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Amassing the Covid-19 driven PPE wastes in the dwelling environment of Chittagong Metropolis and associated implications

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HIGHLIGHTS

- Environmental contamination due to the indiscriminate disposal of PPEs is assessed.
- A detailed survey on PPEs disposal was done in Chittagong city, Bangladesh.
- A brief info on PPE waste production, management, and consequences is given.
- This work may help to increase public awareness on the use and disposal of PPEs.

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ABSTRACT

This study investigates the Covid-19 driven indiscriminate disposal of PPE wastes (mostly face mask and medical wastes) in Chittagong metropolitan area (CMA), Bangladesh. Based on the field monitoring, the mean PPE density ($PPE/m^2 \pm SD$) was calculated to be 0.0226 ± 0.0145, 0.0164 ± 0.0122, and 0.0110 ± 0.00863 for July, August, and September 2021, respectively (during the peak time of Covid-19 in Bangladesh). Moreover, gross information on PPE waste generation in the city was calculated using several parameters such as population density, face mask acceptance rate by urban population, total Covid-19 confirmed cases, quarantined and isolated patients, corresponding medical waste generation rate (kg/bed/day), etc. Moreover, the waste generated due to face mask and other PPEs in the CMA during the whole Covid-19 period (April 4, 2020 to September 5, 2021) were calculated to be 64183.03 and 128695.75 tons, respectively. It has been observed that the negligence of general people, lack of awareness about environmental pollution, and poor municipal waste management practices are the root causes for the contamination of the dwelling environment by PPE wastes. As a result, new challenges have emerged in solid waste management, which necessitates the development of an appropriate waste management strategy. The ultimate policies and strategies may help to achieve the SDG goals 3, 6, 11, 12, 13, and 15, and increase public perception on the use and subsequent disposal of PPEs, especially face masks.

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1. Introduction

The Covid-19 outbreak has changed the structure of people's lifestyles. The obligation to follow health protocols using personal protective equipment (PPE) has become a must for everybody to restrict Covid-19 transmission and ensure safety in the healthcare system. The world health organization (WHO) states that Covid-19 is highly contagious and shows transmission via human-to-human contact, including from asymptomatic individuals and through aerosols and airborne droplets (Prather et al., 2020; Absar et al., 2022). Therefore, WHO suggested using PPE, especially face masks, as the primary media to ensure an adequate level of protection against the transmission of Covid-19. However, it is a matter of solicitude that general people throw away the PPEs to the dwelling environment unconsciously. It is worth mentioning that the PPE, especially the disposable face masks, is made from plastic microfibers. With the increase of inappropriate disposal of PPEs, the probability of transmission of the virus to the general public increases significantly. This is because this virus can survive for several days on an inanimate matter like plastics, fibers, etc. At the same time, the result of environmental contamination by PPE decomposed microplastic/microfiber has been widespread, which eventually creates the worst impact on ecosystems and organisms.

Chittagong is the second-largest and one of the most densely populated cities in Bangladesh. In addition to the cumulative pollution to the dwelling environment of CMA by various forms of livelihood-driven activities, the Covid-19 pandemic is adding extra pollution. Since the first case of Covid-19 was detected in the CMA on April 4, 2020, the confirmed cases as of September 5, 2021 are 72,652, and the city dwellers observed the maximum death rate in the month of July 2021 (CSO, 2021). Consequently, the production and subsequent use of PPE's undoubtedly increased throughout the city area. The PPEs, especially face masks, are usually made by low-grade plastics such as high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polycarbonate (PC) and polynitrile (PN), and the main components of face shields are polyethylene terephthalate (PET), polycarbonate, and polyvinylchloride (PVC) (Chua et al., 2020; Fadare et al., 2020; Patel et al., 2017). Face masks usually contain three layers: the inner layer works as an absorbent made of cotton, the middle layer is a non-woven and non-absorbent material such as polypropylene, and the outer layer is of non-absorbent material such as polyester blend or polyester. Once disposed of, these materials may move from one place to another via streams, wind, rivers, etc., and under various environmental conditions, they may break down into microplastic/microfiber and remain a long time in the dwelling environment (Liubartseva et al., 2016; Andrady, 2017). In this way, the extensive uses of PPEs are generating and subsequently depositing tones of microplastic/microfibre wastes to the environment and polluting the environment increasingly day by day. Due to the non-biodegradability of plastic, the PPE residues will likely remain as a common debris in the terrestrial and aquatic environment for decades, which potentially affect the biota and biological systems (see in Fig. 1). For instance, Mohammad et al. (2019) detected the microplastics (MPs) in the intestines of marine fishes from the Northern Bay of Bengal. Fahmida et al. (2021) detected MPs in the gastrointestinal tract of different freshwater fish species that are commonly consumed by the Bangladeshi populace as a daily diet to meet the protein demand. These studies signify that MPs pollution to the aquatic environment has increased rapidly in recent times. This also indicates that the PPE debris poses a threat to aquatic lives, which is a significant constituent of the food web and hence poses a non-negligible concern on food safety worldwide (Fadare et al., 2020). Moreover, it indicates that the mismanaged PPEs may become the root cause of severe diseases and environmental problems (Nzediegwu and Chang, 2020).

