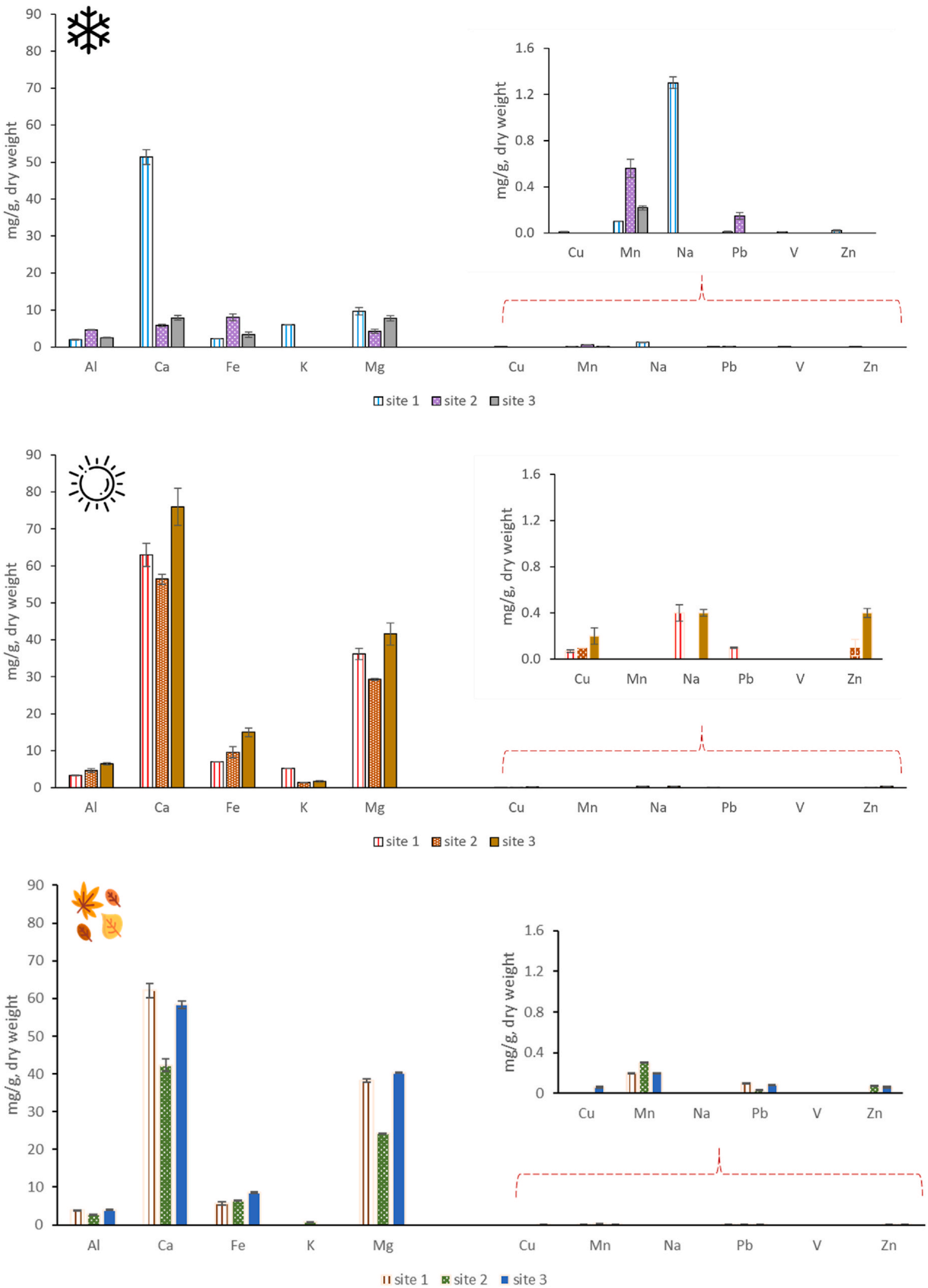

Fig. 3. Concentration of the investigated inorganic elements (mg/g, dry weight) in the road dust samples from the historical city centre of Treviso (Italy) during winter, summer, and autumn monitoring campaign in sites 1, 2, and 3. As, Cd, Co, Cr, Mo, Ni, and Sn were not included in the histograms because were all below the Limit of Quantification (LOQ) values.

