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Assessing Worker and Pedestrian Exposure to Pollutant Emissions from Sidewalk Cleaning: A Comparative Analysis of Blowing and Jet Washing Techniques

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Abstract: Sidewalk cleaning operations are essential to maintaining a clean and safe urban environment. Despite their vital role, these activities, particularly the blowing of road dust, can lead to the resuspension of road dust and associated pollutants, which poses risks to human health and the environment. While the role of blowers on particulate matter resuspension has been investigated, there is limited information on emitted bioaerosols. This study aimed to compare the occupational exposure of operators and passersby during sidewalk cleaning using two manual methods—blowing and jet washing—in two distinct urban environments. The study focused on metal road traffic tracers (copper (Cu), zinc (Zn), manganese (Mn), cadmium (Cd), and lead (Pb)) and cultivable/non-cultivable microorganisms. We showed that blowing resuspends inhalable particles containing metals (Cu, Zn, and Mn, but not Cd or Pb) and bioaerosols (fungi and Gram-negative bacteria) throughout the year. This represents an important source of exposure for the blower operators and poses a potential long-term respiratory health risk for them. Operators working in cabs are shielded from such exposure, but passersby, especially vulnerable populations, may be at risk. While jet washing reduces operator exposure to Gram-negative bacteria in comparison to blowing, it does not mitigate fungal exposure, particularly in vegetated sites. These findings underscore the necessity for the implementation of effective protective measures and the development of alternative cleaning methods to mitigate exposure risks.

Keywords: bioaerosols; sidewalk cleaning; blowers; exposure assessment; emission load; microbial diversity; worker safety; public health

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1. Introduction

Street and sidewalk cleaning is widespread in urban communities and serves as a key strategy for maintaining roadways and preventing sediment accumulation. Its primary purpose is to remove litter and debris from streets, which plays an important role in improving the visual appeal of the environment and addressing potential risks to public health and the ecosystem. Despite the evolution of street cleaning methods from manual to mechanical in Western societies over time, manual cleaning methods, such as blowing or jet washing, are still used alone or combined with mechanical methods in urban environments to remove dust and trash from places inaccessible to mechanical sweepers, such as areas harboring parked cars, small alleyways, and busy city areas [1,2]. However, these manual methods raise concerns about the resuspension of inhalable particles into the air, which can have harmful effects on both workers and passersby.

Road dust is a complex mixture of particles from different sources. These include particles from vehicle exhaust and wear [3], including microplastics [4] and metals [5–7], which accumulate on road and sidewalk surfaces all the year round [6,8]. In addition, road dust contains primary and secondary particles from both anthropogenic sources, such as demolition/construction activities and industrial emissions, and natural sources, including the short- and long-range transport of resuspended soils, vegetative debris, and animal feces [9]. The nature and composition of street dust is expected to vary widely based on local climate, geology, population and traffic density, and infrastructure [1]. Within this mixture, inhalable dust is of particular concern, representing particulate matter (PM) ranging in size from 1 μm to about 100 μm [5]. This dust had the ability to be easily resuspended in the air and to travel in suspension over long distances. Routine street cleaning activities are known to contribute to the resuspension of these inhalable particles from street dust, introducing pollutants into the ambient air [2]. These particles include microbial components, both cultivable and non-cultivable entities [10].

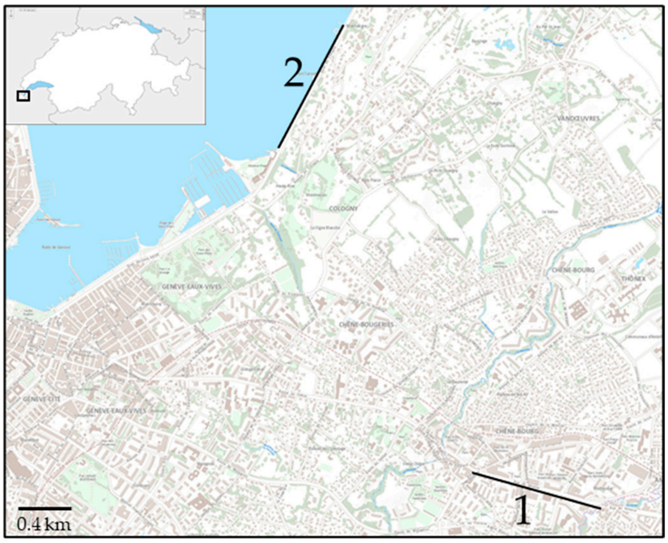
Blowers, common manual tools in street cleaning, have been reported to pose various occupational hazards to workers [10]. Their activity has been shown to emit aerosols that significantly affect street sweepers' respiratory outcomes and peak expiratory flow rates compared to controls. These outcomes include allergies, respiratory problems, coughs, colds, asthma, bronchitis, and diseases such as malaria, typhoid, and gastrointestinal disorders [11]. However, the activities of street cleaners are associated with various health risks beyond respiratory problems. These include skin problems such as cuts, irritations, and infections, as well as hearing and musculoskeletal problems [11]. Furthermore, as they work mostly outdoors, these workers are exposed not only to environmental and traffic pollution (such as dust, particulate matter, ozone, carbon monoxide, and nitrogen oxides) but also to extreme temperatures [12] and UV radiation [13]. Occupational solar UV exposure is a significant factor in the development of cutaneous squamous cell carcinoma [14].