It has been reported that SARS-CoV-2 can survive on objects for a long time, potentially remaining infectious through numerous surfaces, including trash cans, face masks, etc., even after disposal for up to 7–30 days (Young, 2020). Several recent studies reported this fact more specifically. Doremalen et al. (2020) studied the everyday surfaces in households or hospital settings. They observed that the SARS-CoV-2 virus in plastic items or surfaces could be survived for several hours after direct contamination. Kampf et al. (2020) reported that SARS-CoV-2 could remain active on inanimate hard surfaces for up to nine days. Because of the improper handling or unsafe disposal of the healthcare waste owing to the Covid-19 pandemic, currently a significant amount of PPEs, especially contaminated face masks are in the process of becoming infectious wastes. This indicates that the idea of using one-time plastics to reduce SARS-CoV-2 transmission may pose an extra threat to the public health. Although the primary route of SARS-CoV-2 transmission is human contact or respiratory droplets, the contact with surfaces (fomites) can be a secondary or extra route of exposure to the virus (Perlman, 2020; Zeri and Naroo, 2020). Contamination can also happen from the contact of soiled hands or the spread of aerosol particles (Dietz et al., 2020; Nghiem et al., 2020). In this way, it creates an occupational risk to the garbage collectors and waste management personnel. This fact shows the importance of proper strategies

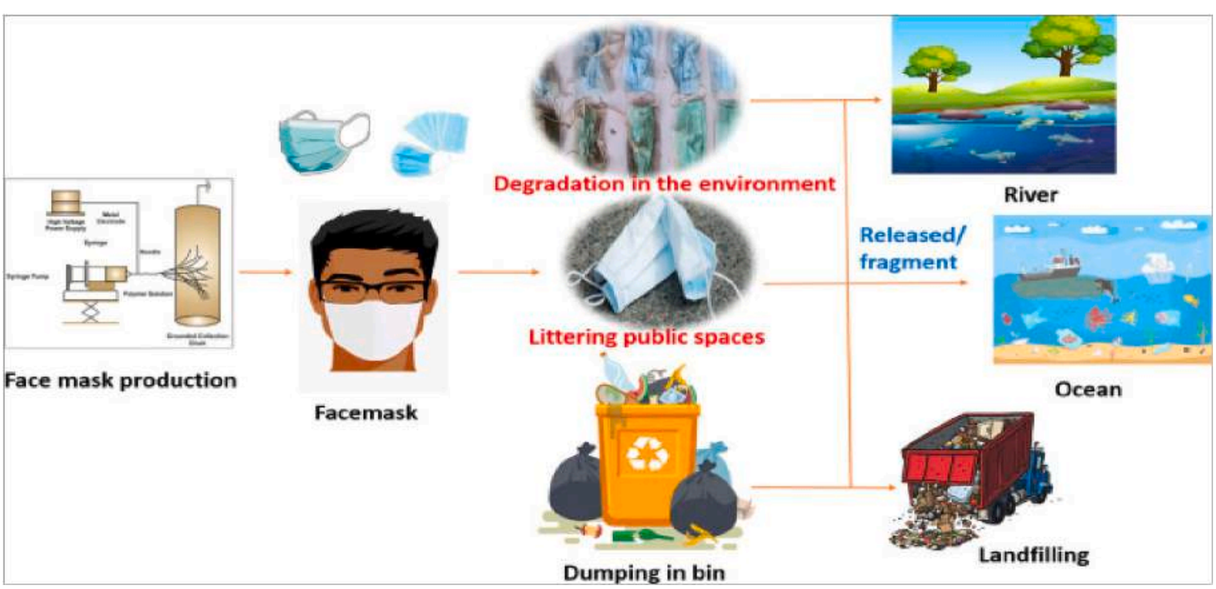

Fig. 1. The footprint of the face mask, reproduced from Fadare and Okoffo (2020).