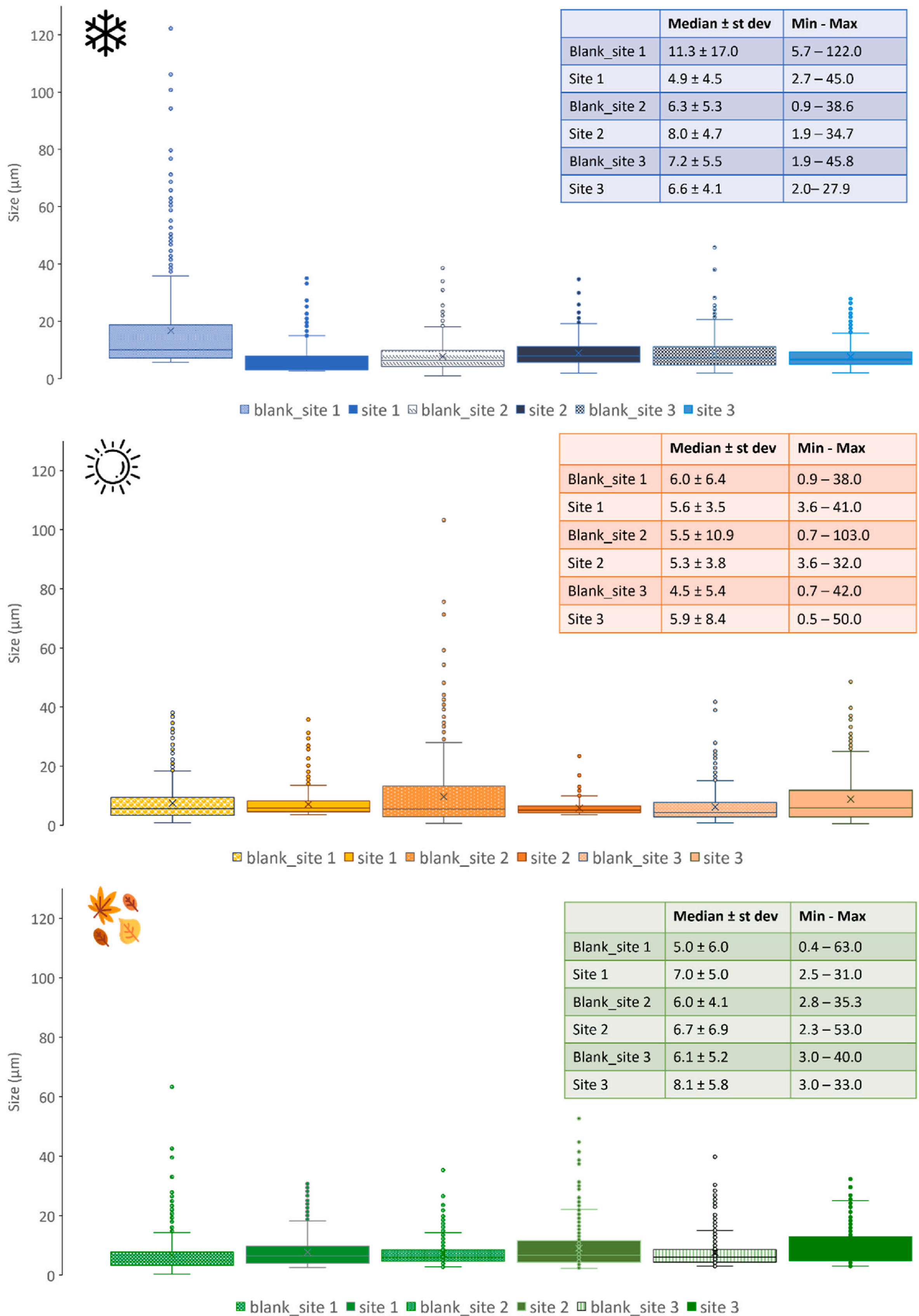

Fig. 4. Comparison of the particle size (in µm) of blanks *vs* environmental samples collected by personal air samplers in winter, summer, and autumn and analysed by SEM. At least 500 particles for each sampling episode were measured.

3.2.2. Inhalable dust concentration

The concentration of the total inhalable dust, collected over 60 min for all samplings (i.e., blank and worker with the blower), is reported in Fig. 5. The results showed a higher data variability in winter (2.2 ± 1.4 mg/m^3) with respect to summer (2.7 ± 0.7 mg/m^3) and autumn (1.1 ± 0.1 mg/m^3). Moreover, the threshold value of 10 mg/m^3 suggested by the American Conference of Governmental Industrial Hygienists (ACGIH) for indoor dust exposure, depicted as a dotted line, highlighted that this threshold has never been exceeded during the whole monitoring campaign, either for the blank nor for the worker. While the use of a reference value referred to outdoor conditions would be preferable, the threshold value of ACGIH is the only one available that can be used as a comparison.

