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An emerging source of plastic pollution: Environmental presence of plastic personal protective equipment (PPE) debris related to COVID-19 in a metropolitan city

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ABSTRACT

The COVID-19 pandemic has resulted in an unprecedented surge of production, consumption, and disposal of personal protective equipment (PPE) including face masks, disposable gloves, and disinfectant wipes, which are often made of single use plastic. Widespread public use of these items has imposed pressure on municipalities to properly collect and dispose of potentially infectious PPE. There has been a lack of structured monitoring efforts to quantify the emerging trend of improperly disposed of PPE debris. In this study, we present a baseline monitoring survey to describe the spatial distribution of PPE debris during the COVID-19 pandemic from the metropolitan city of Toronto, Canada. Our objectives were to: (1) quantify PPE debris types among surveyed areas and; (2) identify PPE debris densities and accumulation of surveyed areas. A total of 1306 PPE debris items were documented, with the majority being disposable gloves (44%), followed by face masks (31%), and disinfecting wipes (25%). Of the face masks, 97% were designed for single use while only 3% were reusable. Of the surveyed locations, the highest daily average densities of PPE debris were recorded in the large and medium-sized grocery store parking lots and the hospital district (0.00475 items/m², 0.00160 items/m², and 0.00133 items/m² respectively). The two surveyed residential areas had the following highest PPE densities (0.00029 items/m² and 0.00027 items/m²), while the recreational trail had the lowest densities (0.00020 items/m²). Assuming a business-as-usual accumulation, an estimated 14,298 PPE items will be leaked as debris in just the surveyed areas annually. To facilitate proper disposal of PPE debris by the public we recommend development of municipal efforts to improve PPE collection methods that are informed by the described PPE waste pathways.

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1. Introduction

The use of personal protective equipment (PPE) has supported significant advancements in public health, especially during pandemics (Larson and Liverman, 2011). According to the World Health Organization (WHO), PPE includes disposable gloves, surgical masks, and N95 facepiece respirators (World Health Organization, 2020a). These are made of primarily single-use plastics that serve to reduce contamination and spread disease. Originally, intended to protect health-care workers from infection and injury (Patel et al., 2017), PPE is now being widely consumed by the public in response to the COVID-19 pandemic.

The coronavirus (SARS-CoV-2) initially broke out in Wuhan, China in late 2019, resulting in COVID-19, a severe acute respiratory syndrome (Rothan and Byrareddy, 2020). COVID-19 has high rates of human transmission through respiratory droplets (van Doremalen et al., 2020; Zhou et al., 2020) and the virus has been shown to persist for up to 3 days on inert plastic surfaces (Kempf, 2020a).
et al., 2020; Perlman, 2020; van Doremalen et al., 2020). Precautionary measures aimed to reduce spread have been implemented by governments worldwide to limit physical contact by restricting travel and closing non-essential store front businesses (Centers for Disease Control and Prevention, 2020a; European Commission, 2020; Government of Canada, 2020a). Effective methods to avoid contracting COVID-19 include diligent hand hygiene and washing (Centers for Disease Control and Prevention, 2020b), disinfecting surfaces (Centers for Disease Control and Prevention, 2020c), and the use facing coverings in public places (Leung et al., 2020). Although single-use PPE items are not specifically recommended for use in the above guidelines for the public, global demand and consumption for PPE by the public has greatly increased (Prata et al., 2020; Zambrano-Monserrate et al., 2020).

PPE is produced from a variety of different polymers and materials: polyacrylonitrile, polypropylene and/or polyurethane face masks (Czig et al. and Ronkay, 2020; Leonas and Jones, 2003), latex, vinyl, synthetic polymers, and/or nitrile disposable gloves (Government of Canada, 2019), and other synthetic fibers (e.g., disinfectant wipes; Sattar and Maillard, 2013). Leakage and improper disposal of PPE can cause stress to infrastructure and waste management systems. PPE waste generated by medical sectors moves through tightly regulated and specialized waste management systems that often involve waste sterilization and incineration (Qian et al., 2016; Windfeld and Brooks, 2015; World Health Organization, 2017). In contrast, publicly generated PPE waste from this pandemic is a new phenomenon with which we have no previous experience or waste management strategy. We do not know how much, what types, and the environmental effects that this waste will have. For example, the Annacis Island Wastewater Treatment Plant of Metro Vancouver has observed an increased number of discarded masks, disposable gloves, and disinfectant wipes coming from household sewage since the beginning of the COVID-19 pandemic. The plant estimates that due to these contaminants, Canada-wide maintenance costs could exceed $250 million per year (Rasmussen, 2020).