While we recognize the health risks posed to blower operators due to their exposure to blown road dust, there remains a significant gap in our understanding of the various particles they are exposed to, particularly biological agents suspended during their activities. Current research does not provide a comprehensive understanding of the exposure of both workers and the general population to biological agents released during road blowing, especially over different seasons. In addition, there are significant gaps in the literature when it comes to comparing the exposure levels associated with different street cleaning methods, with a particular focus on the distinction between blowing and jet washing techniques. The limited understanding of the impact of bioaerosols is a central concern and calls for a thorough study that spans different seasons and different street cleaning activities. This study attempts to fill these gaps by conducting a comparative analysis of occupational exposure during blowing and jet washing across seasons. The primary objective of this study was to characterize bioaerosol emissions during street cleaning operations of two distinct urban environments. Our focus extends to determining the exposure levels of workers, including blower operators and drivers, as well as passersby crossing during these street cleaning activities. The secondary objective was to compare the exposure levels of these different populations to inhalable dust, bioaerosols, and metals, between two different methods of sidewalk cleaning: manual blowing and jet washing.

2. Materials and Methods

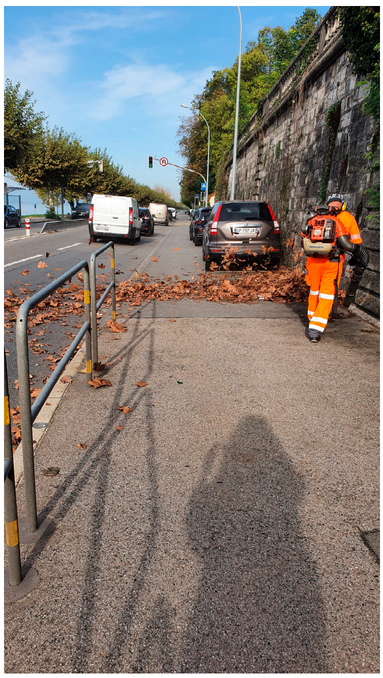
2.1. Study Area

This study was conducted in the canton of Geneva, Switzerland, which is known for being one of the most densely populated regions in the country. The canton has a population of 517,802 and a density of 12,898 inhabitants per km^2. It is located within the French-speaking region, and it is situated on the shores of Lake Geneva (see Figure 1). Although an efficient public transport system is available, a significant number of people choose to commute personally, resulting in a daily traffic flow of 11,931 cars on the city roads in 2022. During the winter season, rock salt (NaCl) is used as a deicing agent in the region. For the purposes of this study, two distinct environments were chosen to accurately represent the routes regularly cleaned by road crews. One of these environments was an urban environment, specifically Rue de Genève (site 1, Figure 1). This street serves as a busy main thoroughfare for the city center and includes a tram line. The landscape is diverse, with intermittent vegetation and buildings. Litter such as cans, glass, and PET bottles, paper, dead leaves, and other debris accumulates routinely. The second environment was a vegetated area located on the shores of Lake Geneva, specifically Quai de Cologny (site 2, Figure 1). This two-lane road is heavily used by commuters, and it runs along the lake. The street is bordered by deciduous vegetation, which results in a continuous deposition of dead leaves throughout the year. The presence of parked cars makes sidewalk cleaning difficult.



(**a**)

(**b**)



(**c**)

Figure 1. Sampling areas within Geneva city: site 1 along rue de Genève, a busy cantonal street with a streetcar line; site 2 along Quai de Cologny, a busy cantonal street with trees bordering the lake. (**a**) location of the city map; (**b**) photo of site 1 during blowing; (**c**) photo of site 2.

2.2. *Equipment for Street Cleaning Activity*

The cleaning of the sidewalks was performed using either an electric or thermal leaf blower model, namely, the Pellenc ULIB 1200 Airion 2 (Pellenc, Pertuis, France) or the

Husqvarna 580 BTS (Husqvarna Switzerland AG, Mägenwil, Switzerland) (Figure 1c). The dust from the asphalt sidewalks was directed towards the mechanical water-spraying sweeper (Euro 6, Bucher C401 model), which followed the operator on foot down the street. The sweeper is equipped with a filter system that, according to the company's specifications, can capture over 99% of particulate matter (PM) with a diameter ranging from 1 to 10 μm. For street cleaning by jet washing, the Pony P4-T (Boshung, Payerne, Switzerland) was used to generate a high-pressure water jet (Figure 1b) that directed dust from the asphalt sidewalks onto the road. The same model of mechanical water-spraying sweeper (Euro 6, Bucher C401 model) followed the Pony to clean the road.