3.2.3. Metals and PAHs concentrations

The results obtained by ICP-MS analysis on the composition of the material deposited over the 60 min sampling on the filters from personal air samplers are shown in Figs. S9–S11, showing that none of the elements investigated exceeded the lowest values suggested for indoor workplace exposure at the national level (D.lgs, 2008) and, when unavailable, at the international level (Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH) and ACGIH) (Table S5). Indeed, the threshold values considered were as follows: Al: 2 mg/m^3; As: 0.002 mg/m^3; Cd: 0.002 mg/m^3; Cr: 2 mg/m^3; Cu: 0.1 mg/m3; Fe: 5 mg/m^3; Mg: 5 mg/m^3; Ni: 0.015 mg/m^3; Pb: 0.15 mg/m^3; Zn: 5 mg/m^3).

The results on total PAHs and benzo(a)pyrene concentrations detected by GC-FID onto the personal samplers filters are reported in Table S6, while the occupational exposure limits of benzo(a)pyrene concentration contained in PAH mixtures for different countries are in Table S7 (i.e., 0.07 μg/m^3 over an 8-h workshift and 0.0056 μg/m^3 for 15 min). The results obtained for benzo(a)pyrene were all below the limit of quantification (i.e., <0.01 μg/m^3).

3.3. Resuspended airborne particles by particle counter

Due to the high sampling frequency of the particle counter (every 2 s), only the most significant events are displayed in Fig. 6, for a total time of 360 s. The profiles recorded, ranging from 0.5 to 10 μm size classes, showed signals due to the leaf blower and the mechanical water-flushing sweeper, but also to other vehicles passing-by (i.e., buses, cars).

In detail, the counts recorded differed quite significantly among the samplings, ranging from a few thousands counts (in autumn) to below 2000 counts (in summer and winter). This could be related to the meteorological conditions (e.g., relative humidity, temperature, wind speed and direction) as well to the fact that the path followed by the worker with the leaf blower and by the water-flushing sweeper was not standardized but it varied according to the characteristics of the road and the amount of material to be moved and collected (leaves and other deposited material). However, from the spectra displayed in Fig. 6, it can be observed that, regardless the absolute intensity recorded, the duration of a resuspension event ascribable to the leaf blower and to the mechanical sweeper is similar to those caused by other motor vehicles (e.g., buses or cars). It is worth to notice that, because of the aim of the cleaning, the residence time of the leaf blower and of the water-flushing sweeper was always higher than the simply transit of motor vehicles in the street, which could suggest that the effect of these cleaning activities on the PM dispersion would not be significantly different than those from other motor vehicles.

The data collected showed that RD resuspension events ascribable to the leaf blower are always shorter than 30 s, while those attributed to the mechanical sweeper are longer, with a maximum duration of 90 s.

4. Discussion

An experimental design to assess pedestrians' exposure to a street sweeping in an urban environment has been developed by conducting a mobile air sampling campaign, gathered information from road dust, from personal air sampling and from portable particulate matter detector. Easy-to-use and portable air pollution sensors providing high-resolution data are constantly increasing, driven by recent advances in technology (Snyder et al., 2013). The approach herein proposed allowed to investigate human exposure under the worst-case scenario in terms of both meteorological (no intense precipitation for three days before sampling, no extreme temperature and winds events) and sampling conditions (60 min of exposure without PPE and sampling along the direction of a wind-driven plume resuspended by the blower). With such experimental design, the highest potential exposure to dustiness was

