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The case of "public congregation vs. COVID-19 PPE pollution": Evidence, lessons, and recommendations from the annual pilgrimage to the Catholic Holy Site in Mexico City, Mexico

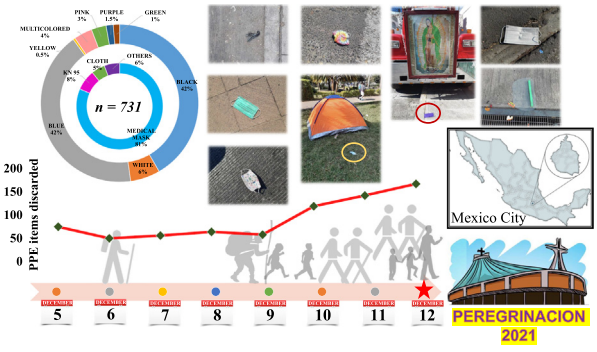
Gurusamy Kutralam-Muniasamy [a,*], V.C. Shruti [b,*]

[a] Department of Biotechnology and Bioengineering, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Ciudad de México, Mexico
[b] Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), Ciudad Universitaria, Del. Coyoacán, C.P. 04510 Ciudad de México, Mexico

HIGHLIGHTS

- First study investigating the pollution from COVID-19 personal protective equipment (PPE) in Mexico City
- The PPE density per day varied between 4.1×10^{-3}–13.9×10^{-3} items m^{-2}.
- The color classification revealed the prevalence of black and blue medical masks.
- Increased COVID-19 PPE litter in the study area is influenced by major public events.
- Much efforts are required to promote public awareness and social responsibility.

GRAPHICAL ABSTRACT



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ABSTRACT

Pollution from personal protective equipment (PPE), particularly face masks, has surfaced in the marine and terrestrial environments globally since the COVID-19 outbreak due to improper disposal practices and inadequate waste management, raising widespread alarm and attention. Our understanding of the prevalence and distribution of PPE in highly populated metropolitan areas is still emerging, and studies focusing specifically on developing countries in Latin America remain sparse. This study attempted to "kill two birds with one stone" by (1) addressing this knowledge gap by analyzing the degree of improper dispensing of PPE in Mexico City (Mexico) and (2) investigating the impact of massive public congregations on PPE contamination during the yearly pilgrimage to the Villa de Guadalupe on December 12th. Our survey findings revealed 731 PPE items within a 6-kilometer radius between December 5 and December 12, 2021, with daily densities ranging from 4.1×10^{-3}–13.9×10^{-3} PPE items m^{-2}. Face masks were the most disposed type of PPE (94%), with gloves and face shields accounting for just 6% of the total. The PPE disposal more than doubled as the pilgrim day approached, with an estimated disposal rate ranging from 151.52 to 506.06 items day^{-1}, substantiating the surge in the disposal of used PPE to large public congregations that filled the surroundings during the pilgrimage. The observed average PPE density of 7.8×10^{-3} items m^{-2} was higher than in the metropolitan environments of Canada, Ghana, and Turkey. To our knowledge, this first study describes information showing the need to pay attention to the major impact of public events and mobility on COVID-19 PPE pollution, as well as emphasizes the necessity for adequate management facilities in improving PPE disposal.

1. Introduction

Since the emergence of coronavirus disease (COVID) in China in late 2019, the world has been dealing with the COVID-19 pandemic, which

* Corresponding authors.
E-mail addresses: mgurusamy@cinvestav.mx (G. Kutralam-Muniasamy), shrutiv@geologia.unam.mx (V.C. Shruti).

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has become the global health crisis of our time. Using a range of personal protective equipment (PPE), including face masks, wet wipes, gloves, shields, and aprons during the pandemic to limit the transmission of COVID-19 is one of the most effective human-made measures. Face masks of two types: single-use-disposable (melt-blown nonwoven fabrics and include N95 and surgical masks) and reusable (cloth masks) have been prevalent in recent years, which includes a variety of forms, colors, and designs with different filtering performance. Furthermore, polyurethane, polycarbonate, polypropylene, polystyrene, polyacrylonitrile, polyethylene, or polyester make up a large component of face masks (Fadare and Okoffo, 2020; Aragaw, 2020). The unprecedented demand, production, and usage of PPE, particularly face masks, has had a large impact on the plastic waste associated with COVID-19 PPE (Adyel, 2020). For example, Chowdhury et al. (2021) estimated that 0.15 million to 0.39 million tons of plastic waste could eventually end up in the coastal and marine environment. Poor PPE management and disposal practices can result in littering the terrestrial and marine habitats, and like other discarded plastic, they degrade slowly and remain in the environment for an extended period of time, causing widespread concern among the public and scientific community (Kutralam-Muniasamy et al., 2022). Furthermore, face masks have become a possible source of billions of microplastics after being discarded into the streets and into oceans (e.g., Morgana et al., 2021; Wang et al., 2021; Saliu et al., 2021; Ma et al., 2021; Li et al., 2021), releasing a variety of organic and inorganic pollutants into the environment (e.g., Liu and Mabury, 2021; Fernández-Arribas et al., 2021; De-la-Torre et al., 2022). Also, research has developed indicating that PPE, like other marine litter, can interact with biota. Ingesting PPE or the microplastics released by PPE could harm organisms´ health and end up in the food chain of aquatic and terrestrial environments (Kutralam-Muniasamy et al., 2022; Silva et al., 2021; Kwak and An, 2021). Thus, it is critical to comprehend where they are deposited and accumulated, as well as when the general public is exposed to discarded PPE, particularly face masks. This prompted the researchers to assess novel PPE pollution driven by the COVID-19 pandemic and identify the prevalence and distribution of disposed PPE items in a multitude of environments.

