Environment International 187 (2024) 108697

Contents lists available at ScienceDirect

Environment International

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

Full length article

Examining the effectiveness of municipal street sweeping in removing road-deposited particles and metal(loid)s of respiratory health concern

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ARTICLE INFO

Handling Editor: Xavier Querol

Keywords:
Road dust
Metals
Urban
Street sweeping
Non-exhaust emissions

ABSTRACT

Road dust is a demonstrated source of urban air pollution. Given this, the implementation of street sweeping strategies that effectively limit road dust accumulation and resuspension should be a public health priority. Research examining the effectiveness of street sweeping for road dust removal in support of good air quality has been limited to date. To address this, the study aimed to assess the use of a regenerative-air street sweeper to efficiently remove road dust particles and metal(loid)s in size fractions relevant for respiratory exposure in Toronto, Canada. As part of this, the mass amounts, particle size distribution and elemental concentrations of bulk road dust before and after sweeping at five arterial sites were characterized.

Sweeping reduced the total mass amount of thoracic-sized (<10 μm) road dust particles by 76 % on average. A shift in the size distribution of remaining particles toward finer fractions was observed in post-sweeping samples, together with an enrichment in many metal(loid)s such as Co, Ti and S. Overall, the mass amounts of metal(loid)s of respiratory health concern like Cu and Zn were greatly reduced with sweeping. Traffic volume and road surface quality were predictors of dust loadings and elemental concentrations. Road surface quality was also found to impact street sweeping efficiencies, with larger mass amounts per unit area collected post-sweeping where street surfaces were distressed.

This study demonstrates that street sweeping using advanced technology can be highly effective for road dust removal, highlighting its potential to support air quality improvement efforts. The importance of tailoring sweeping service levels and technologies locally as per the quality of road surface and traffic patterns is emphasized. Continued efforts to mitigate non-exhaust emissions that pose a respiratory health risk at their source is essential.

1. Introduction

Airborne $PM_{2.5}$ is a major cause of global mortality and morbidity, with exposures contributing to an estimated total of 4.4 million deaths in 2019 (Fuller et al., 2022). In Canada, chronic exposures to $PM_{2.5}$ are responsible for a reported 8 % of all-cause, non-accidental deaths in adults over the age of 25 (i.e., ca. 10,000 deaths/year) (Health Canada, 2021). In the US, ambient $PM_{2.5}$ exposures are estimated to result in between 85,000 to 200,000 deaths per year (Tessum et al., 2021). Airborne pollution exposures are often disproportionately experienced by those having a low socioeconomic (SES) and racialized status, highlighting the existence of associated inequities in burdens and health outcomes (Hajat et al., 2015; Miao et al., 2015; Tessum et al., 2021). In a study conducted in Quebec, Canada, for instance, schools characterized by greater rates of material deprivation and lower neighborhood socioeconomic status (SES) were shown to be more likely located in areas with comparatively higher industrial emissions of $PM_{2.5}$, NO_2 and SO_2 (Batisse et al., 2017).

Non-exhaust emissions, including those from road dust resuspension, are a recognized critical source of airborne pollution, including $PM_{2.5}$ and contaminants of health concern like polycyclic aromatic hydrocarbons (PAHs), per- and polyfluoroalkylsubstances (PFAS), antimony (Sb), zinc (Zn) and lead (Pb) (Pant and Harrison, 2013; Amato et al., 2013, 2014; Kumpiene et al., 2021; Wiseman et al., 2021; Ahmadireskety et al., 2022). Traffic is a primary source of non-exhaust emissions, including pollutant-bearing particles released from asphalt and

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https://doi.org/10.1016/j.envint.2024.108697
Received 29 January 2024; Received in revised form 30 March 2024; Accepted 23 April 2024
Available online 24 April 2024
0160-4120/

automotive components such as brake and tire wear, exhaust systems, and catalytic converters (Zereini et al., 2012; Bozlaker et al., 2014; Wiseman et al., 2018; Baensch-Baltruschat et al., 2020; Fromell et al., 2023). A variety of transition elements capable of inducing the generation of reactive oxygen species (ROS) such as iron (Fe), copper (Cu), and nickel (Ni) are emitted in significant quantities, also as metal-bearing particles in the thoracic- (<10 μm) and respirable- (<2.5 μm) size fractions (Adamiec et al., 2016; Wiseman et al., 2021). Metal-bearing particles are also emitted in the nano-scale range as ultrafine particles (UFP) (Kukutschová et al., 2011; Levesque et al., 2021; Beauchemin et al., 2021; Avramescu et al., 2024). Given their larger reactive surface areas and oxidative potential, UFP generated from traffic-related sources is a significant human health concern (Tian et al., 2019; Hammond et al., 2022).

Particles and associated contaminants generated from traffic-related activity can accumulate on urban roads in considerable amounts, highlighting the importance of road dust as a source of airborne contamination. For instance, an estimated annual average of 5.4 and 2.9 tonnes per km of roadway was reportedly collected in New York and San Francisco, respectively (Luk, 2019). While the bulk of deposited material is generally expected to fall in the coarser size range that is not readily resuspended to the air, the overall volume of road dust that can accumulate along roads is significant. As such, the proportional contribution of road dust to fractions of respiratory health concern is an issue, even if it is small relative to the total mass deposited. Using sweeping collection data by the City of Toronto, Wiseman et al. (2021) estimated, for example, that an average of over 50 metric tonnes of Fe is available for resuspension as thoracic-sized (<10 μm) particles in Toronto annually.

The potential for road dust to serve as a major urban contaminant sink and source, with implications for air quality, highlights a critical need for effective municipal street sweeping programs. Most municipalities in North America and Europe have road dust management programs in place, involving the deployment of various sweeping technologies (e.g., mechanical broom, vacuum, regenerative air), chemical suppressants, flushing with water, etc. (Amato et al., 2010; Luk, 2019). While the focus has been on improving the quality of stormwater runoff, street sweeping can also have substantial air quality benefits, as shown in several studies that reported reductions in ambient air pollution, including concentrations of PM_{10} and $PM_{2.5}$. Studies have also shown that sweeping, typically done in combination with the use of wetting or dust suppressants, can be highly effective in reducing airborne PM (Amato et al., 2010; Kupiainen et al., 2011; Denier van der Gon et al., 2013). The City of Toronto, for instance, conducted a field study in 2014 to examine how the use of regenerative-air street sweepers can help mitigate airborne PM_{10} and $PM_{2.5}$ concentrations (City of Toronto, 2015a). The city reported an average reduction of 36 % for PM_{10} and 39 % for $PM_{2.5}$ concentrations following sweeping. For this, a street sweeping testing protocol developed for the specific climate of Toronto was used (City of Toronto, 2016); one which requires that water not be applied as a dust suppressant, since it normally cannot be used during the winter months.

While studies have shown that street sweeping can help improve air quality, there remains a critical need for more data on its effectiveness in removing on-road particle size fractions of respiratory health concern, including consideration given to the importance of site-specific factors (e.g., road surface quality, street sweeping service levels). Along with this, further study is needed to assess how street sweeping can effectively remove contaminant-bearing particles such as transition metals that have significant ROS potential, and which are potentially accessible to the human lung via resuspension processes. This is especially important considering that non-exhaust emissions are predicted to become an increasingly significant source of airborne pollutants, given market trends toward the purchase of SUVs and electric vehicles, which are heavier in weight than older gas-fueled vehicles (Timmers and Achten, 2016).

This study aimed to conduct a preliminary examination of the effectiveness of using a regenerative-air street sweeper in removing dust from arterial roads, including thoracic-sized fractions and associated metal(loid)s of public health concern in Toronto, Canada. As part of this, five arterial roads located in different priority neighborhoods were chosen for inclusion. The primary goal was to generate knowledge to help address the lack of experimental data regarding the on-road effectiveness of street sweeping, as a function of various local considerations such as asphalt quality. This study was conducted in support of a Toronto City Council directive issued in 2017 requiring that Transportation Services consider street sweeping service levels (i.e. frequency) as part of municipal efforts to improve air quality along roadways (City of Toronto, 2017a). In doing so, emphasis was placed on assessing neighborhoods with identified vulnerable sub-populations such as those with a high immigrant population and percentage of children and elderly in optimizing street sweeping efforts. Each site was sampled pre- and post-sweeping a total of four times between July to November 2019.