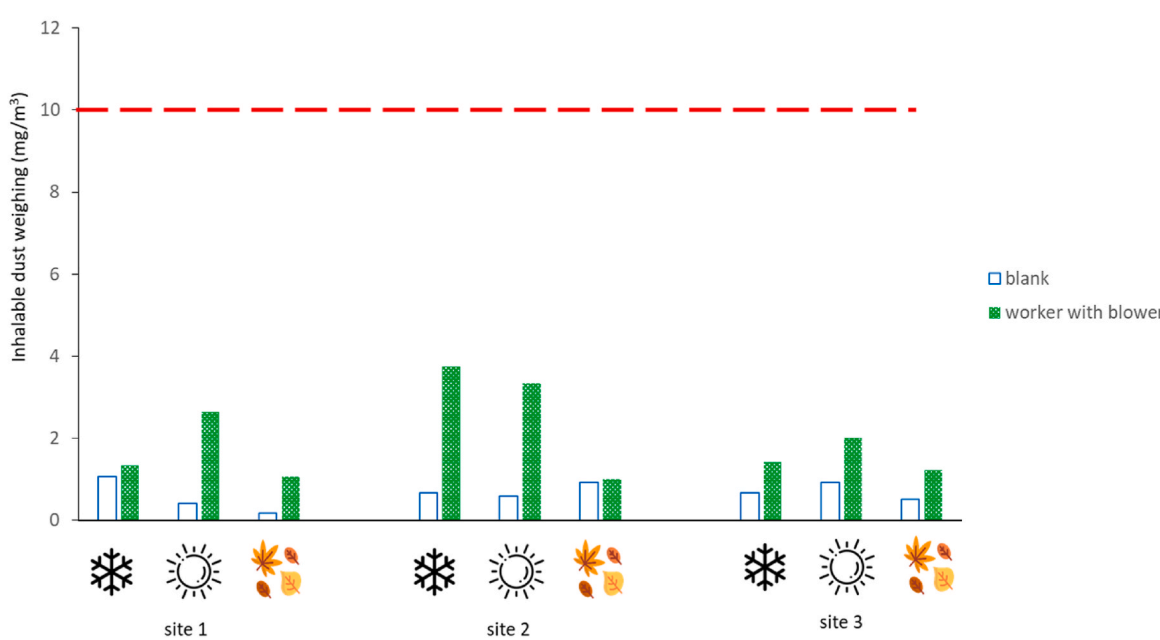

Fig. 5. Total concentration of inhalable dust from personal air samplers in winter, summer, and autumn. The dotted line indicates the threshold limit value suggested by ACGIH (10 mg/m^3).