2.3. Study Design

Personal air sampling is effective in determining a person's exposure to contaminants in the air throughout their routine workday. To investigate the variation in personal exposure to inhalable particles, metals, and bioaerosols resuspended in the air during street cleaning activities, personal active air sampling were conducted on blower operators and on drivers on two sites over the four seasons. The use of personal protective equipment was systematically documented. To ensure consistency of meteorological conditions for comparison, the two sites were sampled on the same day: site 1 (rue de Genève) was sampled in the morning, and site 2 (Quai de Cologny) in the afternoon, except during the summer season when both sites were sampled consecutively on the same morning. To clean up site 1, two leaf blowers and one sweeper driver were systematically required, while site 2 generally only required one leaf blower and one sweeper. The two sites take a similar amount of time to clean. The electric leaf blower was used during the autumn, winter, and spring seasons, while the thermal leaf blower was used only at site 2 during the autumn season. Sidewalk cleaning with a water jet requires the contribution of three road workers at a time on both sites: one handling the water jet, one driving the Pony, and one driving the sweeper. This method was used only during the summer season. The study also estimated the exposure of pedestrians during road cleaning activities. Specifically, personal air sampling was conducted on pedestrians (scientific collaborators of the project who participated in data collection) who were either following or preceding the blower operators during their activity at distances ranging from 5 to 10 m. This was undertaken for the entire duration of the activity at each site. The background levels of PM and bioaerosols were monitored in the ambient air before and after the cleaning activities using a real-time particle reader device pDR-1500 (Thermo Fisher Scientific Inc, Franklin, MA, USA) and the microbial air sampler MAS100 Eco (MBV AG, Staefa, Switzerland), respectively. Stationary sampling of bioaerosols was also conducted at a distance of 2 m behind the blower operator during blowing or jet washing with MAS100 Eco (MBV) to document the punctual exposure of passersby. Sampling was conducted once per season during autumn 2022 (31 October 2022), winter (27 February 2023), spring (8 May 2023), and summer 2023 (10 July 2023) on sunny days with no precipitation on the day of sampling (Tables S1 and S2). The temperatures were consistent with seasonal averages from previous years. Meteorological conditions at each site were measured using a PCE-THB40 device (PCE Instruments UK Ltd., Hampshire/Southampton, United Kingdom) to record temperature, relative humidity, and atmospheric pressure. Additionally, a VelociCalc Plus (TSI Incorporated, St Paul, MN, USA) device was used to measure wind speed.

2.4. Personal Air Sampling

Two personal air samplings were collected in the breathing zone of each operator. One sample was collected on a mixed cellulose ester (MCE) membrane filter (25 mm diameter, 0.8 μm pore, ref. 225-1930 SKC), while the other was collected on a polycarbonate filter (25 mm diameter, 0.8 μm pore, ref. 225-1601 SKC). Both filters were mounted in IOM samplers (SKC). The sampler was connected to a Gilian GilAir Plus (Sensidyne, Clearwater, FL, USA) portable pump and an AirCheck XR (SKC Inc, Eighty Four, PA, USA) portable pump, respectively, both operating at a flow rate of 2 L min^{-1}. The duration of air sampling is specified in Table S3. Prior to each sampling campaign, the flow rate of each pump was calibrated using the IOM Calibration Adapter accessory and an IOM sampler loaded with a representative filter and cassette in line. The preparation and assembly of the IOM sampler for bioaerosol sampling were conducted in accordance with the SKC operating instructions for bioaerosol sampling. Following collection, inhalable dust masses were determined gravimetrically by weighing the MCE filters prior to preparation for metal composition analysis. The bioaerosols analysis was performed from polycarbonate filters. Real-time concentration measurements of inhalable particles (PM_{10}) emitted during cleaning were monitored using the pDR-1500 (Thermo Fisher Scientific Inc, Franklin, MA, USA). Stationary sampling of bioaerosols was also conducted with the MAS100 Eco by direct impaction of bioaerosols onto different solid culture media at a flow rate of 100 L min^{-1} for 12 s to 2 min. All the instruments used for stationary measurements were calibrated by the manufacturers prior to sampling.

2.5. Inhalable Dust Quantification

Gravimetric measurements of particles loaded on MEC filters were performed using a Mettler Toledo XP2U microbalance (Mettler-Toledo (Schweiz) GmbH, Greifensee, Switzerland) (readability of 2 μg) in the Forensic CHUV Toxicology and Chemistry Unit Gravimetric Analysis Facility. Filters were preconditioned for 24 h prior to weighing in a chamber that maintained environmental conditions at a constant air temperature of 21 °C (±0.5 °C) and a constant relative humidity (RH) of 40% (±1%).