2. Experimental

2.1. Background and study area

As of 2021, the City of Toronto had a total population of 2,794,356 individuals (City of Toronto, 2022). Encompassing an area of 630 km^2, the city has an estimated population density of 4,435 individuals per km^2. Toronto has an extensive road network with 5,600 centreline-kilometres of road (City of Toronto, 2019). In terms of road management in the winter, Toronto relies heavily on salting (Noehammer et al., 2014). This is different from other major cities located in northern temperate zones, where sanding and the use of studded tires are more common and which can be a major source of road dust and PM_{10} following the winter months (Kupiainen et al., 2017).

In choosing sites for sampling, emphasis was placed on Toronto neighborhoods with populations identified to be more at risk for higher exposures and health impacts. This included a consideration of social, economic and demographic parameters such as population density, percent of children (0–14 years) and elderly (65 + years), education levels, income status, and unemployment rates. Additionally, priority was given to assessing sensitive use properties, including long-term care homes and schools, located within 500 m of roads with 100,000 vehicles/day or 100 m of roads with 15,000 vehicles/day.

Five sites were chosen for sampling (see Fig. 1): (1) Weston Village (WV), (2) St. Lawrence Market (LM), (3) University Ave (U), (4) Downtown Yonge (DY), and (5) O'Connor (OC). Samples were collected from major arterial roads at each location. Regularly scheduled street sweeping was suspended prior to sample collection. Dates when sweeping occurred were noted and considered in the statistical analysis of total sample amounts collected, and their respective particle size fractions, at sampling sites.

2.2. Sample collection and processing

The pavement surfaces of sampling locations were visually inspected for signs of distress in accordance with that recommended as part of the ASTM International, 2018, which is also used by Toronto to evaluate road conditions (City of Toronto, 2019). An exact pavement condition index (PCI) rating was not calculated, as stipulated by the standard, as this requires a more rigorous inspection over a larger area of road. However, the presence of the following indicators and their severity were noted in qualitative terms and coded for statistical purposes: presence of alligator cracking and spalling (advanced joint/crack deterioration), traverse and longitudinal cracking, edge cracking, weathering, ravelling and potholes, as well as the extent of prior patching (see Table 1 for pavement rankings). The sites were ranked, with corresponding details on distress indicators, as follows: (1) WV, DY and LM:

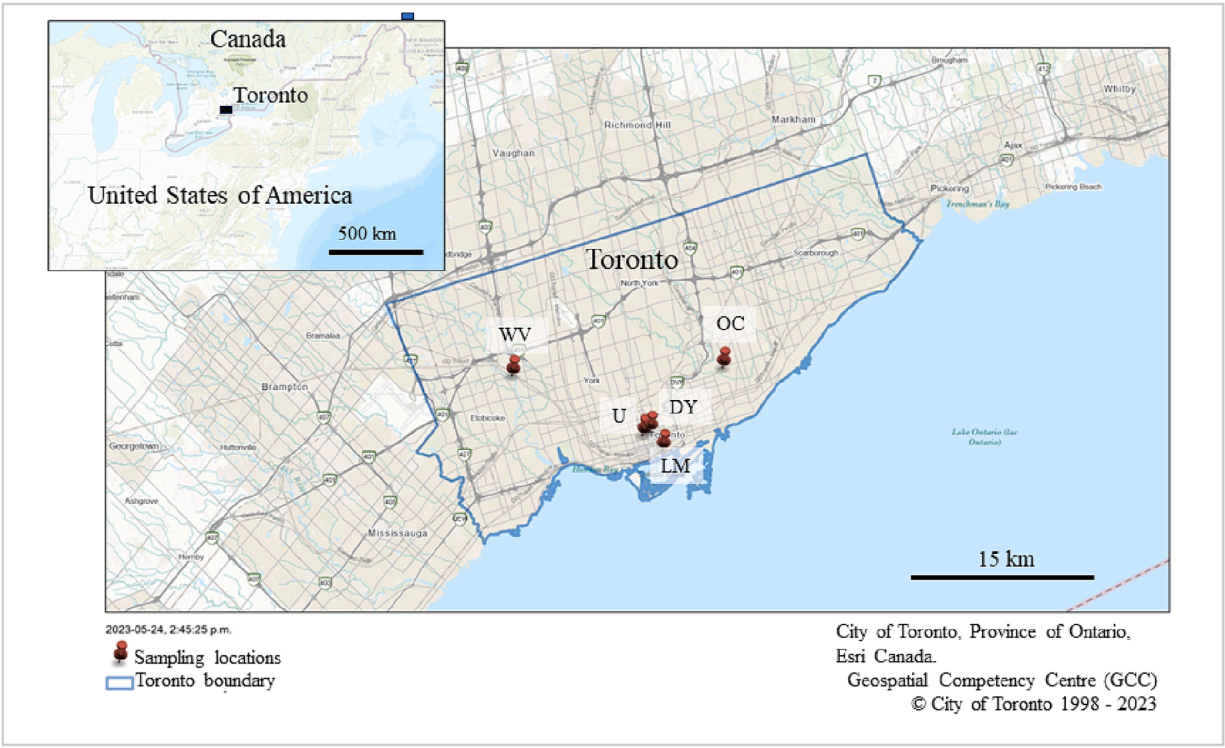

Fig. 1. City of Toronto sampling sites.

Table 1
Road type/tempo limit, pavement conditions and traffic counts for each site.

Sample Location	Coordinates	Road Type (Tempo Limit)	Pavement Condition Ranking	Total Traffic Counts (6-hour period incl. AM Peak, Off Peak and PM Peak only)[1]			
				Cars	Trucks	Buses	Total
WV	43°41′59.9″N 79°31′02.1″W	Major arterial (50 km/hr)	1 (good)	6353	426	241	7020
LM	43°38′51.2″N 79°22′14.3″W	Major arterial (40 km/hr)	1 (good)	8000	365	76	8441
U	43°39′29.4″N 79°23′22.4″W	Major arterial (50 km/hr)	2 (fair)	15,685	223	115	16,022
DY	43°39′39.6″N 79°22′59.0″W	Major arterial (40 km/hr)	1 (good)	5736	207	35	5978
OC	43°42′21.8″N 79°18′44.9″W	Major arterial (50 km/hr)	3 (poor)	9396	771	181	10,348

[1] Traffic counts are consolidated numbers for data collected during AM peak (7:30 AM – 9:00 AM), off peak (1:00 PM – 3:00 PM) and PM peak (4:00 PM – 6:00 PM) periods (weekday) by the City of Toronto, which can also be accessed via their open data program at https://open.toronto.ca/dataset/traffic-volumes-at-intersections-for-all-modes/. The numbers represent average total traffic counts recorded over a 6-hour time period for a minimum of two different dates for each site.

good conditions (low severity edge cracking, longitudinal and transverse cracking and weathering and raveling present; see Fig. 2(a) for an example) (2) U: fair conditions (medium severity patching, longitudinal, transverse, block and edge cracking, low severity weathering and raveling present), (3) OC: poor conditions (medium severity spalling and block cracking and high severity patching, longitudinal and transverse cracking, edge cracking, alligator cracking, and weathering and raveling; see Fig. 2(b)).

The City of Toronto's street sweeping service levels were rescheduled at each site to allow for a general assessment of how sweeping frequency impacts road dust accumulation and composition. The mean number of days which had elapsed since the city had swept the sampling sites using regenerative-air street sweepers (TYMCO, DST-6) and the date of sample collection was 15 (±17). Road dust samples (n = 40) were collected using a ProGuard® 4 Portable (ProTeam, 142 CFM) wet/dry vacuum, equipped with high-efficiency dust bags, at five different locations immediately before and after streets were swept using a city-operated regenerative-air street sweeper. Road dust collected by the street sweeper, itself, was not examined in this study. In accordance with the City of Toronto's PM_{10} and $PM_{2.5}$ testing protocol for street sweepers (City of Toronto, 2016), water was not applied during sweeping for dust control to assess for particle entrainment efficiency under all possible temperature scenarios (i.e. water can't be used during colder winter months). Pre- and post-sweeping samples were collected on four different occasions at each site between July and November 2019.