Currently, PPE pollution has been well-documented in several oceans, tourist beaches (e.g., Thiel et al., 2021; De-la-Torre et al., 2021, 2022; Akhbarizadeh et al., 2021; Rakib et al., 2021), and freshwater systems (e.g., Cordova et al., 2021), with the majority of investigations focusing on the marine ecosystem (Kutralam-Muniasamy et al., 2022). In view of the decrease in current SARS-CoV-2 instances, almost all countries have withdrawn or postponed their lockdown bans and have resumed activities under strict restrictions. Resuming activities will result in increased waste management burdens, and it is vital to understand how this process of normalization will unfold in terms of waste management and COVID-19 PPE pollution. Currently, only a few have investigated improperly discarded PPE in the streets of metropolitan cities near schools, hospitals, and residential areas in Canada (Ammendolia et al., 2021; France, 2021), Kenya (Okuku et al., 2021), South Africa (Ryan et al., 2020), Ghana (Amuah et al., 2021), Bangladesh (Abedin et al., 2022), and Turkey (Akarsu et al., 2021). These study findings strongly suggest that public mobility has a substantial effect on the disposal and buildup of PPE waste in metropolitan areas. Nonetheless, there is a dearth of knowledge on how public mobility associated with massive social gatherings impacts COVID-19 PPE pollution in densely populated areas, and studies on this issue are lacking. We sought to draw attention to massive public gatherings since they are well recognized for their potential to generate hundreds of tons of solid waste in a short period of time, posing challenges to local governments and necessitating extra-care specialized waste management solutions, particularly in developing countries. In current work, we aim to investigate the changing patterns of occurrence, characteristics, and density of PPE items during the yearly pilgrimage of millions of people to the Villa de Guadalupe in Mexico City (Mexico), in order to better understand the impacts of massive public gatherings on PPE littering during the COVID-19 pandemic. By doing so, this study achieved “two birds with one stone” by: (1) addressing the knowledge gap of COVID-19 PPE pollution in Latin American metropolitan areas and (2) investigating the influence of massive public gatherings on PPE pollution in the urban environment. Therefore, the findings of this study will help to identify societal behavioral trends regarding PPE improper disposal during public gatherings, and this data will be crucial in laying the groundwork for future waste management tools and regulations in Mexico City. It also serves as baseline information for the general public, researchers, the media, and government authorities in order for them to adopt and enhance efforts to prevent PPE contamination at future public gatherings.

2. Methodology

2.1. Study area

Mexico City is one of the world's largest and most densely populated metropolitan regions, housing nearly 21 million inhabitants. In the lively Mexico City neighborhood of Tepeyac, stands the most-visited religious site in the West: The Villa de Guadalupe (Basilica of Guadalupe). This national shrine receives as many as twenty million pilgrims annually from villages (pueblos), cities, and suburbs, and even across international borders. Every year in mid-December, millions of pilgrims surge up a broad avenue in Mexico City toward the Villa de Guadalupe from the states around Mexico City, including Tlaxcala, Puebla, Estado de México, and Querétaro for the “Día de la Virgen.” In Mexico, this religious pilgrimage has been practiced for generations. For example, on December 12th, 2019, more than 10 million pilgrims from various Mexican states visited the Basilica de Guadalupe (GDF, 2019). Due to the COVID19 pandemic circumstances, there were no pilgrimage activities in 2020. With the resumption of activities, a larger number of visitors are expected on this yearly pilgrimage to the Villa de Guadalupe. With this in mind, the state government has taken a number of immediate actions. Only those having a complete COVID-19 vaccine system were encouraged to participate in the pilgrimage activities, and masks were required as well as supplied if necessary. Pilgrims were not permitted to remain within the atrium or temples. The local government has placed more than a hundred sanitation workers and volunteers to manage the solid waste resulting from the pilgrimage. More importantly, the government has requested people schedule their visits before December 12th to avoid social overcrowding and contact among people. Taking into account the constraints and understanding the prevailing COVID-19 pandemic, pilgrims from the surrounding states began making the pilgrimage earlier on December 12th (Azteca Noticias, 2021). Thus, the study was conducted between December 5 and December 12, 2021, to evaluate the improperly disposed PPE items. Moreover, we have limited our PPE littering survey until December 12 since public camping places will close after that day, and most pilgrims will not go beyond that date.

2.2. Sampling and PPE analysis

We monitored PPE littering at three different locations within a 6-kilometer radius of the Villa de Guadalupe, as shown in Fig. 1. The three sites include camping sites 1 and 2, and a walking site. Camping sites 1 and 2 were mainly selected due to the presence of intensive human activities during the pilgrimage season. Camping Site 1 is a recreational park (Parque del Mestizaje) where pilgrims have a short-stay until they complete their rites, while Camping Site 2, often known as “casa de peregrinos” or “house of pilgrims,” is a government-run facility that is only open to pilgrims during the month of December. The distance walked by pilgrims between camping sites 1 and 2 and the Villa de Guadalupe is referred to as the “walking site.” Furthermore, the sampling sites cover a cumulative area of approximately 36,536 m^2 (camping site 1: 3446 m^2; walking site: 14,054 m^2; camping site 2: 19,036 m^2). To avoid any health risks associated with the pandemic, rigorous safety protocols were taken during data collection, always including the use of masks, social distancing, and hand sanitizer. In addition, local restrictions were followed as advised during the pilgrimage. We began monitoring PPE disposal every day at 10:00 a.m. local time and continued for 6 h before scheduled sanitation personnel cleaning operations in order to avoid bias. This time interval for PPE monitoring was