2.6. Elementary Analysis of Inhalable Dust

Metal concentrations in dust collected on MEC filters were determined via inductively coupled plasma mass spectrometry (ICP-MS) following the NIOSH method 7301. Briefly, after digestion in a digitube at 95 °C first in 1.25 mL of HCl 30% for 25 min and then in 1.25 mL HNO_3 65% for 15 min, the samples were diluted with 50 mL of H_2O milliQ. ICP-MS (iCAP Q ICP-MS Thermo Fisher Scientific, Waltham, MA, USA) analysis was carried out for Mn, Zn, Pb, Cu, and Cd. Standard solutions were diluted with 2% HNO_3 (Trace Metal Grade, Fisher Scientific LLC, Pittsburgh, PA, USA) to concentrations of 1, 5, 20, 100, 400, and 1000 μg L^{-1} to measure the calibration curve. Standards were provided by SCP Science (Courtaboeuf, France) and Fluka (Merck KGaA, Darmstadt, Germany). The limit of detection (LOD) for each metal was determined to be 0.1 μg/sample, and the limit of quantification (LOQ) was established as 0.25 μg/sample. Procedural reagent blanks and filter blanks were included in all batches. Calculations of LOD were based on the variability of procedural blanks (three times the standard deviation of eight or more procedural blanks). Data were processed directly from the Qtegra ISDS software (Thermo Fisher Scientific, Waltham, MA, USA). The ICP-MS analysis was performed by the Forensic Toxicology and Chemistry Unit of the University Hospital of Vaud (CHUV).

2.7. Enumeration of Cultivable Microorganisms and Identification

The polycarbonate filters (0.8 μm, 25 mm, ref: 225-1601, SKC), including the blank filters, were soaked in 2 mL of an extraction fluid (0.001% Tween 80 in Millipore water), vortexed for 2 min, and sonicated in a sonication bath (Branson 5210, Branson, MO, USA) for 15 min. A total of 100 μL of the eluates at different dilutions (1:1, 1:10, and 1:100) was plated on tryptone soja agar (TSA; Oxoid PO5012A, Thermo Fisher Diagnostics AG, Reinach, Switzerland) for enumeration of cultivable bacteria, on Thermo Scientific™ Pseudomonas CFC selective agar (CFC; Oxoid PO0291A, Thermo Fisher Diagnostics AG, Reinach, Switzerland) for enumeration of cultivable *Pseudomonas*, and on dichloran glycerol agar (DG18) for enumeration of cultivable fungi. TSA plates were incubated at 36 °C for 24 h to 48 h, CFC at 30 °C for 24 h, and DG18 at 25 °C for 3 days. Colony forming units (CFUs) were automatically counted with Scan 500 (Interscience) and analyzed using Scan software (Interscience, Versailles, France).

Bacterial and fungal colonies with distinct phenotypes were isolated and subcultured on the respective media to obtain pure cultures. The DNA of each isolate was extracted following the FastDNA spin kit for soil protocol (MP Biomedicals, Illkirch-Graffenstaden, France). For the bacterial strains, the V6–V8 region of the bacterial 16S rRNA was amplified with the forward primer 341F and the reverse primer 785R. The PCR reactions were performed in 25 μL reaction mixture using 1 μL of DNA, 0.3 μM of each primer, 0.2 mM dNTP mix, 1x KAPA HiFi fidelity buffer, and 0.5 U of Kapa HiFi HotStart DNA polymerase (Kapa Biosystems KR0369, Cape Town, South Africa). The DNA samples were amplified using the Biometra T1 thermocycler (Biolabo Scientific Instruments, Châtel-Saint-Denis, Switzerland) under the following conditions: an initial denaturation at 95 °C for 2 min, followed by 30 cycles of denaturation at 95 °C for 30 s, annealing at 53 °C for 40 s, and extension at 72 °C for 1 min, with a final extension performed at 72 °C for 10 min. For the fungal strains, the ITS region of the fungal rRNA was amplified with the forward primer ITS1F and the reverse primer ITS2. The PCR reactions were performed in 25 μL reaction mixture using 1 μL of DNA, 0.3 μM of each primer, 0.2 mM dNTP mix, 1x KAPA HiFi fidelity buffer, and 0.5 U of Kapa HiFi (HotStart) DNA polymerase (Kapa Biosystems KR0369, Wilmington, MA, USA). The DNA samples were amplified using the Biometra T1 thermocycler (Biolabo Scientific Instruments, Châtel-Saint-Denis, Switzerland) under the following conditions: an initial denaturation at 95 °C for 2 min, followed by 30 cycles of denaturation at 95 °C for 30 s, annealing at 50 °C for 40 s and extension at 72 °C for 1 min, with a final extension performed at 72 °C for 10 min.

The amplicon products were visualized using gel electrophoresis and fragments of about 400–500 bp purified using the NucleoSpin® Gel and PCR Clean-up kit (Macherey-Nagel GmbH and Co. KG, Düren, Germany). Finally, each purified fragment was sequenced with the 785R primer for bacterial clones and ITS1F for the fungal clones in a Sanger sequencing facility (Microsynth AG, Balgach, Switzerland). Taxonomic identification was conducted by blasting the obtained quality trimmed sequences against the non-redundant database with blastn (https://blast.ncbi.nlm.nih.gov/).