Vacuum bags for sample collection were conditioned in a lab under ambient conditions and then weighed, with mass noted, prior to sampling. Two separate 2 x 2 m sections of the road surface were measured and marked for sampling before and after street sweeping, beginning from the curb and extending laterally into the traffic lane (including the first wheel track). At the OC, U, Y, and LM sites, the designated pre-sweep segments were located < 20 m of the post-sweep segments. For

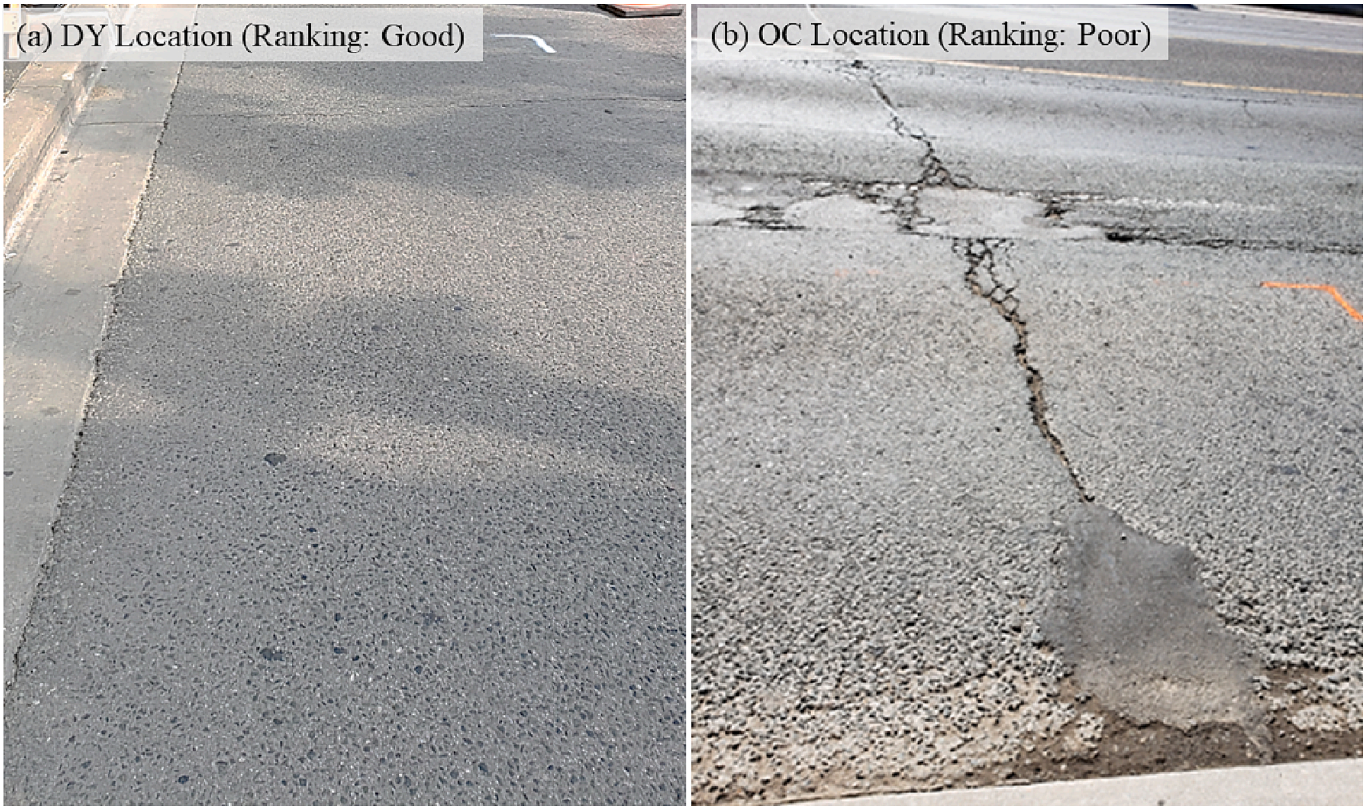

Fig. 2. Examples of road surface conditions, DY (a) and OC (b) sites shown.

the WV site, the post-sweep segment was located approximately 90 m further away on a downward sloping stretch of the road (ca. 4 % slope grade).

A different section of the road at each site was first vacuumed with a different bag for conditioning purposes to minimize cross-contamination between locations. A handheld brush was used to manually dislodge debris from all visible cracks present, including that at the confluence between the asphalt and curb, to ensure maximum pickup efficiency during vacuuming. The 2 x 2 m sections of the surface were systematically vacuumed repeatedly in different directions (parallel, perpendicular and diagonally to the curb) before and after the regenerative-air street sweeper (TYMCO, DST-6) swept the road. This amounted to an approximate 45 min reserved for sample collection, with 15 min for vacuuming the road surface before the sweeper passed (referred to as pre-sweep samples) and another 15 min spent vacuuming an adjacent area after the sweeper had swept the road (referred to as post-sweep samples). Special attention was paid to optimizing the collection of fine material from the road surface during sampling, especially closer to the curb, where lateral sloping supports the accumulation of road sediments curbside (Gustafsson et al., 2019). Samples were air-dried (with bag) for several days under ambient conditions prior to weighing and retrieval. Bags containing samples collected under damp conditions were placed in a drying oven at 60–70 °C for up to 72 h prior to extraction. Care was taken to ensure that all loose material was retrieved from the vacuum bags for weighing and further processing. Emptied bags were weighed again to estimate mass particle retention (calculated to be 8.6 % (±5.4 %) on average). Information regarding the pore size of the vacuum filter bags used for collection was unfortunately not available from the manufacturer. Given this, bags were kept for later particle extraction and analysis to confirm the diameter of retained particles (described below). Once samples were extracted from the bags and weights noted, they were sieved to separate the < 2 mm fraction from larger debris (with the mass of the < 2 mm and > 2 mm also noted for later mass calculations of street sediments) for further processing.

On each sample date, the number of city transit vehicles and trucks (including 3–4 and > 4 axles) were counted in 15-minute intervals beginning at 7:30 AM to 6:15 PM (see Table 1). The average count for these vehicle types was calculated for inclusion in the statistical model. Data on total traffic counts (cars, trucks and transit vehicles) for each site, including data collected from 2009 to 2019 for weekday periods, were provided by the City of Toronto.

2.3. Analyses

Electrical conductivity and pH were measured for the < 2 mm fractions using a road dust:distilled water ratio of 1:1 (Smith and Doran, 1996). Loss-on-ignition (at 550 °C) was also determined for bulk fractions (Nelson and Sommers, 1996). The particle size distribution of < 2 mm and smaller-sized fractions were assessed using a two-step procedure. First, samples were dry-sieved for 10–15 min using an electromagnetic sieve shaker (W.S. Tyler, RX29E) to isolate and determine the particle size distribution of sand- and silt-sized fractions (2000–1000 μm, 1000—500 μm, 500–250 μm, 250–125 μm 125–63 μm and < 63 μm). To characterize the < 10 and < 2.5 μm particle-size fractions accessible to the human lung, a modified version of the micro-pipette method for water dispersible clay, originally proposed by Burt et al. (1993) and described by the US Department of Agriculture (2014), was applied. For this, 2 g of < 2 mm sample were added to 50 mL Falcon tubes, which was determined to be an optimal amount of sample to characterize the < 10 μm and < 2.5 μm fractions in sweepings. The tubes were then filled to 35 mL with distilled water and placed in an end-over-end shaker overnight. Tubes were then filled to the 45 mL mark and shaken vigorously by hand. The percent < 10 μm and < 2.5 μm particle size fractions were determined gravimetrically for aliquots (2.5 mL) of suspensions, sampled using estimated settling times according to using Stokes' Law.

A random selection of vacuum bags (n = 26) used for pre- and post-sweep sampling were cut into sections of approximately 10 x 10 cm and placed into 500 mL sample jars with 300–350 mL of distilled water to characterize the size of retained particles. Samples were vigorously shaken for 10 min and the suspension poured into an evaporating dish. This was done a total of 4–5 times, with repeated additions of distilled water until the water ran clear, and the sample suspensions dried at ca. 70 °C on a heating place. Once dried, samples were gently ground manually using an agate mortar and pestle to break down aggregates. The particle size distribution was assessed using the same micro-pipette method. Entrapped particles (100 %) were confirmed to have mean diameters of < 10 μm, as fitting for bags labelled as high efficiency and with an extra layer of filtration. Bags used to collect pre-sweepings retained 5.6 % (±3.9) of total sample on average. An average of 3.1 % (±1.2) of total sample retained were particles with a diameter of < 2.5 μm, suggesting that finer particles were preferentially entrapped. Average values for the retention of post-sweepings were higher with 11 % (±5.9) of the total amount collected. About 4.6 % (±1.7) of the total retained in post-sweeping bags had a particle diameter of < 2.5 μm. Differences observed in particle entrainment in pre- vs. post-sweeping bags are assumed to reflect a shift in the particle size distribution of road dust, with sweeping resulting in a shift toward finer particle sizes in sediments left behind on the street surface. Data on the sample mass retained by bags were considered in the calculation of the particle size distribution and fractions with a diameter of < 10 μm and < 2.5 μm of total collected.