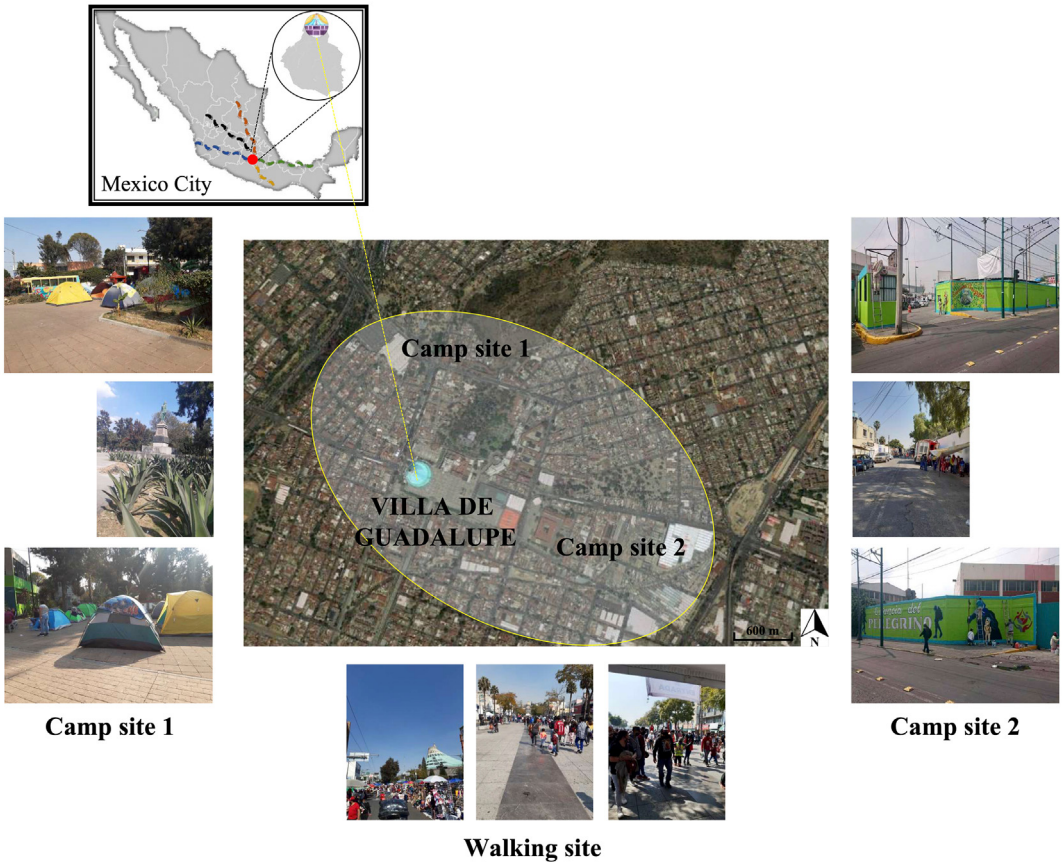


Fig. 1. Map of the study area, Villa de Guadalupe (Mexico City), and sample locations.

chosen due to the increasing number of pilgrims to the Villa de Guadalupe. We walked a 6 km radius to look for PPE discarded on the streets, under cars, in parking lots, and near camping areas. To ensure that the disposed PPE items were covered thoroughly, one person went along one side of the roadway while the other walked down the other. Dumpsites throughout the camping area were also inspected to ensure the accuracy of the PPE disposal data. Visually identified PPEs were photographed and counted.

The density of PPE items was calculated using the following equation (Okuku et al., 2021):

$$C = n/A$$

where C is the density of PPE items per m^2, n is the number of PPE, and A is the surveyed area (m^2).

Daily PPE release in this study was estimated using the following equation:

$$D = n/t$$

where D is the daily release of PPE (items/day), n is the number of collected undamaged PPE items on the second day of sampling, and t is observation time (day).

2.3. Statistical analysis

The obtained data were grouped by sites to determine their influence on the PPE density. The Shapiro-Wilk test invalidated the data's normal distribution ($p < 0.05$); hence, non-parametric tests were performed. Kruskal-Wallis and Dunn's multiple comparison tests were employed to analyze and compare whether there were any significant differences between sites. The statistical significance threshold of 0.05 was used. GraphPad Prism (version 7 for Windows) was used to carry out all statistical analyses.

3. Results and discussions

PPE litter was recorded in all three sampling locations and on all days throughout the study period. Face masks, face shields, and gloves were among the PPE items visually identified. For wipes, we adopted the same method as Ammendolia et al. (2021) to distinguish paper-based tissues or paper towels from synthetic wipes. We found that the disposed wipes were paper-based rather than synthetic, and as a result, there were no synthetic wipes in our surveys. A total number of 731 PPE items was found over a cumulative area of 36,536 m^2 for the three sample locations. Throughout the survey, improperly disposed PPE materials were visually identified, counted, and photographed in a multitude of urban settings, as seen in Fig. 2. Face masks accounted for 94% of the total (n = 689), with other PPE items (i.e., gloves and face shields) accounting for the remaining 6% (n = 42) (Fig. 3). We classified the face masks based on their types and colors. A variety of colored (black, blue, yellow, purple, green, and pink) and white mask items from surgical, KN95, and cloth were identified. There were face masks for adults and children in the discarded PPE items, with adult face masks accounting for 99% of the total. The face masks that were spotted were either strapless or intact, but not torn or damaged. The surgical masks documented were mostly double-layered, with no three-layered masks with disposable layers found. KN95 masks with or without respirators were also observed. As shown in Fig. 3, surgical masks dominated with 87% of the total (n = 596), followed by KN95 (n = 56; 8%) and reusable cloth masks (n = 37; 5%). When the face masks were sorted by color, it was determined that black and blue-colored masks made up 84% (n = 578) of the total masks. Other face masks that composed 17% (n = 111) of the total were white (n = 42; 6%), multicolored/designed (n = 26; 4%), pink (n = 21; 3%), green (n = 9; 1%), purple (n = 10; 1.5%), and yellow (n = 3; 0.5%) (Fig. 3).

The relative abundance and density of PPE items recorded in the study area are shown in Table 1. Fig. 3 shows the distribution of PPE items from

Fig. 2. A few examples of different colors and types of face masks spotted at the sampling locations from the streets, parking lot, under the vehicle, and near the sewer system.

the sampling sites. The abundance of disposed PPE items during our survey were in the range of 50 to 167, with an average disposal of 91.375 PPE items. The number of PPE items was significantly higher on the first sampling day than on subsequent sampling days (Days 2–5), indicating that pilgrims arrived earlier to perform religious rituals throughout the weekend and left PPE items in the areas where they camped and walked. Furthermore, no significant variations were identified from sample days 2 to 5, indicating that the number of pilgrims was lower compared to the first day of sampling and that locals had a bigger effect on PPE littering. Nonetheless, the abundance of PPE items in the next three consecutive sampling days (Days 6–8) significantly increased as the pilgrimage day approached. The abundance for sample days 6, 7, and 8 was 119, 142, and 167 PPE items, respectively. It should be noted that the abundance from the final three days of sampling was 428 PPE items, which is equivalent to 58% of the total PPE items detected in this study. According to government officials, the number of pilgrims visiting the Villa de Guadalupe between December 10 and December 12, 2021 (sample days 6 to 8) has grown massively (GDF, 2021). This dramatic increase in the number of pilgrims to the Villa de Guadalupe substantiated the surge in the disposal of PPE items in the sample days 6 to 8. At the same time, it is worth noting that there were no improperly discarded PPE items within the atrium or temple for the entire study, reflecting pilgrims' and the general public's responsible behavior. However, given the Villa de Guadalupe's surroundings, we cannot say the same because of the prevalence of improperly disposed PPE items within a 6 km radius across the study period.