2.8. Characterization of Bacterial Communities' Composition

DNA was extracted using the commercial kit FastDNA™ SPIN Kit for Soil (MP Biomedicals, France). Extracted DNA samples were shipped to a sequencing service provider (Microsynth, Balgach, Switzerland) where library generation and sequencing were performed. Library preparation was performed using the primer set 341F and 805R targeting the V3–V4 region of the 16S ribosomal RNA (rRNA) gene. The amplicon library was sequenced on a MiSeq (2×250 bp paired-end). Bioinformatic analysis was performed using DADA2 (v1.26) according to a previously well-described standard pipeline [15]. Briefly, retrieved sequences were filtered and trimmed based on the sequencing quality (228nt forward reads, 220nt reverse reads), and paired-end reads were merged after dereplication and sample inference. Taxonomy was assigned by matching the sequences to the Silva reference database (v138.1) [16]. Resulting amplicon sequence variants (ASVs) and taxonomy tables (Table S4) were used to describe the composition in bacteria of bioaerosols emitted during blowing. Sequences have been deposited into the NCBI BioProject database under accession number PRJNA1093432.

2.9. Statistical Analysis

Descriptive statistics (means with standard deviations (SD)) were used to describe the inhalable dust load and bioaerosol concentrations in samples. For further statistical analysis, concentrations of cultivable fungi and mesophilic bacteria were expressed as colony forming units per cubic meter of air (CFU m^{-3}) and log transformed. Kruskal–Wallis non-parametric tests were performed to identify differences between groups. One-way analysis of variance (ANOVA) and Bonferroni post hoc tests were used to discern significant differences in bioaerosol exposure between blowers, drivers, and pedestrians during roadside cleaning of each site. A p-value of less than 0.05 was considered statistically significant. All analyses and graphs were conducted using STATA 18 for Windows software (StataCorp LLC., College Station, TX, USA).

3. Results

Investigation of personal exposure to inhalable dust revealed that pedestrian operators using blowers were consistently exposed to higher levels of inhalable dust at site 2 than at site 1 across all seasons ($p = 0.021$), albeit generally below 4 mg m^{-3}, except for one instance observed under windy conditions (Table 1). To assess the exposure of passersby and drivers to blown dust, real-time monitoring of PM_{10} was conducted at their respective proximity during the spring season at the most emissive site, site 2. The results revealed a low level of exposure of passersby to inhalable dust (0.072 $\pm$ 0.140 mg m^{-3}) compared to blower operators, indicating that the blown dust settled within short distances, with only a small fraction dispersing further than a few meters. Furthermore, being in a cab was protective against dust exposure, with sweeper drivers exposed to average levels of only 0.003 $\pm$ 0.009 mg m^{-3}. The Pony driver was exposed to a higher level of inhalable dust (0.321 $\pm$ 0.108 mg m^{-3}) than the sweeper driver, likely due to driving with the window open and in a closer proximity to the operator using the water jet.

Table 1. Level of exposure to inhalable dust of blower operators. Concentrations are expressed in mg m^{-3}.

Site	Autumn (31 October 2022)	Winter (27 February 2023)	Spring (8 May 2023)	Summer (10 July 2023)
Site 1	1.55 [1]	1.96 [1]	2.05 [1]	0.95 [3]
Site 2	3.88 [2]	40.7 [1a]	3.07 [1]	2.53 [3]

[1] electric blower; [2] thermic blower; [3] water jet; [a] intermittent wind gusts were observed during sampling.

The screening for personal exposure to different metals revealed that blower operators were consistently exposed to Cu emissions during sidewalk cleaning activities but not to a detectable level of Cd or Pb, regardless of the urban environment (Table 2). Exposure to Zn (0.2 μg·m^{-3} on site 1; 3.4 μg·m^{-3} on site 2) and Mn (0.3 μg·m^{-3} on site 1; 10.7 μg·m^{-3} on site 2) was observed among blower operators when screening for these metals was conducted during the winter season.

Table 2. Level of exposure to copper, cadmium, and lead of blower operators. Concentrations are expressed in μg·m^{-3}.

Site	Metal	Autumn (31 October 2022)	Winter (27 February 2023)	Spring (8 May 2023)	Summer (10 July 2023)
Site 1	Cu	1.3	<LOD [1]	0.8	0.5
Site 2	Cu	4.4	2.6	0.8	5
Site 1	Cd	<LOD [1]	ND [2]	<LOD [1]	<LOD [1]
Site 2	Cd	<LOD [1]	ND [2]	<LOD [1]	<LOD [1]
Site 1	Pb	<LOD [1]	ND [2]	<LOD [1]	<LOD [1]
Site 2	Pb	<LOD [1]	ND [2]	<LOD [1]	<LOD [1]

[1] The limit of detection (LOD) for each metal = 0.1 μg/sample, the limit of quantification (LOQ) = 0.25 μg/sample.
[2] Not determined.