Metal and metalloid concentrations were determined by Actlabs Inc. (Ancaster, ON, Canada) for pre- and post-sweep samples (n = 40; <2 mm). Samples were acid-digested with hydrofluoric acid (HF), perchloric acid ($HClO_4$), nitric acid (HNO_3) and hydrochloric acid (HCl) and the digests analyzed using multi-element determination using a combination of ICP-MS and ICP-OES. The limits of detection (LOD) were 0.01 % for Na, Mg, K, Ca, Al, Fe and S, 0.001 % for P, 0.0005 % for Ti, 1 μg/g for V, Cr, Mn, Zr, Sn and Ba, 0.5 μg/g for Ni and Pb, 0.2 μg/g for Zn and Cu, 0.1 μg/g for Cd, Co, As, Sb, La and Ce, and 0.05 μg/g for Mo. While the 4-acid digestion procedure for digestion, certain minerals including zircon, chromite and barite may not be completely dissolved, resulting in lower rates of recovery.

2.4. QA/QC

The following certified reference materials (CRMs) were included as blind samples for analytical purposes: San Joaquin soil (NIST 2709a) and Trace Metals – Silt Clay 1 (Sigma-Aldrich CRM045-50G). In addition, SBC-1 (USGS Shale), SDC-1 (USGS Mica Schist), DNC-1a (USGS Dolerite), OREAS 72a (OREAS Nickel Sulphide Ore), OREAS 77b (OREAS Nickel Sulphide Ore), OREAS 98 (OREAS Copper Ore), OREAS 101b, OREAS 522, OREAS 923 and OREAS 621 were included as CRMs by the commercial lab. Recovery rates for the blind CRMs fell within ± 5 % on average for Na, Fe, Al, Ca, Cr, Cd, Ni, Co, Zn, As, Ba, Ce and Cu. For other certified elements such as Mn, Cr, V and Pb, average recoveries were within either ± 10 % or ± 20 %. Of the two blind CRMs included, Sb was only certified for San Joaquin soil (NIST 2709a). Recovery rates were poor for this element, with < 30 % on average. However, recoveries were excellent for other CRMs included by the lab for QA/QC purposes (e.g. 99 % for SBC-1, 86 % for DNC-1a and 112 % for OREAS 923). The variability of recovery rates between different CRMs suggests that results may be quite different depending on the type of matrix being examined, highlighting a need to interpret results with caution. As for the other elements certified in the CRMs used by the lab, recoveries fell within ± 20 % on average.

2.5. Data analysis

The initial sample set encompassed 40 pre- and post-sweeping samples collected on four different dates from July to November 2019 for each location. For data analysis and interpretation, a decision was made to exclude the first pre- and post-sweeping samples collected from the WV site, as the resultant data could not be reliably validated for further inclusion in the final data set (n = 38, including 3 sample sets from the WV site and 4 sample sets each from U, DY, LM and OC).

A Wilcoxon Signed Rank Test was performed to assess statistically significant differences in the mean amounts of total sample collected per m^2 and the > 2 mm, <2 mm, <10 μm and < 2.5 μm particle size fractions pre- and post-sweeping. This was also done for the elemental concentrations measured in < 2 mm samples. To assess for possible changes in metal(loid) concentrations in road dust over time (between 2015/2016 and 2019), a Mann-Whitney test was conducted using data on elemental concentrations in bulk (<2 mm) road dust from arterial roads examined in an earlier Toronto study for comparative purposes (Wiseman et al., 2021). Data was log transformed to meet the assumption that mass amounts and elemental concentrations are symmetrically distributed (Reimann et al., 2008). Associations were determined to be significant at a level of $p < 0.05$.

Additionally, a Spearman's rank correlation analysis was used to determine associations between the total sample amount collected pre-sweeping for all locations, as well as the corresponding > 2 mm, <2 mm, <10 μm and < 2.5 μm particle size fractions, and the following variables: (1) month of sample collection, (2) number of days since last recorded city sweeping for the respective locations, and (3) total traffic count and number of cars, trucks and buses (per 6 h period, including AM peak, off peak and PM peak periods). The impact of rainfall on road dust loadings and their particle size distribution was not considered given uncertainties relating to how much precipitation is needed to have a discernable impact (Keuken et al., 2010).

A Spearman's rank correlation analysis was also applied to assess the role of pavement condition in the mass accumulation of road dust at the respective sites, as well as associations with traffic volumes and sweeping efficiencies. For this, pavement conditions, as reported in Table 1, were codified, and treated as ordinal data. Given the limited number of sites and associated surface quality rankings that were used for this purpose, the results are to be interpreted with caution. Correlation coefficients > 0.5 and > 0.7 were ranked as moderate and strong, respectively.

3. Results and discussion

3.1. Chemical and physical characterization

The pH of samples fell mostly in the alkaline range, with a mean of 8.22 (±0.76) and 8.20 (±0.48) for pre- and post-sweeping samples, respectively. Samples collected prior to sweeping had a mean EC of 1243 (±673) μS/cm. The average EC for post-sweeping samples was slightly less with 1194 (±702) μS/cm. The mean LOI was 5.61 % (±2.03) for pre-sweeping samples and 6.09 % (±1.89) for post-sweeping samples. No significant differences for these variables were found for samples collected before and after sweeping. A significant association was observed between LOI and EC in pre-sweeping samples ($r_s = 0.48$, $p = 0.039$).

The sample amounts collected, and their associated particle size fractions, were found to be highly variable across space and time. The mean amount of total road debris collected before street sweeping for all locations was 571 (±822) g/m^2 (Table 2). The City of Toronto has an approximate total of 14,350 km length of roads (City of Toronto, 2020). Using a standard lane width of 3.65 m (City of Toronto, 2017b), this translates into a total road surface area of around 52.4 km^2. Using pre-sweeping amounts, an approximate mean amount of 29,908 (±43,054) tonnes of accumulated road debris is estimated for Toronto prior to streets being swept. For < 2 mm, <10 and < 2.5 μm particle size fractions, amounts of about 21,684 (±14,980), 1990 (±2409), and 576 (±681) tonnes are estimated. Calculated amounts for the total mass of < 10 and < 2.5 μm particle size fractions are of particular concern, given the potential for these fractions to be resuspended to the air and pose a respiratory health risk. The estimates are based on samples collected

Table 2
Mean (SD) sample mass collected (g/m^2), including mass estimates for the > 2 mm, <2 mm, <10 μm and < 2.5 μm particle size fractions[1.]

Location	Sample Type	Total bulk (g/m^2)	Particle size fraction in g/m^2			
			>2 mm	<2 mm	<10 μm	<2.5 μm
All sites	Pre-sweeping	571 (822)	127 (286)	443 (576)	38 (46)	11 (13)
	Post-sweeping	130 (143)	15 (20)	115 (125)	9.3 (9.1)	3.4 (4.7)
WV	Pre-sweeping	55 (16)	11 (2.6)	43 (11)	1.8 (0.57)	1.8 (0.80)
	Post-sweeping	43 (2.4)	4.4 (1.7)	38 (1.0)	2.6 (0.50)	0.60 (NA)[2]
U	Pre-sweeping	171 (73)	28 (25)	142 (48)	8.2 (2.9)	2.8 (0.74)
	Post-sweeping	90 (20)	11 (5.3)	79 (19)	6.3 (4.0)	1.6 (0.6)
LM	Pre-sweeping	751 (567)	36 (24)	715 (546)	80 (40)	16 (12)
	Post-sweeping	62 (15)	1.6 (1.8)	60 (15)	9.3 (7.3)	1.5 (0.6)
DY	Pre-sweeping	70 (21)	17 (11)	53 (12)	3.6 (2.8)	1.2 (0.68)
	Post-sweeping	46 (13)	6.1 (3.8)	40 (11)	2.6 (1.6)	0.80 (0.39)
OC	Pre-sweeping	1678 (1112)	516 (484)	1162 (646)	88 (34)	28 (23)
	Post-sweeping	391 (66)	50 (18)	341 (79)	24 (5.3)	11 (5.1)

[1] Values reported for mean mass amounts for the > 2 mm and < 2 mm particle size fractions may not add up to bulk amounts given due to such factors as sample loss during processing and rounding of numbers.
[2] Value could not be reported, as the results for only 2 samples were available.

from 2 x 2 m segments beginning at the curb. However, dust loadings can be highly variable across a road's transect, with the greatest amounts commonly occurring curbside (Gustafsson et al., 2019). Coarser particles also tend to migrate toward the curb, resulting in road dust that is preferentially enriched with larger particles (Wang et al., 2020). As such, total road dust loadings for the city may be overestimated. At the same time, the thoracic-sized fraction is potentially underestimated, so caution must be exercised in interpreting the results.