It is unfortunate that some negative pandemic-related behaviors of the public with regard to PPE disposal tend to persist in metropolitan areas. This might be due to a lack of public awareness and social responsibility regarding PPE disposal; in addition, they may be unaware that they are dealing with infectious waste, either knowingly or unknowingly, whose disposal could have serious environmental and health concerns. Because the face masks were single-use disposable, the pilgrims likely did not find them useful when returning from their pilgrimage, necessitating their disposal. During our PPE evaluation, we noticed that the local government has installed numerous organic and inorganic containers for depositing solid waste, taking into account past years' solid waste experiences. However, because PPE waste was unfamiliar to everyone prior to the COVID-19 pandemic and there was no previous understanding of this waste, only a limited number of PPE disposal bins have been established to drop the used face masks and gloves into. More importantly, the PPE disposal bins

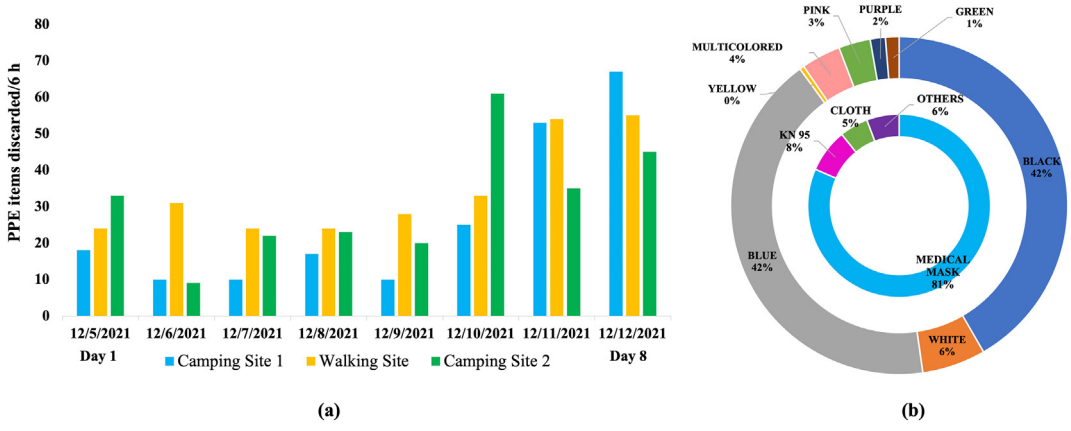


Fig. 3. Quantity, distribution, and characteristics of disposed PPE items in the vicinity of the Villa de Guadalupe (Mexico City). (a) PPE abundance by day and sampling sites. (b) Percentage composition of littered face mask items for the whole study period. Others: gloves and face shields.

Table 1
Relative abundance of PPE items during the yearly pilgrimage to Villa de Guadalupe 2021.

Date	Total (PPE items h^{-6})	Average (PPE items h^{-6})	Daily release (items day^{-1})	Density (PPE items m^{-2})
12/05/21	75	25		7.8×10^{-3}
12/06/21	50	16.67	151.52	4.1×10^{-3}
12/07/21	56	18.67	169.70	4.6×10^{-3}
12/08/21	64	21.33	193.94	5.3×10^{-3}
12/09/21	58	19.33	175.76	4.8×10^{-3}
12/10/21	119	39.67	360.61	10×10^{-3}
12/11/21	142	47.33	430.30	11.8×10^{-3}
12/12/21	167	55.67	506.06	13.9×10^{-3}

have not been evenly distributed considering the human hotspots during the pilgrimage. Similarly, there were no signs suggesting that PPE items should not be discarded on the streets but should instead be disposed of in the bins located around the Villa de Guadalupe. Hence, one of the primary reasons for increased littering and improper disposal in the streets and surrounding areas can be attributed to a lack of adequate PPE disposal bins. Similarly, Ammendolia et al. (2021) observed similar limitations in Canada's Toronto, attributable to inappropriate disposal of used face masks in metropolitan settings. The disposed PPE items were spotted on the streets, near the atrium, underneath cars, trucks, and bikes, in the parking lot, and near sewer systems (Fig. 2). As seen in Fig. 2, a few face masks were deliberately thrown down, owing to straps breaking or loosening while others were being spun about and dumped. And, at times, the masks spotted under vehicles and in the parking lots appeared to have been quickly discarded, leaving the locations for no apparent reason. Children's masks would have fallen to the ground and been abandoned instead of being properly disposed of in the bins while they were playing or wandering around. Among the abandoned PPE items, black and blue surgical masks predominated because they were less expensive and more widely accessible than KN95 during the pilgrimage. In addition, the local state government had taken the necessary precautions and had the authority to distribute face masks, particularly blue masks, to those in need. When pilgrims were mandated to wear face masks, local shopkeepers grabbed the opportunity, and the number of stores selling masks items (particularly blue and black surgical masks) within a 6 km radius more than quadrupled, contributing to unprecedented supply, use, and PPE littering.