Waste management protocols for PPE disposal are being developed in response to the pandemic on regional levels and can vary in approach (World Health Organization, 2020b). In Toronto, Canada, the city’s waste management division released Special Waste Disposal Instructions to inform residents of how to dispose of personal hygiene and sanitary waste during COVID-19 (e.g., “wipes, tissues, napkins, paper towels and other sanitary and hygiene products” (City of Toronto, 2020b). These instructions advise the public to dispose of PPE in garbage bags along with the domestic waste that is diverted to municipal waste management facilities (City of Toronto, 2020a). As the integration of COVID-19-related debris through regular waste management processes is new and because of the potential for both environmental and infrastructure degradation, implementing an effective collection system with proper disposal is necessary to reduce the release of COVID-19 contaminated plastic into the environment (Georgia Department of Natural Resources, 2020).

Since the early start of the pandemic and despite management efforts and announcements, there have been worldwide anecdotal reports of improper disposal and littering of PPE by the public in environmental spaces (Canning-Clode et al., 2020; Prata et al., 2020; The Observers France 24, 2020). An estimated 2% of pre-pandemic plastic waste is mismanaged by littering (Forrest et al., 2019; Jambeck et al., 2015; Lebreron et al., 2019). A recent (and conservative) estimate of the global mismanagement of PPE found that a monthly average of 129 billion face masks and 65 billion gloves contributed to environmental plastic pollution (Prata et al., 2020). Given the global scale of consumption of PPE, our aquatic and marine environment will likely be subjected to more plastic pollution from these emerging debris items.

Although initial estimates offer insight into the mounting problem of PPE on a global scale, little empirical data have been collected because the pandemic has restricted the ability for individuals and organizations to conduct field studies, especially those in coastal areas (e.g. OSPAR Commission, UNEP, NOAA) (Canning-Clode et al., 2020). In addition to the lack of debris data collected during the pandemic, there is also a growing need to identify key debris items within the emerging PPE category (Canning-Clode et al., 2020). There should be a focus on identifying macroplastics (>5 mm) so that we can better understand the way in which fragmentation can eventually lead to the generation of microplastics (<5 mm) (Fadare and Okoffo, 2020). Therefore, the COVID-19 pandemic offers a unique opportunity to monitor and characterize environmental spillage from a pulse-like event that results in plastic polluting our environment (McCleery et al., 2020).

In this study, we conducted a PPE monitoring survey to assess debris abundance of face masks, disposable gloves, and disinfectant wipes that were improperly disposed of and present in the urban environment. Surveys took place in Toronto, Canada, a metropolis of approximately 2.9 million people (2018) located in Southern Ontario (City of Toronto, 2020b). We conducted an accumulation survey for at least 5 weeks in a variety of settings including two residential areas, a recreational trail near a major river system in Southern Ontario, two commercial grocery store parking lots and the downtown hospital district. We have established the baseline of PPE accumulated during the pandemic. Our objectives were to: (1) quantify PPE debris types between surveyed areas, and (2) identify PPE debris densities and abundance of surveyed areas. This research will examine the prevalence and distribution of PPE debris in different contexts and can help to inform PPE management during pandemic events.

2. Materials and methods

2.1. Data collection

Surveys were conducted in six different locations throughout metropolitan Toronto, Ontario, including two residential areas in the same community (i.e., long residential and short residential), two commercial grocery store parking lots (i.e., large and medium sized), a recreational trail, and a hospital district to include a range of human activity (see Supplementary Material Table S1 for detailed descriptions of each). Locations were selected in order to adhere to shelter-in-place orders from the provincial government that were in place at the time of sampling (Government of Ontario, 2020a). Surveying took place between May 27 and June 30, 2020 with the grocery and hospital surveys occurring every seven days, and the residential and recreational trail surveys occurring every two and five days.