Significant reductions in the mean amount of material collected from the roads were observed after the street sweeper passed ($z = 3.73$, $p < 0.001$), with a mean of 571 (±822) and 130 (±143) g/m^2 (total debris) collected pre- and post-sweeping, respectively. This represented a mean removal efficiency of 77 % for bulk material for the regenerative-air sweeper employed in this study (Fig. 3). Particles < 2 mm in diameter comprised most of the bulk material collected before and after sweeping. For pre-sweep samples, the < 2 mm particle size fraction amounted to

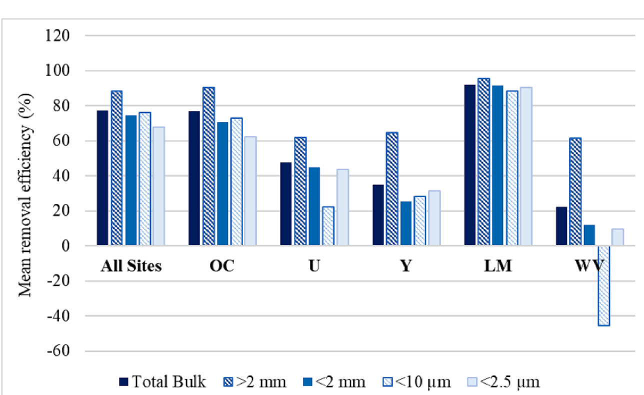

Fig. 3. Mean removal efficiencies (%) for total bulk road dust collected and the respective particle size fractions.

82 % of the mass collected. Post-sweep samples had a mean of 90 % of particles < 2 mm, demonstrating a shift toward smaller particle diameters in remaining road surface debris following sweeping. The removal efficiency for this fraction was estimated to be 74 % on average, which is higher than that reported elsewhere. For instance, Kim et al. (2020) reported a mean removal efficiency of 61 % for total bulk material from a highway in Korea using a vacuum-assisted broom sweeper. In an earlier study, the City of Toronto (2015a) reported a removal efficiency of 66 % for silt-sized particles using a regenerative-air street sweeper, as part of a field study conducted in 2014 to examine the effectiveness of different sweeping technologies (mechanical vs. regenerative-air). A much lower silt removal efficiency was reported for the mechanical sweeper (26 %). Similar to this study, the City of Toronto used an aged regenerative-air sweeper which was part of the original fleet purchased by the municipality in 2007/2008. (City of Toronto 2015a). This study also reported reductions of 51 % and 47 % in the measured maximum concentrations of ambient PM_{10} and $PM_{2.5}$ using the regenerative-air sweeper. In contrast, maximum PM_{10} concentrations after sweeping using the mechanical sweeper were reportedly reduced by 12 %, while maximum $PM_{2.5}$ concentrations increased by 9.5 %. This study, as well as the results reported here, highlight the importance of choices made regarding the use of sweeping technologies to effectively clean municipal streets as a public health intervention.

For the particle size fractions of human health concern, the mean pre-sweep amounts of the < 10 μm and < 2.5 μm fractions were estimated to be 38 (±46) and 11 (±13) g/m^2, respectively. Considering the total mass collected (> 2 mm + < 2 mm fractions), the < 10 μm fraction amounted to 6.7 % of total sweepings on average, while the < 2.5 μm fraction amounted to 1.9 % of the total. There are no known studies that have reported estimated amounts for these size fractions in street sweepings for comparison. Polukarova et al. (2020) reported a mean of 2.6 % for < 63 μm fractions in street sweepings collected in 2017 in Gothenburg, Sweden, which is relatively low compared to that found for even finer fractions in this study. With sweeping, there was a slight increase in the mean proportional size of these two particle size fractions, from 6.7 % to 7.9 % and 1.9 % to 2.1 % for PM_{10} and $PM_{2.5}$, respectively. The overall mass of the particle size fractions were sizably reduced with sweeping, however, with means of 9.3 (±9.1) g/m^2 for the < 10 μm and 3.4 (±4.7) g/m^2 for the < 2.5 μm fractions. The results demonstrate how particle size fractions of concern to human health can still be significantly reduced in mass terms using regenerative-air sweeping technology, even without the application of water.

The bulk mass and particle size distribution, as well as the pick-up efficiency of the regenerative-air street sweeper used, varied as a function of location. The most mass per unit area was consistently collected at the OC site (Table 3), with a mean pre-sweeping bulk amount of 1678 (±1112) g/m^2. This was followed by LM (751 (±567) g/m^2), U (171 (±73) g/m^2), DY (70 (±21) g/m^2) and WV (55 (±16) g/m^2). Average post-sweeping amounts were 391 (±66) g/m2 for the OC site, 90 (±20) g/m^2 for the U, 61 (±15) g/m^2 for LM, 46 (±13) g/m^2 for Y and 43 (±2.4) g/m^2 for WV. Similarly, the mass of > 2 mm and < 2 mm per m^2 collected before sweeping ranged from highest to lowest in the same order for the respective locations. A comparable pattern was generally observed for < 10 and < 2.5 μm fractions, albeit with some slight deviations for the latter in terms of the sites with the lowest mass amounts for these fractions (i.e., for DY and WV).

There were some interesting differences in the proportional amounts of the individual size fractions for samples collected from the respective sites, which highlight the complex nature of assessing the sources, accumulation, and particle size distribution patterns of road dust. Most notably, the LM site had the highest relative percentage amounts of particles with diameters < 10 μm (13 % in pre-sweeping and 15 % in post-sweeping samples). This was around 2 times more compared to the percentage amounts of these two fractions in pre- and post-sweeps from the OC, which had the largest bulk amounts of all locations. The road surface quality at the LM location was ranked as good, with the presence

Table 3
Median (25th/75th percentiles) concentrations (mg/kg) and mass (mg/m^2) amounts for measured elements in pre-and post-sweeping samples (all sites, n = 38), with estimated removal efficiencies (%).

Element	Concentrations		Mass Amounts		Removal efficiency (%)[1]
	Pre-sweeping (mg/kg)	Post-sweeping (mg/kg)	Pre-sweeping (mg/m^2)	Post-sweeping (mg/m^2)	
Major elements					
Na	13,800 (11700/16700)	13,700 (11300/15500)	2439 (1775/9589)	955 (777/1585)	61
Mg	24,000 (21800/26500)	23,700 (22800/29200)	4215 (1777/15796)	1562 (1290/2393)	35
Al	35,300 (30100/38500)	35,400 (30400/40100)	5666 (3788/23219)	2436 (1741/3974)	57
Fe	43000** (37600/55200)	49100** (43800/55500)	7212 (3374/31016)	3166 (2365/4625)	56
K	10,400 (8000/12400)	10,400 (8000/12000)	1469 (889/7836)	703 (496/1152)	52
Ca	11,500 (10900/12800)	11,700 (11100/13300)	17,209 (8181/81643)	7587 (5438/11218)	56
P	400 (400/500)	400 (400/500)	70 (30/260)	30 (20/50)	57
S	1400*** (1100/1800)	0.1600*** (1400/2100)	280 (80/790)	120 (70/260)	57
Ti	1900*** (1700/2300)	2300*** (1800/2500)	420 (130/1170)	150 (100/260)	64
Trace elements					
Cd	0.30 (0.20/0.50)	0.40 (0.30/0.50)	0.00008 (0.00002/0.0002)	0.00003 (0.00002/0.00005)	63
V	38** (34/46)	45**(40/49)	0.0065 (0.0031/0.0265)	0.0030 (0.0022/0.0042)	54
Cr	129 (109/164)	152 (121/178)	0.0241 (0.0096/0.0702)	0.0108 (0.0066/0.0291)	55
Mn	830 (711/1580)	944 (767/1420)	0.1606 (0.0782/0.6001)	0.0616 (0.0474/0.0876)	62
Ni	33 (26/36)	37 (29/43)	0.0056 (0.0023/0.0215)	0.0030 (0.0016/0.0040)	46
Co	7.9*** (6.6/10)	9.3*** (7.6/13)	0.0018 (0.0006/0.006)	0.00063 (0.00047/0.0013)	65
Zn	357 (305/408)	368 (328/465)	0.0704 (0.0218/0.2777)	0.03 (0.02/0.05)	57
As	3.7** (3.1/4.6)	4.1** (3.8/6.2)	0.00052 (0.00025/0.00270)	0.00028 (0.00021/0.00042)	46
Zr	90**(69/100)	97**(88/113)	0.0135 (0.0062/0.0628)	0.0074 (0.0043/0.0122)	45
Sb	3.6 (3.3/5.0)	3.9 (3.7/4.7)	0.00079 (0.00033/0.00327)	0.00035 (0.00017/0.00062)	56
Mo	8.7 (7.4/11)	9.6 (8.5/11)	0.0013 (0.00060/0.00598)	0.00064 (0.00045/0.00098)	51
Sn	15 (11/30)	20 (12/38)	0.0041 (0.0020/0.0107)	0.0017 (0.0012/0.0032)	59
Ba	352 (314/386)	348 (314/387)	0.0656 (0.0212/0.2730)	0.0261 (0.0140/0.0378)	60
La	11** (10/13)	12** (11/13)	0.00225 (0.00090/0.00781)	0.00083 (0.00052/0.00132)	63
Ce	25 (23/27)	27 (24/28)	0.00486 (0.00198/0.01730)	0.00179 (0.00118/0.00301)	63
Cu	158 (130/230)	181 (150/254)	0.0256 (0.0181/0.1000)	0.0154 (0.0105/0.0230)	40
Pb	59 (46/83)	70 (50/98)	0.0086 (0.0054/0.0396)	0.0053 (0.0043/0.0130)	38