There is still a fundamental point to be asked: Are public gatherings the critical players driving the disposal of PPE items in the Villa de Guadalupe's surroundings? We answer yes, and more evidence can be obtained by analyzing the changing pattern of the number of PPE items based on the locations studied (Fig. 4). There was a significant difference in the amount of PPE items between the camping sites (CS1 and CS2 combined) and walking site. Fig. 4 shows the PPE littering was found higher in the camping sites than in the walking site. The number of PPE items ranged from 19 to 112 in the camping sites and from 24 to 55 in the walking sites. Camping sites accounted for two-thirds ($n = 458$) of the total, with walking sites accounting for only 37% ($n = 273$). As shown in Fig. 4, the number of discarded PPE items remained relatively consistent with no significant differences throughout sample days 1–5 and sampling sites. However, a greater number of PPE items were found on next sample days 6 to 8 in the camping sites ($n = 286$) than walking site ($n = 141$). The dominance, with a two-fold rise in disposed PPE items at the camping site, could be attributed to a greater number of pilgrims from outside the city during the pilgrimage in the study area. It is essential to note that the locations of the camping sites are the only places where pilgrims can stay for a brief period of time during their annual pilgrimage until they return. And any discarded PPE items detected in these areas must be ascribed to pilgrims rather than locals living nearby to the surroundings. The observed rise in the concentration of

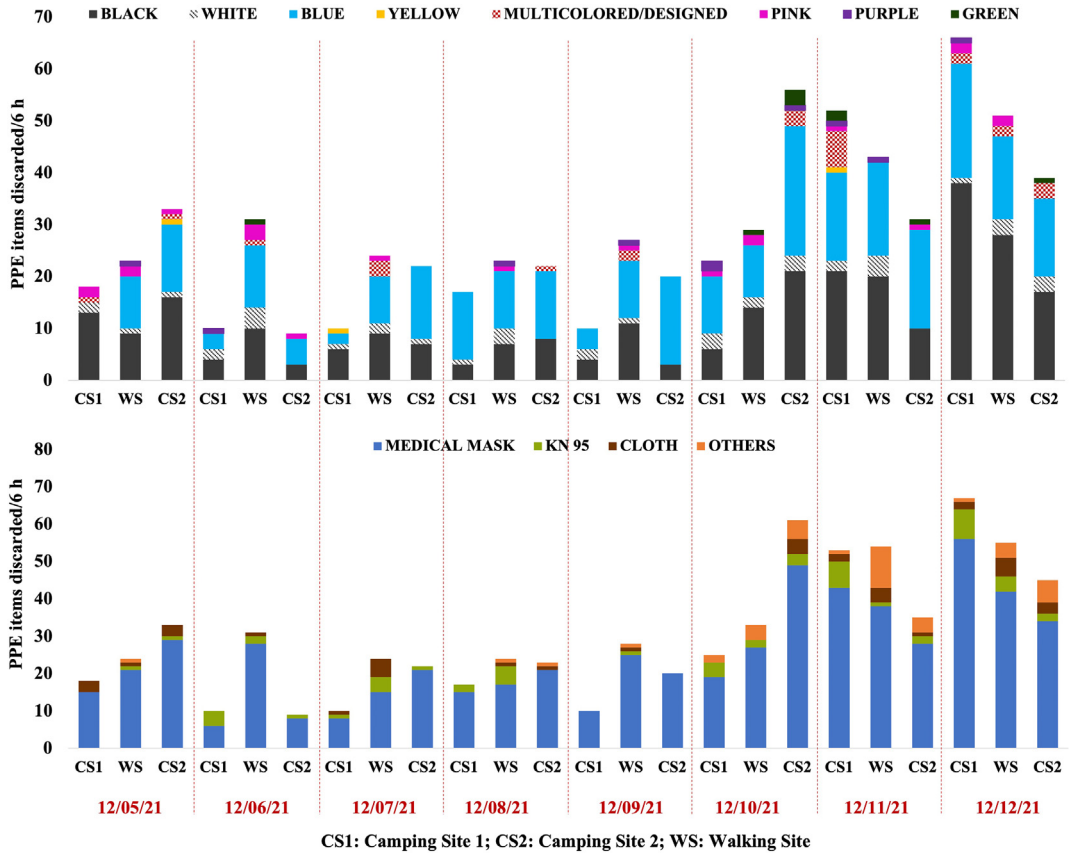


Fig. 4. The distribution of COVID-19-related PPE litter by sample site is heterogeneous. Color (a) is at the top, and type (b) is at the bottom.

PPE littered at the camping site as the pilgrims approached on sampling days 6 to 8 is clearly indicative of the increased disposal behavior of pilgrims staying and their influence on the discarded items in the study area. It shows that the surroundings of the Villa de Guadalupe in Mexico City suffer from PPE littering during the pilgrimage due to the contributions of the pilgrim population, and there has been less guidance from public sanitation officials to pilgrims on how to dispose of PPE items for environmental and health protection. Furthermore, the data evidence leads to two major findings: (1) Public mobility within cities and neighborhoods during a major event (say national or regional) roots for PPE littering and contamination. (2) Their short stays in designated areas will not only contribute to solid waste, but will also increase the amount of PPE littered in the surrounding area, posing additional challenges and barriers to waste management.

According to local government officials, the total number of pilgrims in 2021 was found to be 63% lower than in 2019 (GDF, 2021). We believe that if the projected pilgrims, such as those in 2019, gathered in Mexico City, the amount of PPE items disposed of improperly would be more than the number seen in this study. Furthermore, the information on the PPE littering the pilgrimage route is unclear because the bulk of pilgrims have traveled 120–250 km to Mexico City in autos and on foot, necessitating attention into this subject. At the same time, based on our findings, we found that the PPE density ranged from 4.1×10^{-3} to 13.9×10^{-3} items day^{-1}, with an average density of 7.78×10^{-3} items day^{-1}. As expected, the average density of PPE items encountered greater in camping site (1.2×10^{-3} PPE items day^{-1}) than walking site (1.03×10^{-3} PPE items day^{-1}). The Kruskal-Wallis test revealed significant differences (Chisquare = 10.39, $p = 0.0022$) in PPE density between the three sites. According to Dunn's multiple comparison test, the PPE density at camping site 1 differed substantially from camping site 2 ($p = 0.0042$), but not from walking site ($p = 0.1416$), as shown in Fig. 5. Moreover, the estimated daily release of PPE items was between 151.52 and 506.06 items day^{-1}, with an average release of 283.98 items day^{-1}.