for handling and disposal of PPE wastes to avoid the extra route of transmission of the Covid-19 virus (WHO, 2020). It has been reported that necessary financial support for proper protective strategies during the Covid-19 pandemic is absent in many low- and middle-income countries (Abedin et al., 2022). Albeit, in the developed countries, the primary method for the disposal of infectious medical waste is incineration, followed by the landfilling with the residual ash (Windfeld and Brooks, 2015). Since the mismanaged PPEs can act as a potential vector to enhance the global plastic contamination and transmission of Covid-19 disease, therefore incineration may serve as a viable technique to reduce the public health risk from infectious wastes despite there's remain some drawbacks of incineration, which requires strict control of gas emissions (Prata et al., 2019).

The objectives of the present study are to (1) identify PPE debris abundance and densities in different contexts in the Chittagong metropolitan area, (2) calculate the generated PPE wastes in the studied areas, and (3) highlight the appropriate waste management policies and strategies. This research may help the respective authority to properly manage the PPE waste during this pandemic.

2. Materials and method

2.1. Study area and PPE monitoring

By recognizing diverse human activity, the monitoring of PPE waste was conducted on thirty (30) different locations in the Chittagong metropolis for thirteen consecutive weeks from July to September 2021. The surveyed locations were residential areas, commercial areas, bus stations, marine bay areas, city junction/crowded areas, port areas, and hospital areas (Fig. 2). The locations were selected to adhere to observe the actual variation of PPE's wastes distribution. The survey took place during the peak and declining time of Covid-19 cases. It is to be mentioned that the active cases were recorded high in July 2021, and the infection rate gradually decreased in August and September 2021. The sampling consisted of walking along the road and walkways, visual observation of the surroundings, identifying the PPE items, and photographing and recording (Fig. 3). Dumpsites in the metropolitan area were also surveyed.

The same sampling point was surveyed several times after every four days to avoid sampling bias. Following the easy visibility, various types of debris from drains, canal sides, Karnafully river sites, etc., were collected/recorded. A self-designed stick (metal) equipped with a handheld claw was used to collect the PPE debris to prevent us from exposure to direct contact. A spray-type hand sanitizer was frequently used during the survey study. A mobile application was used to record the GPS coordinates and time together with the PPE debris items and types. Google Earth Pro was used to measure the distances among the surveyed places. The non-PPEs debris was skipped from this study. The recorded face masks were categorized as dust masks, surgical masks, reusable masks, medical masks, respiratory, and hand gloves as well as face shields. The collected disposable gloves were classified based on their material types, color, and texture: nitrile (black or blue), polyethylene, and latex (white). The color of the face masks collected from the canals like the Chaktaikhal was observed to change due to the presence of industrial effluents or wastewater. On the other hand, for the estimation of wastes due to face masks and other PPEs, necessary data on the number of daily Covid-19 infected, deceased, quarantined, and isolated patients were collected from the Civil Surgeon Office of Chittagong (CSO, 2021).

2.2. Data analysis and visualization

The collected PPE debris data is displayed in Table 1. The abundance of surveyed PPE wastes was calculated using the recorded data at each location and then the total amount of PPE debris was determined. The