Note: "**" and "***" denote where a significant difference found between elemental concentrations pre- and post-sweeping at levels of $p < 0.05$ and $p < 0.001$, respectively.
[1] Based on calculated amounts for mg/m^2.

of low severity cracking, weathering, and raveling. As such, the potential for entrapment of fine particles was comparatively minimal. This location also had the second lowest traffic counts, including trucks, of all sampling sites and, thus, was not identified as a plausible reason for comparatively higher fraction of particles falling in this size fraction. The LM site is situated, however, about 200 m north of the Gardiner Expressway, which is a six-lane, elevated bridge at this section of highway, with an average daily traffic volume of about 110,000 vehicles per day (City of Toronto, 2015b). Given this, it is speculated that the expressway is a source of particles capable of being resuspended and deposited on surfaces in its vicinity. This is supported by evidence elsewhere demonstrating that levels of air pollution can be particularly high in areas close to the city's busiest roads and highways such as the Gardiner Expressway (Toronto Public Health, 2014).

While the overall sweeping efficiency of the regenerative-air sweeper used was found to be very good, it varied as a function of location (Fig. 3). Most notably, it was lowest at the WV site, with 61 % for the > 2 mm and only 12 % for the < 2 mm size fractions. For the < 10 μm and < 2.5 μm particle size fractions, calculated efficiencies were −45 % and 10 %, respectively. The starkly different efficiencies as a function of particle size could be a result of the slope of the road at this site, with the post-sweep segment for sampling located about 90 m away from the pre-sweep section on a downward sloping gradient of about 4.4 %. It is speculated that the slope may have supported a preferential migration of finer particles to the post-sweeping segment of the road, resulting in a very different particle size distribution. Unfortunately, no studies could be found in support of this observation, so this remains purely speculative. Additionally, spatial differences might play an important factor for variation in size distribution of particles, as shown in a study by Padoan et al. (2017). Efficiencies were also reported to be influenced by the initial mass loading of road dust by Amato et al. (2010), which adds further support to the observed decreased efficiency at the WV site. However, these results are only based on a limited number of paired samples for this location (n = 3). Given the limitations of examining sweeping efficiencies as a function of sampling location, emphasis should be placed on the data set as a whole in this study.

Measured bulk mass amounts for pre- and post-sweep samples were found to be moderately to strongly associated with total traffic counts (pre-sweeps: $r_s = 0.51$, $p = 0.025$; post-sweeps: $r_s = 0.73$, $p < 0.001$). In terms of fleet composition, car counts were moderately associated with pre-sweep (cars: $r_s = 0.48$, $p = 0.039$) sample mass per m^2. This relationship was stronger with the mass per m^2 collected following sweeping ($r_s = 0.73$, $p < 0.001$). Truck counts also moderately correlated with the amount of bulk sample per m^2 collected after sweeping ($r_s = 0.57$, p =

0.010). Additionally, the mass per m^2 of bulk pre- ($r_s = 0.59$, $p = 0.008$) and post-sweepings ($r_s = 0.83$, $p < 0.001$), as well as that for the > 2 mm (pre-sweeping: $r_s = 0.61$, $p = 0.006$; post-sweeping: $r_s = 0.81$, $p < 0.001$) and < 2 mm (pre-sweeping: $r_s = 0.57$, $p = 0.011$; post-sweeping: $r_s = 0.829$, $p < 0.001$) fractions, moderately to strongly correlated with the road surface quality of sampled sites. The results highlight the importance of road surface quality in influencing loadings, as well as its impacts on sweeping efficiency.

Asphalt quality correlated with total traffic ($r_s = 0.775$, $p < 0.001$), car ($r_s = 0.78$, $p < 0.001$) and truck ($r_s = 0.54$, $p = 0.016$) counts. This is not surprising considering that traffic loading is a predictor for road surface quality (Plati and Pomoni, 2019). The resultant asphalt damage, with surfaces with high severity distress indicators like alligator cracking and rutting, supports the accumulation of debris and particles. This, in turn, also reduces sweeping efficiency, as particles can be effectively entrained by cracks, holes, etc. While a limited number of sample sites were assessed in this study, this finding is supported by others, who have reported that the accumulation of particles with a diameter of < 180 μm is associated with pavement quality and the mean texture depth or macro texture of road surfaces in Stockholm, Sweden (Blomqvist et al., 2013; Gustafsson et al., 2019). Amato et al. (2011) also demonstrated that traffic intensity and road pavement type were primary factors influencing road dust (<10 μm) loadings in Barcelona and Girona, Spain and in Zurich, Switzerland.

The mean bulk sample mass collected before and after sweeping was not found to correlate with month of sampling and season (summer vs. fall) nor the duration between the last recorded date of city sweeping as part of its regularly scheduled service. This is in line with prior studies demonstrating that loadings do not increase linearly as a function of time, as road dust accumulation is limited by various site-specific factors (Vaze and Chiew, 2002; Djukić et al., 2018). Loadings on surfaces during dry conditions, for example, are predicted to slow down after several days, as dust will be redistributed by wind and traffic-related turbulence. The lack of a relationship between accumulated debris and service levels may be also reflective of the nature of the study design than the effects of service levels per se. Specifically, the number of days between last city sweeping and sampling was not consistent across sampling sites and dates over the course of the study. The average number of days between sampling and the last sweeping date was 4 for the OC, while it was 26 days for DY. As already discussed, the OC site had consistently the highest amounts of road dust in mass terms, despite the comparatively high frequency of sweeping at this location. The high volumes of traffic and the integrity of the asphalt surface at the OC site (ranked as poor) are clearly important factors contributing to the generation and accumulation of road dust. The dominance of these factors, combined with the lower removal efficiency of the aged regenerative-air sweeper used, may have contributed to an inability to detect a relationship with sweeping service levels. In future studies, it is highly recommended that sweeping frequency or service levels be held consistent across sampling sites to adequately assess for efficiencies.

3.2. Elemental concentrations in road dust pre- vs. post-sweeping

The median concentrations for metal(loid)s measured in pre- and post-sweeping samples for all sites are given in Table 3. The concentrations of many elements in pre-sweepings are comparable to that reported for bulk sweepings (< 2 mm) from arterial roads (n = 23) examined in a prior study of sweepings collected in 2015 and 2016 using regenerative-air street sweepers in Toronto (Wiseman et al., 2021). For example, median concentrations of 877 and 8.3 mg/kg were previously reported for Mn and Co, respectively. In this study, median concentrations of 830 mg/kg for Mn and 7.9 mg/kg for Co were determined for pre-sweepings (Table 3). The elemental concentrations mostly fall within similar ranges reported elsewhere. For instance, median Cu concentrations were also reported to be 158 mg/kg in Padoan et al. (2017) for samples collected in Turin, Italy. This same study also measured comparably higher median concentrations of 463 mg/kg for Cr and 246 mg/kg for Ni. In contrast, a study of road dust deposited on permeable pavements in Denmark reported considerably lower concentrations of Cr, Cu, Pb and Zn for sweepings collected along an arterial road located in a suburban area (Cr: 16.27 mg/kg, Cu: 29.11 mg/kg, Pb: 9.23 mg/kg, Zn 143 mg/kg) (Rasmussen et al., 2023). This could be due to differences in traffic volume and composition characteristics compared to arterials in Toronto, as well as the fact that permeable pavements may allow for elemental leaching from deposited sediments. Rasmussen et al. (2023) also used water to collect sweeps, necessitating that samples first be filtered and dried prior to analysis, which could result in the loss of more soluble elemental fractions and total measurement yields. Variations in reported elemental concentrations for road dust in different studies highlight how results may vary as a function of local conditions and factors such as pavement types, as well as sampling collection and preparation methods.