Will the discarded PPE items be a source of pollution and a threat to the environment? PPE pollution in metropolitan areas may not be as impacting as in coastal or natural areas. However, once discarded, PPE litter in the metropolitan area has a variety of fates that have an impact on the environment, either directly or indirectly. In one scenario, they might be collected, sorted in a biomedical bag, and incinerated with biomedical waste, adding to CO_2 emissions into the atmosphere and impacting global warming. Another possibility is that they will be mixed with municipal solid waste and dumped in landfills. Nonetheless, dumping PPE waste in landfills without adequate treatment has the potential to increase worldwide plastic pollution and the spread of SARS-CoV-2. In addition, PPE waste degrades into microplastics in anaerobic conditions through a variety of physical and chemical processes, which are ultimately deposited in the living environment (Shruti et al., 2020). On the one hand, the long-term deposition of the microplastics in the soil can decrease soil fertility and hamper plants growth. On the other hand, they may leach out of the soil and into neighboring water ways, where they could be consumed by organisms. Given the possibility of a shortage of sanitation personnel, which is especially troublesome in low-resource countries, PPE items may have been inadequately and infrequently removed. Improper collection of PPE wastes would most likely endanger the health of the general public and healthcare personnel. PPE waste negatively influences the livelihoods of the surrounding community as well as visitors to such valuable locations. If these abandoned PPE items are not properly removed, children playing nearby may come into contact with them, causing risk of disease transfer and hazards associated to it. Animals (e.g., stray dogs) and birds (e.g., crows) in cities are more likely to interact and torn the PPE items, either because they mistake them for food or because they are seeking for food. These PPE items are sometimes released directly into aquatic ecosystems or by stormwater and rain runoff that ends up in the sewage drain and finally, wastewater treatment plants. Face masks found alongside the drainage system, as depicted in Fig. 2, can enter the sewer drain immediately due to wind, human activity, or rainwater runoff. Face masks are likely to release a substantial proportion of microfibers comprised of petrochemical polymers such as PP and PE (e.g., Morgana et al., 2021; Wang et al., 2021; Saliu et al., 2021; Ma et al., 2021; Li et al., 2021), as well as their associated organic (e.g., phthalates, antioxidants, organophosphate esters, bisphenols, and plastic additives) (e.g., Liu and Mabury, 2021; Fernández-Arribas et al., 2021) and inorganic (metals such as Zn, Mn, Ti, Fe, and Ca) (e.g., De-la-Torre et al., 2022) pollutants when they reach the aquatic environment or a landfill. Otherwise, the discarded face masks in areas (such as the wilderness in the park) inaccessible to sanitation staff will be exposed to UV light, which will degrade and release microplastics and smaller plastic items in their surroundings until they are collected. In any instance, PPE waste is prone to degradation, releasing micropollutants into the environment. These micropollutants from face masks have widely been demonstrated to have harmful effects on the environment and human health (Kutralam-Muniasamy et al., 2022; Silva et al., 2021).

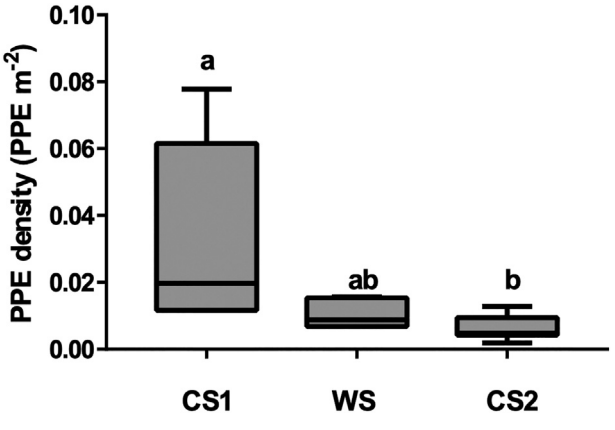


Fig. 5. Boxplot of the PPE density grouped per the camping site 1 (CS1), walking site (WS), and camping site 2 (CS2) using Kruskal-Wallis with Dunn's multiple comparison test. Equal letters indicate no significant differences, while different letters indicate significant differences.

Previously, a few studies validated the occurrence and distribution of improperly disposed PPE items in urban areas (Table 2). Some have examined and reported on PPE disposal findings for weekdays and weekends (e.g., Amuah et al., 2021), while others have done so for a specific time period (e.g., Ammendolia et al., 2021). However, the PPE waste improperly disposed of as a result of responses to public mobility has not been examined or explored in relation to large gatherings in metropolitan areas. To the best of our knowledge, this is the first study that has examined and presented evidence on the subject. Our findings indicate a large number of incidents of PPE improper disposal can be expected in public congregations in metropolitan locations. This is congruent with the plethora of information gained in marine environments, which has linked the rising number of beach visitors to higher PPE disposal (Thiel et al., 2021; De-la-Torre et al., 2021; Hassan et al., 2021). According to the previous studies, the number of face mask items ($n = 578$) observed in this study was higher than in Turkey ($n = 546$), Ghana ($n = 535$), and Canada ($n = 274$) (Table 2). The observed average PPE density of 7.8×10^{-3} items m^{-2} was higher than in the metropolitan environments of Canada ($1.01 \times 10^{-3} \pm 1.55 \times 10^{-3}$ items m^{-2} and 0.0001 ± 0.00005 items m^{-2}). The probable reasons for the differences in the PPE density in metropolitan areas reported in the literature are highly dependent on (i) the type of sampling method used, (ii) the area covered, (iii) the length of sampling, (iv) lockdown restrictions, and (v) public mobility. Despite the lack of a standardized approach for assessing PPE disposal, studies have used the same unit and reported the PPE density in terms of items per m^{-2}. Regardless of the differences in the number of PPE items found, surgical face masks were more abundant in previous investigations, as was the case in our study. While we only observed 3% of cloth masks, France (2022) found 23% of cloth masks, showing that surgical masks are preferred over reusable masks in this region of the world. In contrast to previous investigations, no synthetic wet wipes were found in any

Table 2
Recent studies on littered PPE in metropolitan locations worldwide.