Blower operators exhibited significantly higher exposure to the bioaerosols they re-suspended, including fungi ($p = 0.0003$) and mesophilic bacteria ($p = 0.0001$), compared to drivers, regardless of the urban environment (Table 3). Pedestrians who were either following or preceding the blower operators, on the other hand, were exposed to slightly elevated levels of cultivable fungi at both sites (Table 3). The results of the punctual stationary bioaerosol sampling confirmed that passersby were exposed to substantial levels of bioaerosols, including fungi and mesophilic bacteria (Table S5). While the increased exposure of blower operators to bioaerosols at site 2 compared to site 1 suggested higher emissions of bioaerosols at site 2, no significant difference in exposure levels was detected for pedestrians (p = 0.068 and p = 0.544, respectively) or drivers (p = 0.302 and p = 0.573, respectively) between the two sites.

Table 3. Level of personal exposure to cultivable bioaerosols. Concentrations are expressed in $CFU \cdot m^{-3}$ *.

Site	Season	Worker	Machine	Mould	Mesophilic Bacteria
Site 1	autumn	Blower	electrical blower	5269	6559
Site 1	winter	Blower	electrical blower	26,437	10,033
Site 1	winter	Blower	electrical blower	19,887	5645
Site 1	spring	Blower	electrical blower	11,086	3882
Site 1	spring	Blower	electrical blower	16,635	5543
Site 1	summer	Blower	water jet	2809	274
Site 1	winter	Driver	sweeper	3064	306
Site 1	spring	Driver	sweeper	263	88
Site 1	summer	Driver	sweeper	332	ND
Site 1	summer	Driver	Pony	66	ND
Site 1	winter	Pedestrian		1873	250
Site 1	spring	Pedestrian		2138	1271
Site 1	summer	Pedestrian		2111	281
Site 2	autumn	Blower	thermal blower	5,169,492	37,119
Site 2	winter	Blower	electrical blower	138,670	21,813
Site 2	spring	Blower	electrical blower	31,026	167,798
Site 2	summer	Blower	water jet	23,637	9100
Site 2	winter	Driver	sweeper	5754	719
Site 2	spring	Driver	sweeper	266	266
Site 2	summer	Driver	sweeper	ND	112
Site 2	spring	Driver	Pony	2721	ND
Site 2	summer	Driver	Pony	523	ND
Site 2	winter	Pedestrian		3085	617
Site 2	winter	Pedestrian		3581	179
Site 2	spring	Pedestrian		19,451	2047
Site 2	summer	Pedestrian		9103	1300

* Number of colony-forming units per cubic meter of air; ND: not detected.

Bacterial identification by culture and next-generation sequencing revealed that Gram-negative bacteria were the most frequent and abundant species detected in the inhalable fraction of blower operators. Among the amplicon sequence variants (ASVs) identified, the 19 most abundant (with more than 100 reads) collectively accounted for 72% of all reads. Of these, 13 ASVs belonged to the *Massilia* genus, 3 to *Pseudomonas*, 2 to *Psychrobacter*, and 1 to *Variovorax*. Among the cultivable mesophilic bacteria, a majority of those identified were also Gram-negative species. Interestingly, the blower operators were consistently exposed to many of them across seasons (Table 4). To compare the exposure of blower operators, drivers, and passersby, to Gram-negative bacteria, *Pseudomonas* were selectively cultured from bioaerosols collected over the seasons (Table 5). The results consistently show that blower operators were exposed to cultivable *Pseudomonas* at levels often exceeding 10^3 $CFU \cdot m^{-3}$ during blowing activities at site 2. In contrast, pedestrians occasionally experienced exposure to these bacteria, while drivers were protected from *Pseudomonas* exposure when inside the cab with the window closed.

Table 4. Cultivable species detected in aerosols to which blower operators were exposed.

Species	Autumn	Winter	Spring
Bacteria			
Bacillus cereus		x	x
Bacillus licheniformis	x		x
Bacillus pumilus			x
Bacillus subtilis	x		x
Bacillus velezensis			x
Brevibacillus borstelensis	x		
Brevundimonas sp.	x		
Chryseomicrobium amylolyticum			x
Exiguobacterium sp.	x		
Fictibacillus sp.	x		
Kocuria rhizophila	x		
Kocuria rosea	x		
Lysinibacillus macroides	x	x	x
Mesobacillus subterraneus			x
Pantoea agglomerans	x	x	
Peribacillus sp.	x		
Planococcus ruber			x
Planomicrobium okeanokoites	x		
Pseudomonas sp.	x	x	x
Psychrobacillus lasiicapitis		x	x
Staphylococcus succinus	x		
Stenotrophomonas chelatiphaga	x		
Fungi			
Cladosporium herbarum	x	x	x
Penicillium brevicompactum	x	x	x
Penicillium glabrum	x		x
Aspergillus flavus	x		x

Table 5. Level of exposure to cultivable *Pseudomonas*. Concentrations are expressed in CFU·m^{-3}.