Data were collected using a citizen-science tool developed at the University of Georgia New Materials Institute called the Marine Debris Tracker (https://marine_debris.engr.uga.edu). This mobile application is used to document debris in any environment (e.g., coastal, inland, aquatic and urban) and features an open source database. The application records time and geospatial coordinates associated with user input debris items based on material type (i.e., glass, metal, plastic, etc.) and item type (i.e., jar, bottle cap, plastic bag, etc.). Each data recorded had an individual location accuracy,
which ranged from 4.7 to 2000 m. The average accuracy was 97 m. Out of 1126 data points, 83% had an accuracy of at least 100 m and 95% had an accuracy within 200 m.

For this research, a material category for PPE debris was added to the “University of Georgia New Materials Institute Debris Tracker” list to record specific items including disposable gloves, face masks, disinfecting wipes, and associated PPE packaging such as disinfectant wipe packaging (Fig. 1). Data related to other, non-PPE debris items were not recorded for this study. Face masks were then categorized into different types: surgical masks, dust masks, high grade medical masks (i.e. N95 and KN95), and reusable masks. We classified disposable gloves based on their material types through visual examination of colour and texture: nitrile (black or blue), vinyl (translucent), latex (white) and polyethylene (transparent with a larger fit than vinyl). It was not possible to verify what purpose disinfectant wipes were initially used for prior to becoming debris. To identify this item, we tested their ability to tear to ensure they were not paper-based tissues or paper towels and looked for indicators such as patterns on the wipes (i.e. square or honeycomb) (Bliss, 2016).

We looked for debris at ground-level with a gaze from the standing height of the researcher (~1.7 m from the ground). As we surveyed large areas that varied in size and design with unique human-made and environmental elements, we developed protocols to record PPE debris in a standardized approach for each surveyed location (e.g., consistent area lengths, widths and surface areas). Within our surveys, we measured the width of sidewalks, recreational trails and streets (except for major arterial roads with high traffic). We collected debris that was ~1 m and ~5 m from the closest edge of the sidewalk in residential driveways and commercial parking lots, respectively. By contrast, we surveyed the whole surface area of recreational trail parking lots and small greenspaces (e.g., parks, parkettes, and hospital green spaces). For recreational trail surveys, if there were open and wide grassy areas surrounding the trail, we recorded debris up to 10 m from the closest edge of the trail whereas we surveyed between ~1 or 5 m off trail (depending on visibility) if the trail was surrounded by vegetation. Lastly, we assessed the entire surface area of two grocery store parking lots by surveying PPE debris around the building and down every parking aisle. We recorded debris from under cars if they were visible from eye-level and also from the inside of shopping carts. We were sure to examine infrastructure features like garden beds as these often contained discarded debris. All survey distances were measured through Google Earth Pro, Version: 73.3.7699 (https://www.google.com/earth/versions/).

Given the health risk associated with data collection during a pandemic, appropriate safety measures were taken, and local recommendations were followed. Survey locations aligned with essential activities that were permitted to be conducted during shelter-in-place rules. To reduce exposure, physical distancing was maintained, and monitoring was conducted after 17:00 when there were fewer people outdoors. PPE debris was safely collected by using a specialized metal stick equipped with a hand-held claw (Drive™, Model #rtl5020) to prevent direct contact. Hand sanitizer was carried at all times and used frequently throughout surveys. Following surveys collected PPE was double bagged and securely tied before being placed in the researcher’s residential garbage.

2.2. Data analysis and visualization

Marine Debris Tracker data are open source allowing for data associated with the PPE debris surveys to be downloaded directly from the website. The data were further aggregated by the survey locations. Abundance was measured by recording the count data on every survey day at each location to determine the total amount of PPE debris. Debris density was determined by dividing the item counts by the area covered in each survey and reported in item/m². For each location, the minimum, maximum, mean, and standard deviation (SD) were determined for all survey counts and densities. Total counts and densities were also determined for each survey location and the entire dataset (Table 1). Accumulation rates for each location were determined by dividing the mean counts and mean densities by the frequency of sampling per week (Table 1). Abundance, density, and accumulation were also determined for each PPE type for the entire dataset and for each survey location. Data were extrapolated over time to estimate the annual accumulation of PPE debris in the surveyed areas by taking the survey frequency and multiplying it by the mean survey count resulting in a daily accumulation rate. This value was then extrapolated to an annual debris value for the areas surveyed (Table 1). All data points were used for analysis since the quantity of items is not affected by the accuracy of geospatial coordinates provided by MDT. For PPE debris with recorded subcategories like types of face masks (e.g., surgical, dust, etc.) and disposable glove materials (e.g., nitrile, vinyl, etc.), the proportion within each PPE category was calculated.