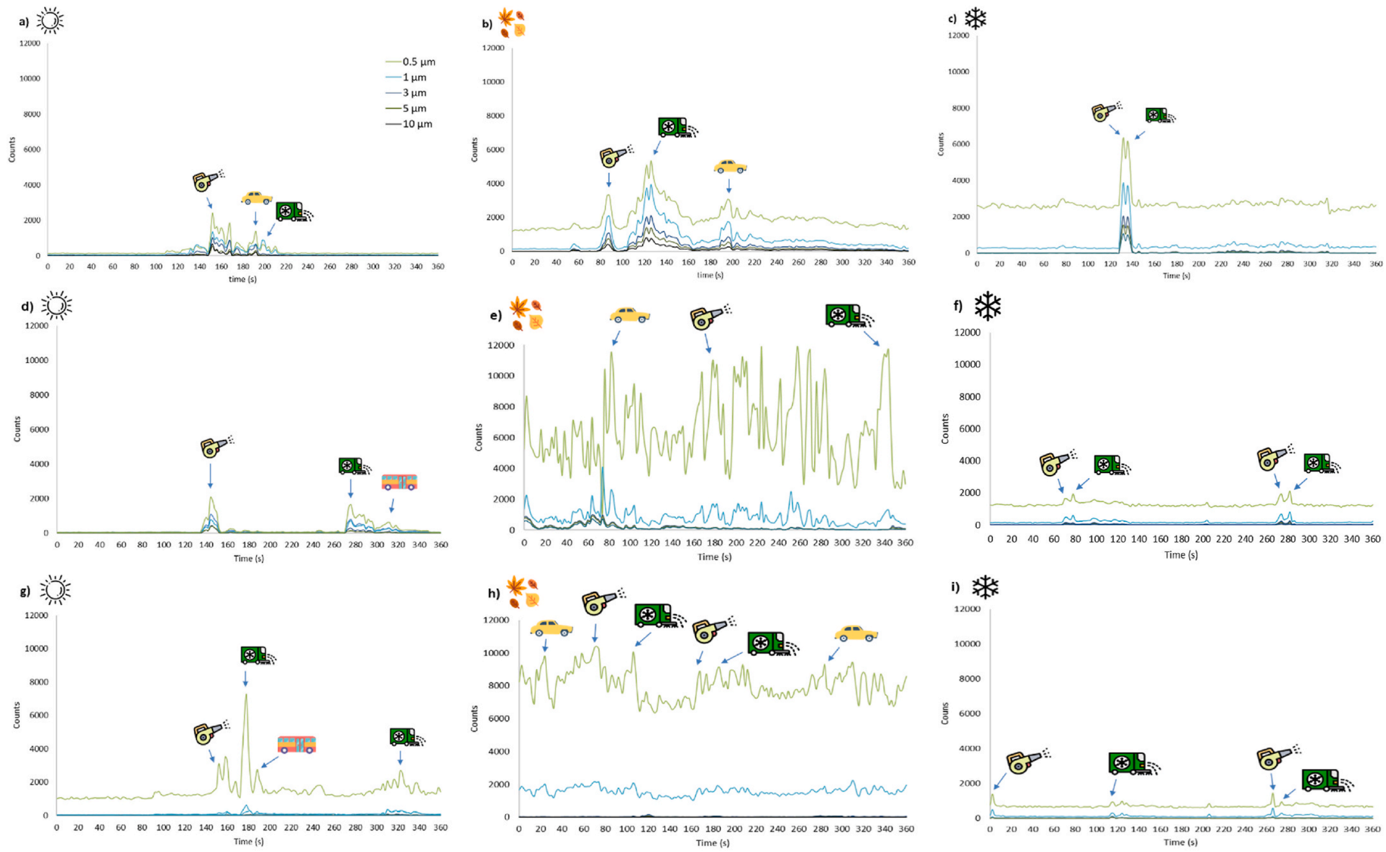

Fig. 6. Typical particle counter spectra of the resuspended particles sampled before, during, and after the street cleaning activity at sites 1 (a, b, c), 2 (d, e, f) and 3 (g, h, i) in summer, autumn, and winter. The profiles correspond to 0.5, 1, 3, 5 and 10 μm size classes. Icons show the attribution of the main peaks observed corresponded to the activity of the leaf blower, of the mechanical sweeper, and of other motor vehicles (e.g., cars or buses).

expected. It is worth noting that the occupational exposure limit values available to be compared with the results herein reported, in which airborne particles dispersion is much more favoured than in a closed system, refer to an indoor environment. In fact, although the use of specific threshold referring to outdoor environment would be preferable, these indoor reference values have been already reported in literature (Fang et al., 2021; Othman et al., 2022; Zhao et al., 2022).

Importantly, the intention of our study was not to replace the outdoor air quality monitoring and to verify compliance with the legislation, but rather to provide information to policymakers on the potential exposure of pedestrians passing nearby the street cleaning. In this context, there are only few studies addressing this issue, but they usually focused on evaluating the risk posed by the noise from commercial leaf blowers (Pollock et al., 2018; Walker and Banks, 2017). The only two peer-reviewed studies addressing the impact of cleaning activities by leaf blowers estimating emissions in the air were by (Fitz et al., 2021) and by (Costa-Gómez et al., 2020). In detail, the first study was focused on the monitoring methodology to measure PM emission rates from small fugitive dust generating activities in a confined area, closer to an indoor environment. Conversely, the work by (Costa-Gómez et al., 2020) was performed outdoor, by assessing the impact of a petrol-powered leaf blower on particle pollution during street cleaning. To achieve this aim, the authors located a real-time particle counter (Dylos DC1700) at a stationary-site for 104 days during 2016 to sample both fine and coarse PM. For each time a blower passed by the sampling point selected, the measurement lasted 16 min, divided by the first 5 min, the minute of maximum concentration and the 10 min after. The results were displayed as boxplot (i.e., median values and interquartile range, expressed in $\mu g/m^3$) of fine and coarse PM resuspension. The authors stated that, compared with background levels, the use of leaf blowers implied an average increase of 1.6 and 1.7 times in fine and coarse PM, respectively. Moreover, they observed that a dust wave effect of high PM levels started 1 min before the passing of the leaf blower and lasted for the subsequent 2 min. Based on this monitoring campaign, the authors explained that, even if the use of leaf blowers for street cleaning contributes to worsening urban air quality, it poses a minor health risk. To conclude, they suggest performing an occupation risk study for assessing personal exposure of leaf blower operators to resuspended PM.