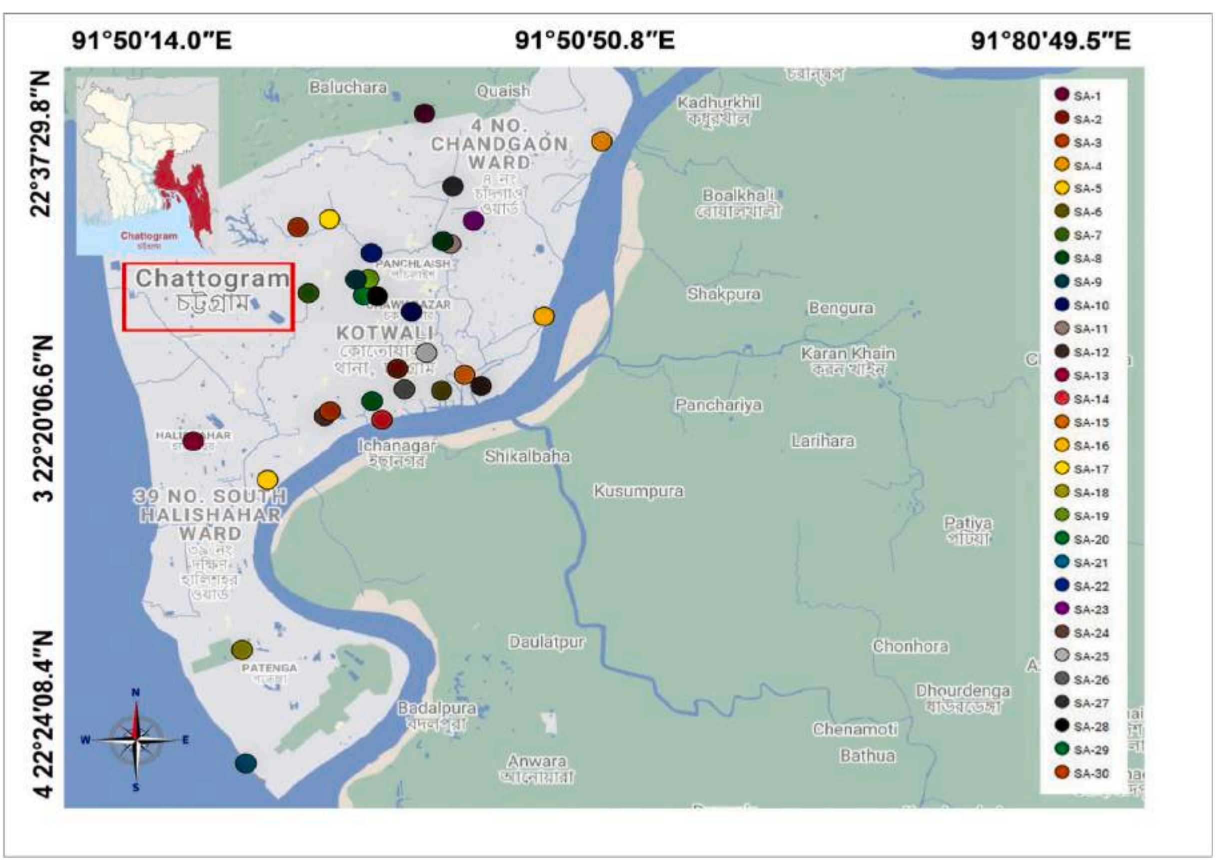

Fig. 2. Sampling points within the Chittagong metropoliton area.

Fig. 3. PPE sampling of different surveyed locations during September 2021.

Table 1
Summary of the surveyed area and the obtained PPE density.

Surveyed months	Total area (m^2)	PPE density (items/m^2)±(SD)
July 2021	4807000	$2.26 \times 10^{-2} \pm 1.45 \times 10^{-2}$
August 2021	6919100	$1.64 \times 10^{-2} \pm 1.22 \times 10^{-2}$
September 2021	6522900	$1.10 \times 10^{-2} \pm 8.3 \times 10^{-3}$

PPE debris density (item/m^2) was calculated by using Eq. (1) (Okuku et al., 2020; Mol and Caldas, 2020):

$$C = n/a \quad (1)$$

where, C represents the PPE density in a unit of (items/m^2), n is the number of recorded or counted PPE, and a is the surveyed area where PPE items were detected.

2.3. Estimation of face mask wastes generated by both urban and rural populations within the Chittagong district

The total amount of face mask wastes generated by the CMA population from April 4, 2020 to September 5, 2021 (CMA, 2021) is determined using the following Eq. (2) (Boroujeni et al., 2021; Mol and Caldas, 2020):

$$TW_F = FMD \times WF \quad (2)$$

where, TWF = Total wastes generated from face mask disposal (ton), WF = Average weight of a face mask, and FMD = Total face mask wastes generated from the daily disposal by urban population, which is estimated using the Eq. (3) (Gasperi et al., 2018):

$$FM_D = P \times U_p \times FMAR \times (FMGP/10,000) \quad (3)$$

Here, P represents the total number of CMA population, U_P denotes the percentage of urban population (100%), FMAR is the face masks acceptance rate by urban population (80%), FMGP is used for an assumption that one person uses one face mask (per capita/day). The term (FMGP/10000) signifies that 1 per 10000 people through a face mask to the dwelling environment after use of it (CMA population, 2021).