MDT data were visualized geospatially using ArcMap 10.8 and overlaid with data provided from the City of Toronto Open Data Portal (https://open.toronto.ca) for watercourses, roads, neighborhoods and major water bodies. Data that had >100 m accuracy were excluded from these visualizations. Graphs were generated using the software program Prism 7.0.

3. Results and discussion

The presence of PPE debris was recorded in 43 of 44 surveys. A total of 1306 items were surveyed over a cumulative area of 245,190 m² for the six sampled locations (Table 1; Fig. 2A). The smallest sampling location by area was the medium-sized grocery

Fig. 1. COVID-19 related personal protective equipment (PPE) debris recorded during surveys: (A) surgical face mask, (B) N95 respirator face mask, (C) dust face mask, (D) reusable face mask, (E) associated PPE packaging (i.e. disinfectant wipe container), (F) nitrile glove, (G) polyethylene glove, (H) nitrile glove, (I) vinyl glove and, (J) disinfectant wipe.
3.1. Quantify PPE debris items and associated categories between surveyed areas

The average count in a given survey was 30 items (SD = 38), with individual survey counts ranging from 0 to 202 items (Supplementary Material Table S2). The highest total count of items was found at the large grocery store (45%; n = 584; Fig. 3A), followed by the hospital district (20%; n = 256; Fig. 3F), and the long residential area (15%; n = 194, Table 1; Fig. 3C). Throughout the recreational trail 143 items were recorded (10%; Table 1; Fig. 3E). The smallest overall counts seen at the short residential area (5%; n = 64; Fig. 3D) and the medium-sized grocery store (5%; n = 65; Fig. 3B). The most reported item was disposable gloves, representing 44% (n = 571) of all items, followed by face masks (31%; n = 403) and disposable wipes (25%; n = 331). Packaging associated with PPE accounted for <1% (n = 1) of all items (Supplementary Material Table S2). Cumulative densities (items/m²) for PPE from the different surveyed locations closely reflect the above findings (Fig. 2B).

Across the six survey locations, the proportion of disposable gloves ranged from 27 to 54%, with an average of 41% (SD = 8.9%). The large grocery store had the highest proportion of disposable gloves at 54% (n = 307), followed by the long residential area (48%; n = 94), and the short residential area (42%; n = 27, Supplementary Material Table S2). Of the 571 recorded gloves, most (59%: n = 337) of these were identified as nitrile, followed by vinyl (27%; n = 154), polyethylene (7.2%; n = 41), and latex (6.8%; n = 39) (Fig. 4A). The high proportion and abundance of disposable gloves were surprising given the absence of government guidelines from both local and national levels recommending use of this PPE item by the general public. Within the province of Ontario, it was only recommended that disposable gloves be used outside the medical sector by personal care industries and their workers (i.e., salons, tattoo studios, etc.) (Government of Ontario, 2020b). Despite recommendations like those from the Centers for Disease Control and Prevention in the United States that explicitly state “in most other situations, like running errands, wearing gloves is not necessary” (Centers for Disease Control and Prevention, 2020d), it is evident that members of the public are choosing to use gloves. Wearing gloves can lead to a false sense of security about protection against COVID-19 despite the fact that the virus can remain inert on plastic surfaces (van Doremalen et al., 2020), and it has been repeatedly advised by multiple levels of governments and health organizations that hand washing is the most effective way to combat COVID-19 (Centers for Disease Control and Prevention, 2020e; City of Toronto, 2020c; World Health Organization, 2020b). As shown by our data (Fig. 1; 4A), gloves come in a variety of different materials and are made for different industries beyond the medical sector such as janitorial, culinary, and mechanical automotive (Dolez et al., 2010). Therefore, because gloves are more readily available than other forms of PPE, this could contribute to the availability and mass consumption resulting in the highest percentage of improperly disposed PPE we recorded in this study. The lowest proportion of gloves by survey location was recorded in the hospital district (27%, Supplementary Material Table S2) which might be because face masks are heavily mandated to be used by patients, visitors and medical professionals and of higher demand in medical

store (8149 m²) and the largest was the recreational trail (72,452 m²), with the average size of sampling areas being 40,865 m². The number of surveys carried out in each location ranged from 4 to 10, with four surveys carried out at the hospital district, five surveys carried out at the large and medium-sized grocery stores, and ten carried out at the recreational trail and the long and short residential areas.