The concentrations of several elements were found to be significantly higher in pre-sweepings here compared to bulk samples collected from arterial roads in Wiseman et al. (2021), suggesting a possible trend in increased concentrations over time. This includes Na (z = -2.28, p = 0.023), K (z = -3.23, p = 0.001), Al (z = -3.37, p = 0.001), Sn (z = -3.19, p = 0.001), Ba (z = -3.66, p < 0.001) and Cu (z = -2.95, p = 0.003). While it is difficult to determine definitive trends in elemental concentrations based on a comparison of results for a limited number of sampled arterial roads, the significant increase for Cu is highlighted. Cu has been the focus of regulatory efforts to restrict its use as a brake friction material in vehicles, due to this metal's toxicity to fish and other aquatic organisms (Malhotra et al., 2020). For example, the States of Washington (2010) and State of California (2010) enacted legislation in 2010 to phase out the use of Cu in brake linings over time, with a goal of restricting the use of this metal to < 0.5 % by weight by 2025. These laws also limit the use of Cd (0.01 %), Cr (VI)-salts (0.1 %) and Pb (0.1 %) in brake friction materials. This was anticipated to result in a reduction of the targeted metals over time with corresponding shifts detected in non-exhaust emissions, as most auto manufacturers would align themselves with the new regulations. The results here suggest, however, that Cu concentrations in road dust have not decreased, as expected (median concentrations increased from 126 mg/kg in 2015/2016 to 158 mg/kg for 2019). Given the overall significant increases in this metal between the two study periods, further study is recommended to monitor Cu concentrations in road dust to validate the effectiveness of regulatory initiatives and the potential for other source contributions.

Many elements were observed to be enriched in post-sweeping samples relative to those collected prior to sweeping. Differences in elemental concentrations between pre- and post-sweeping samples were determined to be statistically significant at $p \leq 0.01$ for Co (z = -3.62, p < 0.001), Ti (z = -3.14, p = 0.002) and S (z = -2.76, p = 0.006). The concentrations of V (z = -2.24, p = 0.019), Fe (z = -2.09, p = 0.036), As (z = -2.01, p = 0.044), Zr (z = -2.40, p = 0.017) and La (z = -2.09, p = 0.036), Ti (z = -3.14, p = 0.002) were significantly higher in post-sweeping samples at a level of $p \leq 0.05$. Cd (z = -1.73, p = 0.084), Ni (z = -1.65, p = 0.099), and Ce (z = -1.89, p = 0.059) were also found to have higher concentrations in post-sweeping samples, albeit at a relatively weak significance level ($p \leq 0.10$). Only Na (z = 1.85, p = 0.064) concentrations were determined to be significantly higher in pre-sweeping samples.

Changes observed in the elemental concentrations of pre- vs. post-sweeping samples are a likely reflection of a shift in the particle size distribution that occurs with sweeping. As shown in Table 3, particles with larger diameters tend to be more efficiently removed with sweeping. Metal(loid)s that are more likely to be associated with finer particle fractions will be preferentially enriched in road dust that is left behind during sweeping as a result. In an earlier study of sweepings collected in Toronto, it was reported that the thoracic fraction is enriched with several traffic-related elements, including Zn, Cd, Sn and Co (Wiseman et al., 2021). The median elemental removal efficiency of the regenerative-air sweeper used in this study was determined to be lowest for Mg and Pb, with 35 % and 38 % for these two metals, respectively (Table 3). The highest median removal efficiencies were observed for Na, Ti, Cd, Mn, Co, Ba, La and Ce (60–65 %).

Zn concentrations in pre-sweeps were not found to be significantly different from those in post-sweepings for all sites, with median concentrations of 357 mg/kg and 368 mg/kg in pre- and post-samples, respectively (Table 3). However, there was particularly a notable increase in concentrations of this element following sweeping for the LM (26 % increase) and Y (69 % increase) locations (Table 4). These findings highlight a need to consider the spatial variability in elemental concentrations as a function of location and related site-specific factors. Zn, itself, has also come under scrutiny as an element of concern in need of regulatory action, especially in terms of its risk as an aquatic toxicant. Tires are considered to be the most important source of Zn emissions on roads, since it is used as a vulcanization agent in oxide form (ZnO) to

Table 4
Median (min/max) concentrations for measured elements in pre-and post-sweeping samples for each site.

Site										
Element	WV (n = 6)		U (n = 8)		LM (n = 8)		Y (n = 8)		OC (n = 8)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Major elements (wt.%)										
Na	1.1 (1.0/1.2)	1.2 (1.0/1.0)	1.6 (1.5/1.7)	1.5 (1.4/1.6)	1.3 (1.3/1.6)	1.3 (1.1/1.4)	2.7 (2.1/3.0)	2.5 (2.3/3.0)	1.2 (1.1/1.2)	1.2 (1.0/1.3)
Mg	2.9 (2.9/3.1)	3.1 3.09/3.12	2.5 (2.3/2.8)	2.3 (2.1/2.5)	2.5 (2.3/2.7)	2.9 (2.3/3.2)	2.1 (1.9/2.4)	2.4 (2.3/2.4)	2.1 (1.9/2.4)	2.3 (2.1/2.4)
Al	2.7 (2.7/3.0)	2.9 (2.9/3.0)	3.7 (3.6/3.9)	3.8 (3.5/4.0)	3.5 (3.4/3.6)	3.5 (3.1/3.6)	5.2 (4.2/6.1)	5.0 (4.8/5.9)	3.0 (2.9/3.4)	3.0 (2.9/3.2)
Fe	6.7 (5.3/6.8)	5.3 (5.0/7.1)	4.0 (3.5/4.3)	4.6 (4.3/4.8)	4.2 (3.7/4.5)	5.2 (4.3/5.8)	3.4 (3.2/3.8)	4.1 (3.8/4.4)	5.4 (5.0/6.2)	5.4 (5.2/5.7)
K	0.95 (0.91/1.0)	0.93 (0.91/1.0)	0.78 (0.74/1.2)	0.80 (0.77/1.3)	1.1 (0.74/1.2)	1.1 (0.77/1.2)	1.5 (1.4/1.8)	1.5 (1.2/1.6)	1.0 (0.70/1.2)	0.96 (0.72/1.2)
Ca	13 (12/15)	13 (11/13)	11 (11/11)	11 (11/12)	12 (11/13)	12 (9.4/13)	11 (9.1/12)	11 (9.8/12)	13 (13/16)	14 (12/14)
P	0.06 (0.05/0.06)	0.05 (0.05/0.05)	0.04 (0.04/0.05)	0.04 (0.04/0.05)	0.04 (0.04/0.05)	0.05 (0.04/0.06)	0.03 (0.03/0.04)	0.04 (0.03/0.04)	0.04 (0.03/0.04)	0.04 (0.04/0.04)
S	0.14 (0.12/0.14)	0.18 (0.16/0.21)	0.20 (0.18/0.24)	0.26 (0.21/0.31)	0.12 (0.11/0.18)	0.19 (0.14/0.23)	0.10 (0.08/0.13)	0.11 (0.10/0.14)	0.16 (0.10/0.20)	0.15 (0.12/0.17)
Ti	0.25 (0.18/0.27)	0.23 (0.23/0.34)	0.21 (0.19/0.23)	0.24 (0.22/0.25)	0.18 (0.17/0.27)	0.27 (0.22/0.36)	0.14 (0.14/0.24)	0.17 (0.15/0.24)	0.20 (0.14/0.21)	0.19 (0.18/0.21)
Minor elements (mg kg^{-1})										
Cd	0.20 (0.20/0.30)	0.20 (0.2/0.4)	0.45 (0.30/0.80)	0.47 (0.33/0.50)	0.45 (0.35/0.50)	0.70 (0.50/0.80)	0.23 (0.10/0.30)	0.40 (0.33/0.60)	0.35 (0.10/1.1)	0.30 (0.30/0.33)
V	58 (52/65)	53 (48/53)	37 (33/38)	42 (39/43)	37 (34/41)	49 (49/55)	32 (24/38)	35 (29/40)	46 (36/51)	46 (42/53)
Cr	211 (164/242)	157 (147/171)	134 (122/217)	140 (130/178)	131 (98/177)	238 (152/936)	84 (56/110)	77 (67/83)	135 (121/142)	170 (121/187)
Mn	2200 (1970/2320)	1410 1270/1530	822 (702/830)	862 (767/944)	734 (689/896)	929 (780/1040)	666 (607/718)	697 (685/714)	1455 (1310/1630)	1548 (1420/1920)
Ni	35 (32/38)	33 (30/41)	38 (32/50)	39 (35/43)	34 (32/36)	43 (37/84)	24 (22/46)	30 (28/37)	26 (23/33)	27 (26/52)
Co	7.6 (6.1/8.5)	8.2 (8.0/11)	10 (7.9/11)	14 (12/15)	9.10 (9.0/11)	11.2 (8.4/13)	6.3 (5.3/11)	7.4 (5.6/15)	6.80 (6.5/7.4)	7.20 (6.7/17)
Zn	364 (311/398)	328 (303/335)	369 (356/459)	381 (328/465)	470 (408/520)	592 (465/631)	270 (232/326)	457 (272/558)	310 (285/372)	330 (305/368)
As	4.8 (3.4/5.4)	6.2 (6.2/6.3)	3.4 (3.0/4.7)	3.7 (3.5/4.5)	3.5 (3.30/4.6)	4.2 (2.1/4.9)	2.8 (2.4/4.2)	4.1 (4.0/8.0)	4.4 (4.2/5.2)	4.8 (3.8/7.6)
Zr	102 (66/118)	95 (84/108)	88 (69/100)	102 (84/108)	92 (76/113)	121 (89/179)	70 (65/98)	91 (71/118)	87 (64/114)	103 (88/130)
Sb	4.5 (3.3/4.7)	3.8 (2.9/6.3)	3.3 (2.5/5.7)	3.8 (2.6/3.9)	5.3 (4.9/5.8)	5.0 (4.0/8.2)	4.4 (2.5/12)	3.9 (3.4/12)	3.4 (3.2/4.2)	3.8 (2.8/4.7)
Mo	12 (11/12)	9.8 (9.6/14)	8.3 (6.8/10)	8.0 (6.7/10)	8.66 (8.5/9.2)	10.6 (8.7/13)	6.8 (5.1/8.0)	8.4 (7.4/11)	11 (7.8/12)	9.9 (9.1/11)
Sn	10 (7.0/27)	22 (12/94)	17 (15/38)	16 (13/20)	13.0 (11/15)	24.5 (17/44)	40 (11/188)	42 (36/88)	11 (7.0/30)	9.0 (7.0/12)
Ba	334 (306/335)	314 (306/321)	353 (333/363)	354 (345/385)	430 (411/457)	412 (393/442)	259 (227/314)	276 (224/387)	370 (352/386)	356 (324/370)
La	11 (9.8/14)	12 (11/12)	11 (11/12)	13 (13/13)	12.2 (12/14)	14.7 (12/17)	9.7 (7.9/16)	11.4 (9.1/14)	11 (10/13)	11 (9.9/12)
Ce	24 (23/33)	27 (26/27)	26 (25/27)	28 (28/31)	26.6 (26/31)	32.9 (26/37)	21 (17/36)	25 (19/27)	24 (21/29)	23 (23/26)
Cu	288 (230/739)	150 (130/159)	169 (130/184)	199 (162/237)	149 (125/158)	233 (152/391)	230 (155/330)	276 (158/441)	98 (72/144)	110 (72/271)
Pb	110 (103/140)	93 (38/99)	42 (37/46)	50 (43/97)	60 (48/84)	90 (65/108)	66 (58/96)	155 (59/891)	58 (43/64)	51 (33/70)