Study location	Environment	Area surveyed (m^2) and number of days	Sampling location	Methods	Key findings	Reference
Kenya	City	NR; 30	Streets	1) A distance between 200 m and 2000 m was surveyed 2) PPE litter was picked from a width of 2 m on both sides of the street	1) 0–5.6 × 10^{-2} PPE m^{-2}	Okuku et al., 2021
South Africa	Urban	NR; 50	Streets	1) Litter was collected from 400 m of street margins	1) Face masks and gloves contributed <1% of total mass 2) Found wet wipes amid other PPE	Ryan et al., 2020
Ghana	City	NR	Streets	1) Survey by transects covering a distance of 100 m to 200 m of different areas like township, suburb, institution, municipal and community 2) Visually identified, counted and photographed	1) Total of 535 face masks along 1720 m stretch 2) Density range 0.04 m to 0.42 m	Amuah et al., 2021
Canada	City	245,190; 34	Street, under cars, residential areas, grocery, and hospital zones	1) Collected debris that was 1 m and 5 m from the closest edge of the sidewalk	1) Face masks constituted 31% (n = 274) of total plastic debris 2) 95% of disposable face masks, 3% reusable masks, and only 2 high-grade masks such as N95 and KN95 3) Disinfecting wipes constituted 25% of total plastic debris 4) 0–8.22 × 10^{-3} PPE m^{-2}; mean density: 1.01 × 10^{-3} ± 1.55 × 10^{-3} PPE m^{-2}	Ammendolia et al., 2021
Canada	City	750,000; 10	Streets, Highway Montreal-Quebec	1) 3 m wide ground surface survey by walking covering urban, town, and rural areas	1) 0.0001 ± 0.00005 items m^{-2}; 2) Per day total range 4 to 10 masks 3) 76% Surgical masks and 24% cloth masks	France, 2021
Turkey	City	40,000; NR	Streets	1) A perimeter of 1 km^2 in three cities was surveyed and the masks found within these perimeters were collected.	1) 30 to 96 face masks km^2 2) Total 210 for Adana, 170 for Mersin, and 166 for Niğde region	Akarsu et al., 2021
Mexico	City	36,536; 8	Streets, under cars, and camping areas	1) Surveyed 6 km radius of the pilgrimage site. 2) PPE litter was monitored along both sides of the road and pilgrimage camping sites. 3) Visually identified, counted, and photographed	1) Abundance: 4.1 × 10^{-3}–13.9 × 10^{-3} items m^{-2}; mean density: 7.8 × 10^{-3} items m^{-2} 2) White and colored (black, blue, pink, yellow and green) face masks were observed 3) 81% surgical face masks, 8% KN95, 5% cloth and 6% others (gloves, face shields)	This study

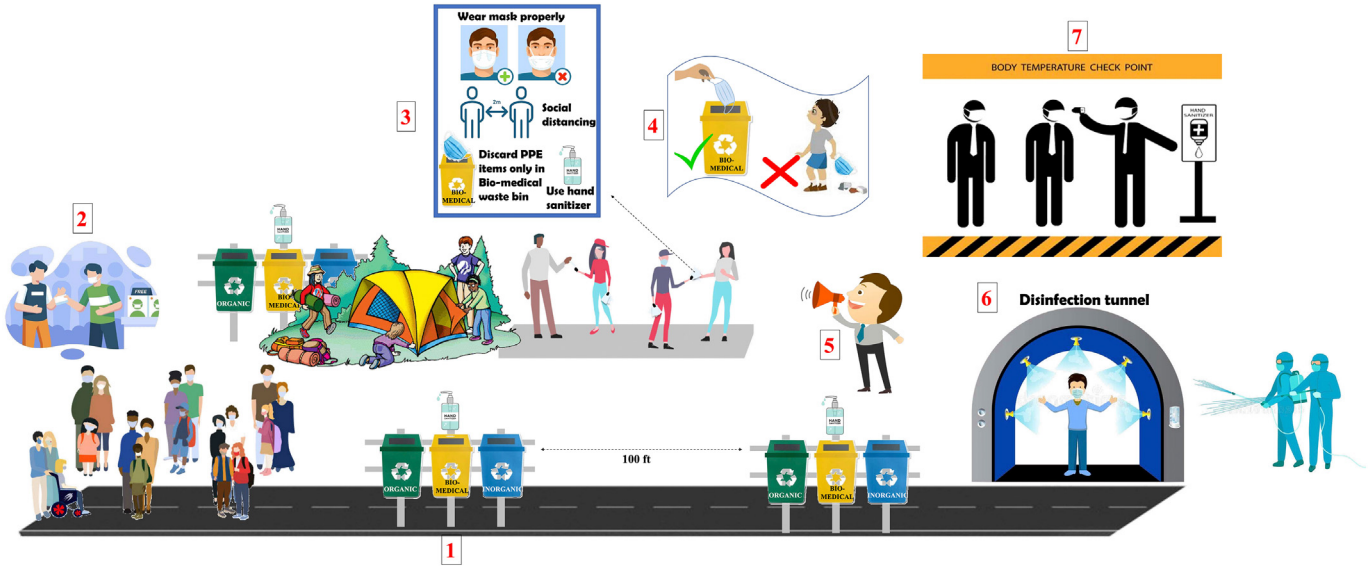
NR: Not reported; PPE: Personal Protective Equipment.

of our surveys. Despite significant efforts to control and manage PPE waste, available research indicates that it is prevalent in the urban environment. Furthermore, the degree of PPE contamination in urban environments is largely unknown all across the world, necessitating future investigation. It is worth keeping in mind that only by monitoring will we be able to gain information on how current waste management strategies have performed and how to improve them.