### Table 1

| Survey location               | density (items/m²) | accumulation rate (items/day) | estimated items/year | Daily min. | Daily mean | Daily SD |
|------------------------------|--------------------|-------------------------------|---------------------|------------|-----------|----------|
| Hospital district             | 4                  | 4                             | 80                  | 3          | 4         | 0.3      |
| Large grocery                 | 5                  | 5                             | 100                 | 2          | 3         | 0.3      |
| Medium-sized grocery store    | 10                 | 10                            | 200                 | 4          | 5         | 0.5      |
| Long residential area         | 10                 | 10                            | 200                 | 4          | 5         | 0.5      |
| Recreational trail            | 10                 | 10                            | 200                 | 4          | 5         | 0.5      |
| Short residential area        | 10                 | 10                            | 200                 | 4          | 5         | 0.5      |
| Total                         | 40                 | 40                            | 800                 | 20         | 25        | 2.5      |

The survey results were conducted across six survey locations, including debris counts, densities (items/m²), accumulation rates (items/day) and estimated items/year in survey locations. Also presented are standard deviation (SD), daily minimum (min.) and daily maximum (max.) counts.
institutions as opposed to gloves.

Face mask proportions ranged from 15 to 64% among the six survey locations, with an average proportion of 32% (SD = 17%). The highest proportion of face masks was in the hospital district (64%; n = 165) while the lowest proportion was seen in the medium-sized grocery store (15%; n = 10, Supplementary Material Table S2). The high volume of masks from the hospital district was generally expected because of the mandatory measures in place to wear face covering (Sick Kids, 2020; University Health Network, 2020). By type, most face masks were surgical masks (95%; n = 381), followed by reusable masks (3.0%; n = 12), and dust masks (2.0%; n = 8) (Fig. 4B). Only two high grade medical face masks (i.e., N95 and KN95) were found in the survey (<1%), with the remaining masks being standard surgical masks that were made available to incoming patients and visitors at some of the hospitals. Overall, the majority of face masks found were intended for single use (i.e., surgical, dust and respirator masks) (97%; n = 391) with a small portion being reusable (3.0%, n = 12) (Fig. 4C). It is important to note that although reusable masks are less likely to be discarded when compared to single-use masks, pollution and debris generation from this category is already happening.

The proportion of disinfectant wipes among the survey locations ranged from 8.6 to 46% with an average proportion of 27% (SD = 12%, Supplementary Material Table S2). The highest proportion of disinfectant wipes found was at the medium-sized grocery store (46%; n = 30), followed by the recreational trail (34%; n = 49), and the long residential area (30%; n = 59, Supplementary Material Table S2). Given that disinfectant wipes are commercially available through multiple retail locations including the grocery stores surveyed, it is unsurprising that this form of PPE debris made up the majority from this survey. The widespread presence of disinfectant wipes was also noted in urban debris surveys in South Africa during the pandemic; within surveys this PPE item exceeded the numbers of face masks and gloves that were recorded (Ryan et al., 2020). Companies that produce sanitary and disinfectant products like Reckitt Benckiser (major producer of disinfectant wipe products) reported 2020 first quarter earnings were up by 12.3%; there was an “exceptional demand” for hygiene related products in March and April (Reckitt Benckiser, 2020). Widespread use of these single-use plastics come with listings from Health Canada as they are an effective means of disinfecting against COVID-19 (Government of Canada, 2020c). Given the prevalence of disinfectant wipes in our surveys we recommend that future investigators include this type of PPE into their studies.