Site	Season	Worker	Machine	*Pseudomonas*
Site 1	autumn	Blower	electrical blower	ND
Site 1	winter	Blower	electrical blower	475
Site 1	winter	Blower	electrical blower	ND
Site 1	spring	Blower	electrical blower	ND
Site 1	spring	Blower	electrical blower	55
Site 1	summer	Blower	water jet	ND
Site 1	winter	Driver	sweeper	ND
Site 1	spring	Driver	sweeper	ND
Site 1	winter	Pedestrian		ND
Site 1	spring	Pedestrian		ND
Site 2	autumn	Blower	thermal blower	5593
Site 2	winter	Blower	electrical blower	35,000
Site 2	spring	Blower	electrical blower	33,306
Site 2	summer	Blower	water jet	ND
Site 2	winter	Driver	sweeper	ND
Site 2	spring	Driver	sweeper	ND
Site 2	spring	Driver	Pony	ND
Site 2	winter	Pedestrian		ND
Site 2	winter	Pedestrian		ND
Site 2	spring	Pedestrian		341

ND: not detected.

4. Discussion

In the present study, we have shown that, although essential for maintaining urban cleanliness, sidewalk cleaning activities resuspend pollutants in the inhalable fraction—microbial agents (fungi and Gram-negative bacteria) and metals (copper, zinc, and manganese)—that may pose potential health risks for pedestrians—both workers and passersby. We have also shown that drivers were protected from such exposure when inside the cab with the window closed.

The first finding of the present study reveals that the level of exposure of blower operators to inhalable dust is more dependent on the site rather than the season or the cleaning method. This observation aligns with previous research that has found differences in the level of road dust accumulation between distinct urban environments. In a study conducted in Barcelona, the city center showed lower PM_{10} values (within a range of 3–23 mg m^{-2}) compared to areas affected by heavy truck traffic (whereas levels reached 24–80 mg m^{-2}) [9]. Since the characteristics of site 1 and site 2 in our study are comparable to these two urban environments, the results obtained suggest a correlation between the profile of the urban environment, the concentration of the dust accumulated on the road, and the exposure of blower operators to inhalable dust. It also predicts an even higher level of exposure of these operators during the cleaning of urban environments with a larger deposition of dust on the road such as a demolition/construction hotspot [9]. To mitigate exposure in such environments, alternative solutions for cleaning urban environments need to be proposed for blower operators. It should be noted, however, that the observed exposure levels were generally below the Swiss occupational exposure limit of 10 mg m^{-3} and even the Norwegian occupational exposure limit of 5 mg m^{-3} for inhalable dust. As a result, the legislative power to push the employers to find alternatives will be limited. Therefore, evaluation of the levels of specific chemical and biological components in inhalable dust may help us to move in this direction.

To identify relevant chemical pollutants for these occupational activities, we investigated operator exposure to various metals previously identified as road dust tracers [6,9] or associated with brake and tire abrasion [17,18]. Our findings revealed consistent exposure of pedestrian operators to Cu, Zn, and Mn during blowing activities, regardless of the urban environment. The concentrations of these metals exceeded those previously reported in urban ambient air in Switzerland [6], suggesting a contribution of road cleaning activities to ambient metal pollution. It is noteworthy that the use of a water jet during road cleaning activities seems to resuspend as many inhalable particles containing Cu than the blower, which suggest that both methods impact the quality of the ambient air by resuspending dust associated with brake and tire abrasion. Interestingly, we did not detect Pb and Cd in the inhalable fraction, despite their predicted presence based on a previous study conducted on road dust in Switzerland in 2009 [6]. Thus, we confirmed the tendency for a decrease in the presence of those metals in road dust, a tendency already reported in 2009 by comparison to 1999, that was partially attributed to the use of lead-free gasoline. Although it is reassuring that Pb and Cd were not found in the dust at the two sites, further investigation is required to ensure that blowers are not exposed to these metals. This could involve conducting a more extensive screening of sites to detect the presence of metals in dust or examining the presence of metals in the hair of blowers. It is worth noting that previous research in China has demonstrated a link between occupational exposure and the accumulation of Pb, Cd, and arsenic in workers' hair [19].