4. Recommendations for tackling a new challenge: COVID-19 PPE littering in public gatherings

Waste management measures are still vital at this point in the pandemic. The handling of PPE waste calls for immediate attention and the adoption of the best practicable approach toward preserving the environment and protecting human health. It is recognized that the effective management of plastic waste in developing countries with densely populated areas has been a great challenge even before the onset of the COVID pandemic. And recently, with the increased use and disposal of PPE, it has worsened the concerns about plastic waste management due to the safety challenges in handling infectious PPE waste. The CDMX government reported that about 510.2 t of waste were retrieved during this year's annual pilgrimage. We appreciate the government's efficient waste management, which includes numerous sanitation staff, three cleaning shifts in and around the Villa de Guadalupe, free mask distribution, medical facilities, and security. Several studies have addressed the problem of PPE waste and management strategies for use in diverse environmental situations such as coastal cities, beaches, and metropolitan areas. Thiel et al. (2021), for example, suggested installing sufficient and strategically placed waste-bins for discarded PPE materials and enforcing strict safety regulations for people in beach environments. Similarly, Ammendolia et al. (2021) called for the installation of numerous PPE waste bins in Toronto (Canada) metropolitan areas to encourage residents to properly dispose of PPE items, as well as the use of reusable PPE items (e.g., cloth masks and cloth gloves) in place of plastic-based PPE. However, our understanding of strategies for managing PPE waste during massive public events in metropolitan areas remains in its infancy.

Given the potential environmental and human health risks posed by intentionally or unintentionally littering PPE in large public gatherings, there is an urgent need for a comprehensive monitoring system for PPE disposal and to identify hotspot areas that allow authorities to implement timely and effective management strategies tailored to large public gatherings. Nonetheless, implementing waste management measures during a pandemic is vastly different and far more challenging than under normal conditions for large public gatherings. It mainly depends on the ways in which societies respond. To assist the government and other organizations in developing efficient PPE waste management programs for large public events, we suggest the following, as illustrated in Fig. 6: (1) Raising funds from the government and local authorities to carry out effective PPE waste management during the event; (2) Identifying and placing waste bins and sanitation staff in public gathering hotspots (e.g., camp sites) with the assistance of locals; (3) Installing waste bins exclusively for PPE disposal with hand sanitizer for every 100 f. of distance and ensuring equitable access and distribution throughout the event area; and (4) Providing free face masks to attendees; (5) Distributing flyers with clear instructions on safety precautions and proper disposal of PPE items throughout the event; (6) Placing sign boards with clear instructions on proper disposal of PPE items; (7) Frequent announcements in regard to safety measures, social distancing, and correct disposal of PPE items; (8) Disinfecting the public before they enter the event area either by installing a disinfection tunnel or by using disinfectant spray; (9) Providing access to people only after a thorough body temperature check, a vaccination record, and the necessary use of a mask;



1. Install PPE disposal bins and hand sanitizer for every 100 feet distance
2. Supply free face masks to people
3. Distribute flyover with clear instructions on safety measures and correct disposal of PPE items all through the event
4. Sign boards with clear instructions on proper disposal of PPE items
5. Frequent announcements in regard to safety measures and correct disposal of PPE items
6. Install disinfection tunnel or disinfectant spray
7. Access to people only after a thorough body temperature check, a vaccination record, and the necessary use of a mask.

Fig. 6. Recommendations for addressing new COVID-19 PPE pollution in the case of large - scale public gatherings.

(10) Promoting the use of reusable masks and gloves; recruiting sanitation personnel and NGO's; (11) Separately collecting and transporting used masks, gloves, personal clothing, and all PPE in closed medical waste bags to final treatments (e.g., landfilling or incineration); and (12) Provide the event's official announcement with the safety measurements and PPE disposal instructions. Last but not least, simply managing PPE waste is insufficient. After managing, there should be a sort of sustainable valorization options (for example waste to energy). The conversion of PPE to oil- and bio-fuels via pyrolysis is one potential recycling solution for the huge amount of synthetic polymer-based PPE generated during the pandemic (Aragaw and Mekonnen, 2021).

5. Conclusion

The COVID-19 pandemic has continued to have a major impact on global plastic pollution. Recent studies have substantially advanced our understanding of PPE contamination in the environment during the COVID-19 pandemic. This study investigated and documented evidence of improper PPE waste disposal and management during public gatherings, as well as its contribution to increased PPE littering in the Villa de Guadalupe neighborhood of Mexico City. To our knowledge, this is the first attempt to raise concerns and provide answers about whether large public events may contribute to PPE pollution in metropolitan areas, thus contributing valuable information to ongoing efforts on the topic of PPE pollution and improving current waste management practices. According to our findings, PPE littering, particularly of face masks, is prevalent across city streets, parking lots, atriums, and recreational areas, increasing environmental plastic pollution in densely urbanized areas. Also, the areas open to the public for camping and short stays during pilgrimage have had higher improper dispensing of PPE waste. These identified sources of information and new data can be used to build solutions to aid waste management during future events or public gatherings. Our findings support previous researchers' views on the importance of proper waste management, and increasing public awareness will be critical to achieving effective PPE waste management. On the one hand, metropolitan government officials must conduct educational campaigns to raise awareness regarding PPE disposal and pollution, as well as take long-term measures for handling PPE waste. Researchers, on the other hand, could undertake citizen science programs as part of their investigation process in order to widen environmental awareness regarding plastic pollution among the local population.

With unforeseen outbreaks continuing to occur throughout the world, we believe that the COVID-19 pandemic will extend for several years, necessitating the use of PPE. More studies are warranted to assess the ongoing plastic pollution burden associated with discarded COVID-19 PPE wastes, as well as to uncover the factors that contribute to PPE pollution in the environment. As the literature on environmental PPE monitoring expands, standardized approaches for comparing and integrating data from worldwide PPE screens will be essential. Given the uprising of large public gatherings, we must take measures to limit the release of used PPE into the environment. Many concerts and entertainment events with massive public gatherings, for example, are generally recognized to take place in coastal regions, and beach concert series are resuming after a prolonged gap. If improper disposal from a large public gathering in a coastal or beach area is not effectively monitored and managed, it will provide a direct conduit of PPE items into the local aquatic ecosystems. The exercise in this study could be expanded with the appropriate design and implementation in order to better understand the impacts of beach events on PPE littering, which is currently unexplored and requires major attention. Furthermore, the knowledge gained from this study and the recommended strategies can be applied to similar areas where major public events are contemplated.

CRediT authorship contribution statement

Gurusamy Kutralam-Muniasamy: Conceptualization, Methodology, Data curation, Writing – original draft. **V.C. Shruti:** Conceptualization, Methodology, Data curation, Writing – original draft.

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.

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