3.2. PPE debris densities and accumulations between surveyed areas

Among all 44 surveys, the daily density of PPE ranged from 0 to 0.00822 items/m², with a mean of 0.00101 items/m² (SD = 0.00155, Table 1). If the null survey value is removed, the minimum becomes 0.00007 items/m². Across the six survey locations, the average density of PPE debris area ranged from 0.00020 items/m² to 0.00475 items/m², with a mean of 0.00140 items/m² (SD = 0.000159, Table 1). Despite repeatedly surveying areas and removing the debris, there was no PPE debris identified (i.e., short residential area) in only one survey. The cumulative densities among surveyed locations, ranged from 0.00475 items/m² for the large grocery store parking lot to 0.00133 items/m² for the recreational trail. Overall, the average cumulative density was 0.04456 items/m² (Fig. 2C). When taking into account time, accumulation rates ranged from 1.8 items/day in the short residential area to 16 items/day at the large grocery store, with an average rate of 6.5 items per day across all survey sites. The extrapolated annual accumulation ranged from 667 items in the short residential area to 6101 items in the large grocery store. In total, 14,298 PPE debris items are estimated to be leaked in the surveyed areas on an annual basis under business-as-usual management (Table 1).

The highest average density of PPE that was identified was the large grocery store parking lot at 0.00475 items/m² (SD = 0.00194, Table 1). This was unsurprising given that the province was in Phase 1 and 2 of lockdowns and grocery stores remained open to the public as an essential service during the time that the surveys were conducted (Government of Ontario, 2020b; Supplementary Material Table S2).
Material Fig. S1). In conducting these surveys, there was an absence of signs indicating how to properly dispose of PPE in general waste bins. In a number of instances, PPE debris was discarded in shopping carts and beside cars; it was unknown whether PPE were unintentionally or intentionally discarded from shoppers. Furthermore, this grocery store was located in a plaza that was enclosed and surrounded by fencing from the neighboring provincial and city expressways, allowing for debris to accumulate. Since commercial parking lots are not public property, they are not subjected to cleaning by the municipality and protocols for debris accumulation.

Fig. 3. PPE types by survey locations: (A) large grocery store, (B) medium-sized grocery store, (C) long residential area, (D) short residential area, (E) recreational trail and, (F) hospital district. Data Sources: City of Toronto Open Data Portal and Marine Debris Tracker. Data points with an error radius >100 m were removed for clearer visualization.
removal vary. The trend of high PPE densities in commercial parking lots was supported by the medium-sized grocery store that had the second highest average density of PPE debris of the surveyed areas (0.00160 items/m²; SD = 0.00047; Table 1). Although this survey location was not as busy as the large grocery store (i.e., parking lots never filled to capacity), there were multiple entry points that could have also contributed to PPE debris accumulation. Overall, it should be noted that although parking lots are developed and intended for commercial purposes, accumulation of debris in these areas can be the beginning of pathways to waterways and natural areas (Sheavly and Register, 2007).

After the two commercial grocery store parking lots, the hospital district survey had the third highest average accumulation of PPE debris (0.00133 items/m²; SD = 0.00026; Table 1). Our survey primarily focused on areas in proximity to medical facilities (i.e. entrances and green spaces from the street level) and although there was a high volume of general traffic, we found trends consistent with this debris arising from the medical facilities themselves (see section below). Similarly, PPE debris including masks and a high number of disinfectant wipes were discarded in proximity to a community health clinic in Durban, South Africa (Ryan et al., 2020). As hospitals have relatively contained and strict waste management systems (Government of Ontario, 2020c; Windfeld and Brooks, 2015) this finding was unexpected. However, given that most hospitals required visitors and patients to wear masks as a safety precaution early in the pandemic (Sick Kids, 2020; University Health Network, 2020) the high quantities of PPE debris are most likely derived from non-medical professionals. Interestingly, it was noted by a representative from the University Health Network (a hospital network that includes some of hospitals that were surveyed) that “the overall flow of garbage hasn’t gone up even though more personal protective equipment (PPE) is going into the trash” (McIntosh, 2020). This might be because many people that would normally visit a medical facility were staying home while COVID-19 patients were being treated. Although total quantities of medical waste were not directly influenced by COVID-19, the outdoor perimeters of these institutions exemplify an increase in leakage from the local institutions in this area.