In order to increase the knowledge on the human exposure of street sweeping activity, in addition to the use of particle counter, employed only at a fix position by (Costa-Gómez et al., 2020), our work collected and merged information also from road dust sampling and personal air samplings, following the workers during their street cleaning inside the city centre. Therefore, the assessment herein performed allowed to evaluate not only the citizens' exposure but also the operators' exposure during their working hours. In this regard, the multi-method approach employed highlighted: i) the compliance with threshold limit of the total inhalable dust by a worker, proposed by ACGIH; ii) a good agreement of the inorganic elements identified into the road dust and into the material collected by the personal air sampler (i.e., calcium, magnesium, potassium, iron, aluminium and sodium), suggesting that the sweeping activity investigated did not introduce additional foreign material to what is already present; iii) the absence of PAHs and inorganic elements exceeding thresholds established for occupational exposure; vi) a similar pattern of inorganic elements within the three different monitoring areas, probably ascribable to crustal elements; v) a "dust wave" effect similar to that reported by Costa-Gómez et al., (2020), lasting on average no more than 90 s, which however was similar to the resuspension time of other monitored motor-vehicles, as cars or buses.

Lastly, besides that the sampling methodology herein employed differed from that of Costa-Gómez et al., (2020) because it was specifically tailored to follow the street cleaning activity over their working-hours, also the engine-powered of the leaf blower was different: electric-powered in our study vs petrol-powered. The latter certainly has a larger impact on the direct PM emissions and potentially on the particles' resuspension. However, despite this, the dust wave observed lasted almost the same time.

5. Conclusions

Outdoor air pollution affecting urban areas could be either reduced or increased by street cleaning activities, which highly depend on the management system adopted, along with the local characteristics. The achievement of both hygiene and aesthetic objectives is particularly relevant, especially for historical city centres and for residential areas. As to not cause detrimental effects on human health and air quality, technical and organisational set-up choices have a pivotal role.

Due to the lack of a standardized method aimed at monitoring the effects of the street cleaning activities in urban areas on the health of workers and pedestrians, this work focused on developing an approach tailored to assess human exposure to resuspended PM under the worst possible conditions. Samples were collected before cleaning activities from road surface, inhalable particles via personal air sampling before and during cleaning activities, as well as resuspended airborne particles through a handheld particle counter before, during and after the street cleaning service. To our knowledge, this is one of the very few studies addressing the topic with this comprehensive approach, performing the monitoring of a mobile cleaning activity within a brief time frame, with the challenge to collect enough amount of sample for the required physicochemical characterization.

According to the results obtained throughout this work and to the air quality data provided by ARPAV, it can be stated that the cleaning service conditions (i.e., time interval and frequency of the service as well as equipment used) were quite suitable and acceptable in terms of low PM_{10}-$PM_{2.5}$ average concentration, low traffic intensity and the almost absence of passers-by. The results obtained suggested that the duration of the dust wave, generated by the investigated sweeping activity, is similar to that of common motor vehicles passing by. In addition, we can speculate that the potential human exposure to this cleaning service should be probably lower when considering the exposure to the workers, since, although they are exposed to resuspended PM in continuous for several hours, they must wear PPE.

To conclude, this work could represent a starting point to design monitoring campaigns which combine experimental data with atmospheric dispersion modelling for providing a tool to local-decision makers for assess human risk.

Author contributions statement

Conceptualization: Andrea Brunelli, Silvia Breda, Petra Scanferla, Antonio Marcomini, Elena Badetti; **Data curation**: Andrea Brunelli, Silvia Breda, Elena Badetti; **Formal analysis**: Andrea Brunelli, Silvia Breda, Elena Badetti; Funding **acquisition**: Petra Scanferla, Antonio Marcomini; **Investigation**: Andrea Brunelli, Silvia Breda, Elena Badetti; **Methodology**: Andrea Brunelli, Silvia Breda, Petra Scanferla, Antonio Marcomini, Elena Badetti; **Project administration**: Petra Scanferla, Antonio Marcomini, Elena Badetti; **Resources**: Petra Scanferla, Antonio Marcomini; **Supervision**: Loris Calgaro, Antonio Marcomini, Elena Badetti; **Validation**: Loris Calgaro, Antonio Marcomini, Elena Badetti; **Writing – original draft**: Andrea Brunelli, Silvia Breda; **Writing – review & editing**: Andrea Brunelli, Silvia Breda, Petra Scanferla, Loris Calgaro, Antonio Marcomini, Elena Badetti.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work and the results reported in this paper. Although Contarina S.p. A. contributed to fund the research, the authors declare that the company did not interfere in any activity of the research, including experimental design, sampling, analysis, interpretation of results and writing.

Acknowledgments

We would like to thank EcamRicert Srl for laboratory analysis and for supporting the experimental design.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2023.101680.

References

Air Resources Board, 2000. A Report to the California Legislature on the Potential Health and Environmental Impacts of Leaf Blowers. https://ww2.arb.ca.gov/sites/default/files/2018-11/Health%20and%20Environmental%20Impacts%20of%20Leaf%20Blowers.pdf.