Similarly, the amount of wastes that were generated from the daily disposal of face masks by the rural population (CDP, 2021) is estimated using the Eq. (4) (Gasperi et al., 2018):

$$FM_D = P \times R_p \times FMAR \times (FMGP/10,000) \quad (4)$$

Here, P represents the total number of population, R_P denotes the percentage of the rural population (54.8%), FMAR is the face mask acceptance rate by the rural populace (63%) (Chowdhury et al., 2022), and other symbols have their usual meaning. The calculated data is shown in Table 2.

2.4. Estimation of medical wastes generated in CMA from 4th April 2020 to 5th September 2021

2.4.1. Medical wastes generation in the CMA by active Covid-19 patients

The generated medical wastes associated with Covid-19 patients was calculated using the Eq. (5) (Purnomo et al., 2021; Sangkham, 2020; Mol and Caldas, 2020; Haque et al., 2020):

$$MW_T = NCC \times MWGR \times Dn \quad (5)$$

where, MWT is the total medical waste (tons), NCC is the total number of Covid-19 cases, MWGR represents medical waste generation rate, 3.40 kg/bed/day during Covid-19 (ADB, 2020; Haque et al., 2020), Dn is the number of days taken into account. An article entitled "Biomedical waste amid Covid-19: perspectives from Bangladesh" published in 'The Lancet Global Health' showed that the generated medical wastes per bed (hospital) in the capital city of Bangladesh was increased from 1.63 kg to 1.99 kg during the 1st to 2nd wave of Covid-19 (Rahman et al., 2020). However, at the 3rd wave/stage of Covid-19, this value has become 3.40 kg for Bangladesh standard (Haque et al., 2020). This is because the use of one-time plastic based PPE equipment related to Covid-19 treatment has increased tremendously.

2.4.2. Medical wastes generation in the CMA only from hospitalized Covid-19 patients

The generation of total medical wastes were estimated based on the hospitalized Covid-19 patients in CMA from April 4, 2020 to September 5, 2021 using Eq. (6).

$$MW_{(HP)} = TAHCP \times MWGR \times Dn \quad (6)$$

where, MW(HP) is the total medical waste (tons) from hospitalized patients, TAHCP stands for total active hospitalized Covid-19 patients, the other symbols have their usual meaning.

2.5. Potentially infectious wastes generated by quarantine and self-isolated patients in Chittagong district from April 4, 2020 to September 5, 2021

According to WHO, quarantined patients do not exhibit any symptoms but have contact with infected patients or have traveled to area which is affected by the pandemic. However, the waste produced by quarantined patients requires special attention (Mihai, 2020). To estimate waste generated from quarantined patients, this study has considered the municipal waste generated by quarantined households (Mihai, 2020). In Bangladesh, the daily municipal waste generation rate is 0.49 kg.inhab.day^{-1} in urban areas and 0.33 kg.inhab.day^{-1} in rural areas (Chowdhury et al., 2022). The latter was considered a conservative option to determine waste flow in quarantined households (Huda et al., 2014; Chowdhury et al., 2022).

$$W_Q = N_{PQ} \times W_{GR} \times D_n \quad (7)$$

where, W_Q is the amount of wastes generated in the quarantine period, N_{PQ} is the number of peoples who were in quarantine, W_{GR} is the waste generation rate in the quarantine period, and D_n is the total days for quarantine (14 days).