Both the long and short residential surveys had lower PPE densities than the commercial grocery store parking lots and hospital district. The long residential area having an average of 0.00029 items/m² (SD = 0.00013) and the short residential area having an average of 0.00027 items/m² (SD = 0.00019; Table 1). Although residential areas consisted mostly of housing structures there were other types of infrastructure (e.g., small commercial buildings, schools, a rehabilitation hospital, bus stops, parks, etc.), which evidently did not seem to contribute to higher quantities of PPE litter in the area. Notably, the majority of houses directly within the surveyed areas were detached homes with a lower population density than multi-family housing (>5 stories) with more residents. As the municipality had asked residents to securely bag up their PPE and other hygiene product waste, this might have contributed to low leakage numbers relative to the other surveyed sites (McIntosh, 2020). Given the stay-at-home orders by the provincial government and the closure of many small businesses and cancellations of community events during this sampling period, this may have resulted in lower counts of PPE in the area. Similarly closures of potential sources for debris (i.e. retail and government buildings) may have resulted with reduced litter loads recorded in debris surveys conducted in South African urban mixed-residential areas during COVID-19 lockdowns (Ryan et al., 2020). As closures varied at different stages of the lockdowns it was suggested by authors that litter loads would have been higher in non-mixed residential areas. Generally during the strictest lockdown litter loads of different types of materials (e.g. plastic, paper, metal, glass, etc.) were the lowest but increased as lockdown restrictions eased (Ryan et al., 2020). Although the presence and mass of PPE debris increased with the duration of the pandemic and lockdowns, overall, PPE consisted of a small proportion of <1% of the total debris collected (Ryan et al., 2020). The low proportion of single-use PPE could be attributed to the widespread use of reusable items like cloth face masks.
Lastly, the recreational trail survey was found to have the lowest density of PPE debris (0.000020 items/m²; SD = 0.00010) after the short residential area (Table 1). Although the recreational trail covered the largest surface area of the locations surveyed, it was restricted to non-motorized modes of transportation (i.e. walking and cycling) which reduces traffic. In addition, people can practice social distancing more easily in the recreational area and may not have a need for PPE like they do inside a store or hospital, so use is likely less. The PPE accumulation rate of the recreational trail was 4.1 items/day, which was relatively lower than the average for all surveys (6.5 items/day; Table 1). Even though the accumulation of PPE was less than that of the other surveyed areas, the trail was in direct proximity to the Humber River, the largest watershed in the region of Toronto which flows into Lake Ontario (Corcoran et al., 2015; Toronto and Region Conservation Authority, n.d.), making it a higher risk region for environmental degradation. Creeks and rivers are significant pathways for plastics to be transported which can increase plastic contamination through rainfall and wind conditions (Corcoran et al., 2015; Hoellein et al., 2014). Corcoran et al. (2015) found that plastic pellets recovered from the Humber River bank were consistently found in the Humber Bay in Lake Ontario, establishing the loading capacity of the river into the lake. Therefore, any PPE debris within proximity of the river would pose an increased risk to both aquatic and terrestrial environments.

The density of PPE debris varied daily due to the differences in survey locations on a given day and time between surveys that allowed for more accumulation between them. For example, on Sample Day 3, only the recreational trail and the short residential area were surveyed resulting in lower quantities for that day (n = 23) and a density of 0.0057 items/m² (Fig. 5A). In contrast, on Sample Day 14, the large grocery, medium grocery, recreational trail, and short residential areas were all surveyed, resulting in a total of 141 items documented that day and a combined density of 0.0156 items/m² (Fig. 5A). When cumulatively added over time across all surveys, PPE debris densities increased linearly ($R^2 = 0.97$), indicating that consistent quantities were documented in each survey over time (Fig. 4B). In terms of accumulation by count, the average daily accumulation across sites was 6.5 items/day, with the smallest accumulation rate occurring at the short residential area and the largest occurring at the large grocery store (Table 1).

We identified an atypical peak from the usual densities of PPE debris found in the parking lot of the large grocery store on day 34 which was the day before a national holiday (Canada Day, July 1st; Fig. 5A). Although PPE densities were relatively higher for the large grocery store compared to the other survey locations, there were 88% more than the average number of PPE debris items at this location than on non-holidays. Other pulse events such as festivals and events can also prompt large changes in waste management (i.e. more waste bins, advertisements, etc.). In previous debris surveys on coastlines of Lake Michigan, it was observed that tourism in the summer months were associated with high debris levels (Hoellein et al., 2014). By contrast, during the tourist season in Mar del Plata, Argentina litter loads were not drastically different from the non-tourist season despite high influxes of people. Although debris was generally associated with areas of high pedestrian traffic and parked vehicles, the lack of debris during this period may have been due to regular removal from street cleaning (Pon and Becherucci, 2012). Therefore, a pandemic is similar in that we need to adapt infrastructure and increase communication to get the public to continue with good waste management practices under dynamic conditions.