AIRUSE, 2013. The scientific basis of street cleaning activities as road dust mitigation measure, AIRUSE LIFE 11 ENV/ES/584, 1-30, October 2013.

Amato, F., Alastuey, A., Karanasiou, A., Lucarelli, F., Nava, S., Calzolai, G., Severi, M., Becagli, S., Gianelle, V.L., Colombi, C., Alves, C., Custódio, D., Nunes, T., Cerqueira, M., Pio, C., Eleftheriadis, K., Diapouli, E., Reche, C., Minguillón, M.C., Manousakas, M.I., Maggos, T., Vratolis, S., Harrison, R.M., Querol, X., 2016. AIRUSE-LIFE+: a harmonized PM speciation and source apportionment in five southern European cities. Atmos. Chem. Phys. https://doi.org/10.5194/acp-16-3289-2016.

D.lgs., 2008. n. 81 - Testo Unico sulla Salute e Sicurezza sul Lavoro.

D.lgs, 13 agosto 2010. n. 155 - Gazzetta ufficiale - Attuazione della direttiva 2008/50/CE relativa alla qualità dell'aria ambiente e per un'aria più pulita in Europa - Allegato III.

Calvillo, S.J., Williams, E.S., Brooks, B.W., 2015. Street dust: implications for stormwater and air quality, and environmental management through street sweeping. Rev. Environ. Contam. Toxicol. 233, 71–128. https://doi.org/10.1007/978-3-319-10479-9_3.

Costa-Gómez, I., Bañón, D., Moreno-Grau, S., Revuelta, R., Elvira-Rendueles, B., Moreno, J., 2020. Using a low-cost monitor to assess the impact of leaf blowers on particle pollution during street cleaning. Air Qual. Atmosphere Health 13, 15–23. https://doi.org/10.1007/s11869-019-00768-8.

Fang, B., Zeng, H., Zhang, L., Wang, H., Liu, J., Hao, K., Zheng, G., Wang, M., Wang, Q., Yang, W., 2021. Toxic metals in outdoor/indoor airborne PM2.5 in port city of Northern, China: characteristics, sources, and personal exposure risk assessment. Environ. Pollut. (Amsterdam, Neth.) 279, 116937. https://doi.org/10.1016/j.envpol.2021.116937.

Fitz, D.R., Bumiller, K., 2000. Determination of PM10 emission rates from street sweepers. J. Air Waste Manag. Assoc. 50, 181–187. https://doi.org/10.1080/10473289.2000.10464004.

Fitz, D., Pankratz, D., Pederson, S., Bristow, J., 2021. A semi-portable enclosure to measure emission rates from small fugitive sources: leaf blower dust example. Aerosol Air Qual. Res. 21, 200566 https://doi.org/10.4209/aaqr.200566.

Horwatich, J.A., Bannerman, R.T., 2009. Pollutant loading to stormwater runoff from highways: impact of a highway sweeping program. 1-122, Geological Survey (U.S.), Madison, Wisconsin.

ISPRA, 2017. Qualità dell'aria, in: Qualità dell'ambiente urbano. XIII Rapporto, pp. 285–330.

Moldoveanu, S.C., 2019. Chapter 2 - pyrolysis of hydrocarbons. In: Moldoveanu, S.C.B. T.-P. Of O.M., Second E. Elsevier, pp. 35–161. https://doi.org/10.1016/B978-0-444-64000-0.00002-0.

NIOSH, 1994. Manual of Analytical Methods (NMAM), Method 5515. Fourth Edition, 8/15/94.

NIOSH, 2003. In: Elements by ICP (Aqua Regia Ashing), Method 7301. Manual of Analytical Methods (NMAM), Fourth Edition.

OECD, 2020. Non-exhaust Particulate Emissions from Road Transport. https://doi.org/10.1787/4a4dc6ca-en.

Ostertagová, E., Ostertag, O., Kováč, J., 2014. Methodology and application of the kruskal-wallis test. Appl. Mech. Mater. 611, 115–120. https://dx.doi.org/10.4028/www.scientific.net/AMM.611.115.

Othman, M., Latif, M.T., Mohd Naim, N.N., Mohamed Zain, S.M.S., Khan, M.F., Sahani, M., A Wahab, M.I., Md Sofwan, N., Abd Hamid, H.H., Mohamed, A.F., 2022. Children's exposure to PM2.5 and its chemical constituents in indoor and outdoor schools urban environment. Atmos. Environ. 273, 118963 https://doi.org/10.1016/j.atmosenv.2022.118963.