To assess the exposure of pedestrians and drivers to bioaerosols, we assessed their personal exposure to cultivable fungi and mesophilic bacteria. Our study provides compelling evidence of the consistent and substantial exposure of blower operators to bioaerosols, often surpassing recommended guideline values for fungi in both urban environments monitored, and for mesophilic bacteria specifically at vegetated sites such as the site 2. Notably, Gram-negative bacteria emerged as the most prevalent and abundant bacteria detected in the inhalable fraction of blower operators. This finding is of particular concern due to the presence of endotoxins in the outer membranes of Gram-negative bacteria, which have been associated with adverse health effects in various workplace settings [20]. The dominance of Gram-negative bacteria in the bioaerosols was confirmed via culture on enumeration media, and on *Pseudomonas*-specific media, as well as through next-generation sequencing. Molecular identification confirmed that the most abundant amplicon sequence variants (ASVs) belonged to the genera *Massilia*, *Pseudomonas*, *Psychrobacter*, and *Variovorax*, which are Gram-negative bacteria. Another noteworthy aspect of our findings is the site-specific nature of exposure to Gram-negative bacteria. This observation highlights the significant exposure of blower operators to fungi and Gram-negative bacteria during the process of blowing highly vegetated sidewalks. This exposure must be recognized as posing an elevated risk of respiratory symptoms and COPD, as previous studies have linked occupational exposure to biological dust with these conditions [21]. In order to protect workers from such exposure, it is necessary to re-assess the current practices of sidewalk cleaning. Instead of manual pedestrian cleaning, adopting small cleaning machines specifically designed for narrow spaces like sidewalks should be a primary consideration. By utilizing these machines, workers can minimize their direct contact with debris and contaminants, reducing the risk of respiratory issues and other health hazards associated with prolonged exposure. The regular usage of such machines necessitates avoiding the placement of parking spaces on sidewalks that require frequent urban cleaning. Keeping these sidewalks clear and accessible facilitates the efficient use of cleaning machines, ensuring that public spaces remain clean for the safety of pedestrians. When coexistence of parking spaces and pedestrian pathways is unavoidable, it is advisable to refrain from parking vehicles during sidewalk cleaning operations in order to permit the usage of such machines and avoid pedestrian cleaning operations. Indeed, while the use of water jets by blower operators resulted in lower levels of mesophilic bacteria, notably *Pseudomonas*, compared to blowers, it is important to note that water jet cleaning still leads to significant resuspension of fungal particles, especially in densely vegetated areas like site 2 in our study. While the use of personal protective equipment (PPE) is currently proposed as a solution to prevent worker exposure in such activities, daily and prolonged use of PPE is hardly feasible for workers, especially during periods of high heat. Therefore, activities requiring the use of PPE should be less frequent and for shorter periods to encourage workers to use them systematically. Furthermore, they should be considered as a secondary measure to be implemented only if other alternative methods cannot be feasibly integrated. For instance, a shift towards the utilization of a sweeper in lieu of the deployment of blowers could potentially serve to minimize the necessity for the extensive use of personal protective equipment.

Our results not only highlight the occupational exposure faced by blowers during street cleaning operations but also increases the attention on the exposure of the general population when crossing operators during this activity. The significant exposure of passersby to resuspended fungi during these practices underscores the urgent need to seek alternatives to blowing for sidewalk cleaning. While the microorganisms identified in our study are not pathogenic, it is essential to conduct a comprehensive biological risk assessment across various sites and scenarios to ensure the safety of the general population. Even without pathogenic species present, occasional exposure to high concentrations of microorganisms can exacerbate respiratory issues in vulnerable populations. Thus, an increase in outdoor aeroallergens, in particular of fungal allergens, were associated with daily increases in hospital admissions for asthma [22]. Therefore, prioritizing the health and well-being of both workers and pedestrians is paramount. Exploring alternative cleaning methods that effectively mitigate these risks is crucial for creating safer urban environments. Addressing these concerns will require collaborative efforts between occupational health practitioners, public health authorities, and urban planners to implement effective measures aimed at reducing bioaerosol exposure and a promoting cleaner and safer urban environment for all. In interpreting our results, it is important to acknowledge several limitations of our study. First, the small number of sites considered may restrict the generalizability of our results to all scenarios of exposure in urban environments. Furthermore, although our study identified and characterized bioaerosols at the genus level, the lack of species-level identification of bacteria and fungi may have limited our ability to fully elucidate microbial composition and associated health risks. Addressing these limitations in future research efforts will be crucial to enhance the robustness and applicability of findings in informing strategies to mitigate bioaerosol exposure during street cleaning operations.

5. Conclusions

Sidewalk cleaning operations, particularly those involving the use of blowers, contribute significantly to the resuspension of road dust and associated pollutants, in particular metals and bioaerosols, including fungi and mesophilic bacteria, in particular Gram-negative bacteria, posing potential occupational health risks for the blower operators. Our investigation highlighted the heightened exposure of blower operators to these bioaerosols, emphasizing the need for effective protective measures. While water jet cleaning methods showed some promise in reducing exposure levels to mesophilic bacteria, they still led to significant resuspension of fungal particles, especially in densely vegetated areas. Therefore, alternative cleaning methods need to be explored to mitigate exposure risks effectively. Additionally, the study underscores the importance of considering the impact of street cleaning operations not only on occupational health but also on public health and the environment. The exposure of the general population during manual cleaning might be one lever to push in initiating this change of habits. Addressing these concerns requires collaborative efforts between various stakeholders to implement measures aimed at reducing bioaerosol exposure and promoting cleaner and safer urban environments for all.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/air2020007/s1: Table S1. Meteorological measurements during sampling rue de Genève; Table S2. Meteorological measurements during sampling Quai de Cologny; Table S3. Total air volume sampled with IOM heads for bioaerosol analysis; Table S4. Relative abundance of various ASVs detected in the breathing zone of a blower during blowing, along with their assigned taxonomy; Table S5. Levels of bioaerosols detected by stationary sampling.

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Informed Consent Statement: All groups of workers involved in the study were informed of the study's purpose and their right to withdraw at any time. We emphasized the importance of informed consent, voluntary participation, and protection of privacy and confidentiality. Only groups of workers who volunteered and consented to participate were enrolled in the study. Additionally, we considered and mitigated any potential minimal risks or harms to participants.

Data Availability Statement: Raw data are provided as Supplementary Materials.

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