Over the course of this study, we faced several limitations. Firstly, our study focused on a single category of debris which limited our ability to compare PPE debris quantities in relation to other debris materials and categories that were also mismanaged during the pandemic. Silva et al. (2020) describes the potential of increased plastic pollution due to higher and demands and use of single-use plastics like food packaging. Therefore, it would be valuable to monitor PPE debris and other single-use plastics being widely consumed during the pandemic to better quantify leaked plastics into the environment. In addition, given the lack of international guidelines adapted for monitoring debris during pandemic conditions, we were unable to use protocols that were adapted widely by different organizations. It was challenging to establish monitoring standards that would accurately measure PPE debris and determine the appropriate number of survey locations. Similar to previous investigations examining litter loads during COVID-19 (i.e. Ryan et al., 2020), we were unable to collect pre-pandemic baseline data. However in previous debris surveys based in coastal environments, medical-related debris comprised a relatively small proportion of the total debris items recorded (~0.2%; Nelms et al., 2020). Lastly, our study could be improved by conducting long-term surveys in different regions to better represent various demographics and populations during this global event.

Overall, the abundance of PPE debris appears to correspond to human activity, with higher abundance and accumulation rates seen at the commercial areas like the large grocery store and the hospital district. It was noted in all of the surveyed areas that only waste bins placed before the pandemic were available to the public, suggesting that integration of targeted waste management infrastructure for PPE waste could help to address the challenge of managing pandemic-specific debris. In addition, these did not have any accommodations for a touch-free option for users to discard.
their waste, which could account for why people opted to discard their PPE on the ground. In order to reduce cases of PPE littering, waste bin types and locations should be modified to facilitate and encourage the proper disposal of PPE.

COVID-19 has elevated global dependency on plastic products to facilitate safety against infection (Vanapalli et al., 2021). Urgent attention is needed to address the threat of plastic PPE litter, and strategies for management can range from reducing excessive use and consumption of PPE items, shifting to sustainable alternatives (i.e., reusable face masks), and prioritization of the problem in political agendas throughout the world (Silva et al., 2021; Vanapalli et al., 2021). For the duration of and following this pandemic global dependency on plastics may be elevated from pre-pandemic levels; therefore, we need to determine leakage points and interventions so that PPE debris leakage does not pose future problems (Vanapalli et al., 2021).

3.3. Conclusions

Our study demonstrates the differences in the spatial distribution of PPE debris among different surveyed areas. Generally, the most abundant debris items were disposable gloves followed by face masks and then disinfectant wipes. The highest number of disposal gloves were found in the parking lot of the large grocery store while the most face masks were found in the hospital district; these surveyed areas also had the highest densities of PPE debris most likely due to high traffic and public use. By contrast, the recreational trail featured the lowest PPE debris densities, but it is important to note this area may have more direct pathways for debris to enter the aquatic environment due to its proximity to the Humber River and for this reason must be closely monitored.

Addressing and reducing the problem of PPE plastic pollution requires transdisciplinary collaboration between natural and social scientists, policymakers, and waste managers on both municipal and national levels. To facilitate proper disposal of the rapidly and continues growth in volumes of PPE waste from the public, we recommend the following: (1) encourage the public to reduce the use of disposable gloves, and wash hands frequently instead, (2) encourage, and make accessible, reusable face masks that can be frequently disinfected, (3) develop proper PPE disposal practices, learn about the nuances of PPE management pathways and implement improved collection methods that are accessible to the public and, (4) raise widespread awareness on proper PPE disposal practices through targeted government promotion and education campaigns. In protecting ourselves against COVID-19, we should not jeopardize the integrity of environmental health and create a future dilemma in the form of plastic pollution from PPE consumption.

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Declaration of competing interest

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Appendix A. Supplementary data

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