help strengthen and mould rubber (Councell et al., 2004; Kreider et al., 2010; Baensch-Baltruschat et al., 2020). It has been estimated that more than 10 % of a tire's mass may be released as particles over time, the bulk of which is commonly washed away as stormwater runoff and transported to local waterways (California Stormwater Quality Association, 2015). In mass terms, an estimated total of 1 to 1.5 kg of treadwear particles are released from a tire during its lifetime (Baensch-Baltruschat et al., 2020). Most of these particles are predicted to fall in the coarse particle size mode. However, as much as 10 % of tire wear particles may be emitted in the < 10 μm size fraction (Grigoratos and Martini, 2014; Giechaskiel et al., 2024). For Toronto roads, it was estimated that Zn is deposited in mean annual amounts of 4.2 (±1.1) metric tonnes in an earlier study (Wiseman et al., 2021). While most of this is expected to remain on road surfaces as coarser particles, approximately 10 % of this was predicted to be resuspended in the thoracic-size range. Tires containing Zn are currently being considered for addition to the California Safer Consumer Products Regulations Priority Products list (California Department of Toxic Substances Control, 2021). However, the tire manufacturing industry has expressed concern that they cannot meet federal safety standards without the use of ZnO, as no other metal oxides are purportedly available which may be used as a suitable substitute (USTMA, 2021). This highlights an even greater need for municipalities to consider employing good sweeping strategies and technologies to effectively mitigate dust as a non-exhaust emissions source of Zn.

This study provides valuable insights into the effectiveness of street sweeping to reduce hazardous road dust particles that can impact air quality. Variability in road dust levels and metal(loid) concentrations across sampling sites underscores how local conditions like road surface quality and traffic patterns can modulate sweeping performance and dust accumulation. Overall, this research demonstrates that advanced sweeping technologies can substantially lower hazardous particulate exposures when implemented judiciously based on local factors.

As evidenced here and elsewhere, it is critical that attention be paid to the management and reduction of non-exhaust emission sources in the interest of supporting healthy urban environments. Investing in municipal street sweeping strategies that consider the importance of reliable technologies tailored to site-specific conditions to effectively remove road dust, especially finer-sized particle fractions that are capable of resuspension to the air, need to be prioritized. In addition to improved air quality, regular sweeping employing advanced regenerative-air street sweeping technology has been demonstrated to be effective in extending the performance and functional life of permeable pavement (Scott et al., 2022). This is particularly important in the context of green infrastructure initiatives being currently undertaken by various municipalities, including Toronto, to mitigate the effects of climate change and associated occurrence of extreme precipitation events. Along with other initiatives, the city is currently considering the use of permeable paving solutions to allow for increased water infiltration (City of Toronto, 2017c). Given this, investing in advanced sweeping technologies such as regenerative-air also makes sense in support of green infrastructure efforts to make cities more resilient.

Other road dust mitigation strategies to reduce emissions at the source should include consideration of pavement aggregate size. Amato et al. (2013), for example, demonstrated that the potential for road dust emissions is lower where larger aggregates are used for pavement. They speculated that larger aggregates are less susceptible to wear and tear processes compared to finer ones, which are more likely to be subject to higher wear rates, due to their greater surface areas. The use of higher grade treadwear to make tires more durable under heavy breaking conditions should also be required (Woo et al., 2022). This is especially important given the recent market trends toward the use of electric vehicles, which tend to be much heavier than fuel-driven cars (OECD, 2020). Van Zeebroek and De Ceuster (2013), for example, have reported that electric vehicles (battery operated) are 22 % heavier on average compared to the market equivalents for traditional vehicles. As vehicle weight is a primary factor in the generation of non-exhaust emissions, policies to promote the manufacture of lighter electric vehicles would also help reduce non-exhaust source emissions.

4. Conclusions

This study demonstrated that street sweeping using regenerative-air sweeping technology can be highly effective in reducing road dust loadings, including particle size fractions and associated metal(loid)s that are especially relevant for air quality and respiratory exposures in urban populations. Sweeping was found to reduce the thoracic-sized fraction in road dust by an average of 76 %. Additionally, significant removal of metal(loid)s was observed with efficiencies varying from 35 % (Mg) to 65 % (Co). Traffic volumes were important predictors of road dust loadings and elemental concentrations, as well as road surface quality. In turn, road surface quality was found to impact the efficiency of street sweeping, highlighting the need to have a comprehensive street maintenance program in place to ensure optimal upkeep of roads in support of air quality improvement efforts. The importance of tailoring sweeping efforts locally considering a range of site-specific factors including climate, traffic volumes and the quality of road surfaces is emphasized. It is essential that this be done in conjunction with other efforts to mitigate non-exhaust emissions that pose a respiratory health risk at their source.

Funding.

This study was funded by the Natural Sciences and Engineering Council of Canada (NSERC: Discovery Grants Program, RGPIN-2018–05966) .

CRediT authorship contribution statement

Sourav Das: Writing – review & editing. **Clare L.S. Wiseman:** Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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 reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

Special thanks go to Vesna Stevanovic-Briatico and Stephen Li, City of Toronto, for their valuable input and work in coordinating sampling and in supporting data needs. The authors would also like to thank Transportation Services and the Environment and Energy Division, City of Toronto, for supporting this study. We are also incredibly grateful for the road operations staff who assisted with sample collection.

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Further reading

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