Self-isolation is established for people who do not show any symptoms, but: (i) have traveled in the areas affected by Covid-19, (ii) direct contact with people who have symptoms or are reconfirmed with coronavirus (Covid-19), (iii) family member in aforementioned cases. The waste generated in such households should also require special attention. If the person in home isolation used food that was supplied by food delivery company, the wastes include the used food containers and tissue paper. It is likely to be contaminated and become infectious waste. The generated waste in self-isolation can be calculated by using Eq. (8), (Chowdhury et al., 2022).

$$W_{SI} = N_{PSI} \times W_{GR} \times D_n \quad (8)$$

where, W_{SI} is the generated waste in self-isolation, N_{PSI} is the number of people in self-isolation, W_{GR} is the waste generation rate in self-isolation which is considered to be 3.40 kg.inhab.day^{-1} (Chowdhury et al., 2022), and D_n is the total days for self-isolation (14 days).

Table 2
Total face mask wastes generated in the Chittagong district from April 4, 2020 to September 5, 2021.

Study Area	Total Population	Urban population (%)	Face mask acceptance rate (%)	Disposal of face mask per 10000 persons per day	Total face mask disposal per day	Average weight of a face mask (g)	Generated Face mask wastes per day (ton/d)	Number of days taken into account	Total face mask wastes generated (ton)
Chittagong Metropolis	5,133,000	100	80	1	4106400	30	123.192	521	64183.03
Chittagong district (sub-urban and rural area)	2841448	54.8	63	1	980981.5	30	29.4	521	15332.7

3. Results and discussion

Table 1 shows brief information on the total surveyed area and PPE wastes abundance. The rate of PPE wastes generation has increased significantly in the CMA during July 2021, which was identified as the peak time of Covid-19. Among the recorded PPEs, the face mask shows the highest number, followed by hand gloves, face shields, and eye-protective glass (see Fig. 4). The percentage of recorded face masks, hand gloves, face shields and eye-protective glass were found to be 97.80%, 2%, 0.10% and 0.10% during July 2021, in August 2021 the respective percentages were 98.58%, 1.40%, 0.01% and 0.01%, and in September 2021, these values show 98.88%, 1.11%, 0.0% and 0.01%, respectively. For these three months (July–September 2021), the mean PPE density was calculated to be 2.26×10^{-2}, 1.64×10^{-2}, 1.10×10^{-2} PPE m^{-2} with a standard deviation of 1.45×10^{-2}, 1.22×10^{-2}, and 8.63×10^{-3} respectively. The number of Covid-19 patients was the highest in Chittagong during the month of July 2021 compared to the other months. Note that, one of the largest festivals for Muslims (The holy Eid-Ul-Adha) was celebrated in July 2021, i.e., during the peak time of Covid-19 cases. Consequently, people were gathered in many temporary markets (to purchase animals like cow/goat for observing the festival) located in many places within the city area. In addition, general people were also visited their home districts to celebrate the festival. All such activities prompted the disposal of a relatively higher number of face masks in the city area than the other time. That's why we had surveyed somewhat a greater area to observe the PPE's wastes scenario in the month of July 2021. In fact, we observed the highest number of PPE wastes in July 2021 than the other months like August–September 2021. The fewer PPE abundances recorded in August and September are also attributed to the lower infection rate of Covid-19 in these months compared to the month of July 2021. In general, a higher number of face masks were found to be littered on the weekends than on working days. This is attributed to some people's leisurely walks, weekly schedule on household cleaning, etc. The number of Covid-19 infections in CMA had reached a record of 15825 on July 2021 (CSO, 2021) since the start of the Covid-19 pandemic, prompting a corresponding increase in public usage of face masks. In such a situation, some people were used double to triple number of face masks which could have potentially increased the disposal of face masks. Interestingly, it has been observed that single-use face mask littering is more likely than its counterpart cloth mask. A similar study was conducted by Rakib et al. (2021) in neighboring Cox's bazar area where 97.9% of face masks were found with an average density of 6.29×10^{-3} PPE m^{-2}. This was due to the illegal dumping and poor solid waste management in the beach area.

Table 2 shows the total face masks wastes generated in the CMA for the whole study period. Since the SARS-CoV-2 virus can survive up to 3 days on plastics or inanimate matter, this provides an additional possibility of transmission of Covid-19 to human beings via fomites (Perlman, 2020; Zeri and Naroo, 2020). It is worth mentioning that the majority of people are unaware of the destructive impact of throwing the face masks in the environment. In addition, there is a lack of strict adherence to proper management of face mask wastes thrown in the dwelling environment. During our survey period, some face masks were found to be very dirty, partially covered with cow dung, mud, various types of waste materials, etc. We counted these face masks during the first round of the survey but didn't collect them, and they were not counted in the next round of the survey. Furthermore, the continuous rainfall in July 2021 carried these face mask wastes into the city drains and finally deposited them in the Karnafully river.