Padoan, E., Amato, F., 2018. In: Amato, F.B.T.-N.-E.E. (Ed.), Chapter 2 - Vehicle Non-exhaust Emissions: Impact on Air Quality. Academic Press, pp. 21–65. https://doi.org/10.1016/B978-0-12-811770-5.00002-9.

Pitt, R.E., Williamson, D., Voorhees, J., Clark, S., 2005. Review of historical street dust and dirt accumulation and washoff data. J. Water Manag. Model. 13 https://doi.org/10.14796/JWMM.R223-12.

Pollock, C., Sparks, G., Banks, J., 2018. Lawn and garden equipment sound: a comparison of gas and battery electric equipment. J. Environ. Toxicol. Stud. 2, 1–9.

Raffaelli, K., Deserti, M., Stortini, M., Amorati, R., Vasconi, M., Giovannini, G., 2020. Improving air quality in the Po valley, Italy: some results by the LIFE-IP-PREPAIR project. Atmosphere 11. https://doi.org/10.3390/atmos11040429.

Snyder, E.G., Watkins, T.H., Solomon, P.A., Thoma, E.D., Williams, R.W., Hagler, G.S.W., Shelow, D., Hindin, D.A., Kilaru, V.J., Preuss, P.W., 2013. The changing paradigm of air pollution monitoring. Environ. Sci. Technol. 47, 11369–11377. https://doi.org/10.1021/es4022602.

United Nations, Department of Economic, Social Affairs, 2019. Population Division. In: World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). United Nations, New York.

Urbistat, 2019. Population density of Treviso province [WWW Document]. URL. https://ugeo.urbistat.com/adminstat/it/it/demografia/dati-sintesi/treviso/26/3.

U.S. EPA, 2007. Method 3051A (SW-846): Microwave Assisted Acid Digestion of Sediments, Sludges, and Oils.

Valotto, G., Rampazzo, G., Visin, F., Gonella, F., Cattaruzza, E., Glisenti, A., Formenton, G., Tieppo, P., 2015. Environmental and traffic-related parameters affecting road dust composition: a multi-technique approach applied to Venice area (Italy). Atmos. Environ. 122, 596–608. https://doi.org/10.1016/j.atmosenv.2015.10.006.

Valotto, G., Zannoni, D., Rampazzo, G., Visin, F., Formenton, G., Gasparello, A., 2018. Characterization and preliminary risk assessment of road dust collected in Venice airport (Italy). J. Geochem. Explor. 190, 142–153. https://doi.org/10.1016/j.gexplo.2018.03.005.

Valotto, G., Zannoni, D., Guerriero, P., Rampazzo, G., Visin, F., 2019. Characterization of road dust and resuspended particles close to a busy road of Venice mainland (Italy). Int. J. Environ. Sci. Technol. 16, 6513–6526. https://doi.org/10.1007/s13762-019-02246-1.

van Kampen, V., Hoffmeyer, F., Seifert, C., Brüning, T., Bünger, J., 2020. Occupational health hazards of street cleaners – a literature review considering prevention practices at the workplace. Int. J. Occup. Med. Environ. Health 33, 701–732. https://doi.org/10.13075/ijomeh.1896.01576.

Walker, E., Banks, J.L., 2017. Characteristics of lawn and garden equipment sound: a community pilot study. J. Environ. Toxicol. Stud. 1 https://doi.org/10.16966/2576-6430.106, 10.16966/2576-6430.106.

Wei, M.-C., Chang, W.-T., Jen, J.-F., 2007. Monitoring of PAHs in air by collection on XAD-2 adsorbent then microwave-assisted thermal desorption coupled with headspace solid-phase microextraction and gas chromatography with mass spectrometric detection. Anal. Bioanal. Chem. 387, 999–1005. https://doi.org/10.1007/s00216-006-0962-8.

WHO, World Health Organization 2018. Ambient (Outdoor) Air Pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

Who, 2021. World Health Statistics 2021: Monitoring Health for the SDGs, Sustainable Development Goals. World Health Organization, Geneva.

Zhao, X., Li, Z., Wang, D., Xu, X., Tao, Y., Jiang, Y., Zhang, T., Zhao, P., Li, Y., 2022. Pollution characteristics, influencing factors and health risks of personal heavy metals exposure: results from human environmental exposure study in China. Build. Environ. 220, 109217 https://doi.org/10.1016/j.buildenv.2022.109217.