Tables 3–6 show the total medical wastes generated in the study area by active patients, hospitalized Covid-19 patients, quarantined Covid-19 patients, and persons in isolation, respectively, from April 4, 2020 to September 5, 2021. Tables 3 and 4 show the total medical wastes generated by total active and hospitalized Covid-19 patients in the CMA are 128695.75 and 17232.18 tons, respectively, for the same period. The proper management of these substantial medical wastes has become a significant issue during this pandemic. Moreover, these wastes were not separated in the source points based on their classification; rather these were dumped simply in the common dustbin located in the hospital area. Fig. 5 shows PPE waste gathering and/or temporary dumping places and how such openly dumped wastes contaminate the environment.

Even many clinics and laboratories keep their wastes in the nearby open dustbin on the street. These wastes are spread in the surrounding environment and drained by rainfall and wind. Various hazardous gases and materials may also be released from these medical wastes, especially from syringes, surgical masks, and medicine bottles. These eventually may act as a potential vector for respiratory diseases to the general people and cleaning personnel. This is attributed to following of "Medical Waste Management act-2008″ policy improperly (Nielsen et al., 2020). A recent study entitled "Effective Management of Medical Waste during Covid-19″ reported that only 6.6% of medical wastes were managed properly and the rest of the 93.4% wastes were not under the control of proper management (MOEF, 2008). All PPEs are non-degradable microplastics products and may remain in the terrestrial environment for a long time. They have been considered the biggest environmental problem and may cause an extra burden to the already struggling municipal waste management system.

3.1. Positive and negative impacts due to Covid-19 pandemic

It is worth mentioning that the Covid-19 pandemic has resulted in both positive and negative impacts on human beings and the dwelling environment (see Fig. 6). The positives include a decrease in air and noise pollution, reduction in emission of greenhouse gases, traffic

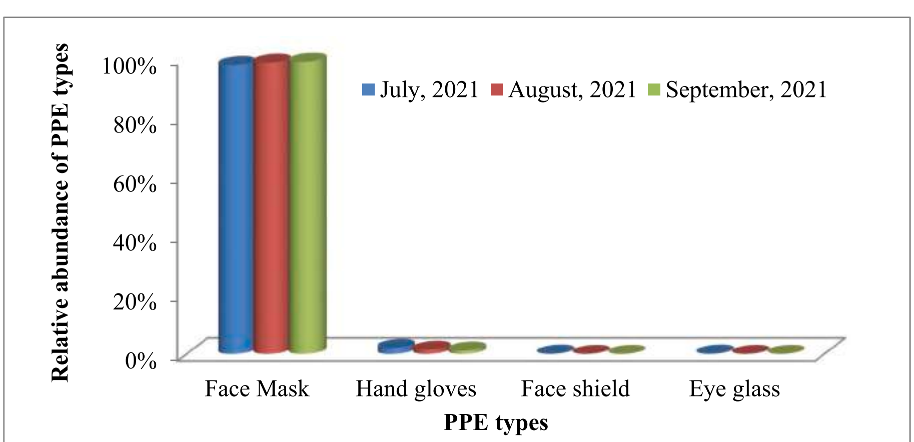

Fig. 4. Distribution of PPEs in the surveyed area.

Table 3
Total medical waste generated in the Chittagong district by active Covid-19 patients.

Area	The total number of Covid-19 confirmed cases	Medical wastes generation per day per person (kg/day/person)	TMWG = Total Medical Waste Generated per day (tons/day)	Dn = Total number of days in the pandemic period (days)	Total medical wastes (tons) generated during the pandemic period = TMWG × Dn
Chittagong Metropolis	72652	3.4	247.0168	521	128695.75
Chittagong district (sub-urban and rural area)	27393	3.4	93.1362	521	48523.96

Table 4
Total medical wastes generated only by hospitalized Covid-19 patients in CMA.

Total number of active hospitalized Covid-19 patients	Medical wastes generation rate (kg/day/person)	TMWG = Total medical wastes generated per day (tons/day)	Dn = Total number of days in the pandemic period (days)	Total medical wastes (tons) generated by hospitalized Covid-19 patients = TMWG × Dn
9728	3.4	33.0752	521	17232.18

Table 5
Total medical waste generated by quarantined Covid-19 patients from April 4, 2020 to September 5, 2021.

Total number of quarantined persons	Daily wastes generation rate (kg/day/person)	TWG = Total wastes generated per day (kg/day)	Dn = Total days in the quarantine period (days)	Total wastes (tons) generated during the quarantine period = TWG × Dn
28193	0.49	13814.57	14	193.40398

Table 6
Total medical waste from isolated Covid-19 patients from 4th April 2020 to 5th September 2021.

Total number of persons in isolation	Daily wastes generation rate (kg/day/person)	TWG = Total wastes generated per day (kg/day)	Dn = Total days in isolation (day)	Total wastes (ton) generated during the isolation period = TWG × Dn
4544	3.4	15449.6	14	216.2944

injuries, etc. The major negative impacts can be identified as the increase of plastic-based wastes, reduction of waste recycling, economic crises, unemployment, etc.

Covid-19 has made a considerable positive impact on dwelling environment by reducing the air pollution. Due to the strict lockdown and shutdown of all kinds of markets, mills, factories, public transports, and institutions during Covid-19 pandemic, the probability of emitting hazardous gases and pollutants in the dwelling environment has been reduced. These resulted in the decrease of major pollutants such as atmospheric particulate matter (PM_{10} and $PM_{2.5}$), NO_2, SO_2, CO, O_3, CO_2, and Non-Methane Volatile Organic Compounds (NMVOCs), etc. In air considerably (De Maria et al., 2021). The sources of these pollutants are mostly industries and automobile exhaust. These pollutants affect the respiratory system, lungs, and mucus secretions. Several authors have reported the improvements in air quality after the lockdown period in countries like Brazil, China, and India, where there were relatively high level of air pollutants before the pandemic (IQAir, 2020). It has also been reported that after two weeks of lockdown in Barcelona, NO_2 was reduced by half and also a reduction in the PM_{10} concentration (Tobias et al., 2020). A similar result was reported for Sale City in Morocco by Otmani et al. (2020). Most of the beaches are polluted due to anthropogenic activities. Since the lockdown situation has caused restricted movement of people in the coastal and beach areas, this eventually enhances the Clean Coast Index of the beaches all around the world (Rakib et al., 2022; Zambrano-Monserrate et al., 2020). Most of the big cities in the world are subjected to noise pollution due to human activities like automobile traffic, loudspeakers in commercial spaces, and sounds from various industrial settings. Although Covid-19 has cause many discomforts and health-related problems to humans, however, the lockdown situation has caused a massive drop in noise levels in many cities (Zambrano-Monserrate and Ruano, 2019).

The main purpose of disposable medical masks and other PPEs is to protect healthcare workers from hazards during medical activities. Currently, it has become mandatory to use face masks by all types of people to reduce the transmission of this virus. The global market for face masks (including respiratory and surgical) was reported to increase from about 14.6 billion in 2019 to 33.4 billion in 2020, with an annual increase of about 23% (Research, 2020). Such an increasing production and subsequent uses of PPEs have added vast plastic wastes to the terrestrial environments and aquatic ecosystem, and polluting them concurrently. Fig. 7 shows the PPE footprints during this pandemic. Moreover, the Covid-19 driven PPE wastes are dumped into landfills without proper management because of the lack of available resources for PPE waste management (Abedin et al., 2022). Once PPEs are dumped into the open environment, they react with air particles and turn as a source of exposure of contaminated air to the surrounding populace.

Furthermore, during the production process, the PPEs release greenhouse gases. Such gases react with municipal wastes and generate microplastics (Shruti et al., 2020). Moreover, in the anaerobic environment, the plastics part of PPEs transformed to MPs via various physical, chemical, and microbial activities (Shruti et al., 2020; Silva et al., 2021). The gradual loading of these MPs into the soil may eventually reduce soil fertility, then negatively affect plants growth and other species. Besides this, the degradation of nonwoven materials generates synthetic micro- and nanofibers via the solar UV-oxidation or exposure to other environmental parameters, and then potentially inhaled by human being (Muenmee et al., 2015). Once enter the human body, the MPs can cause oxidative stress to negatively affect reproductive capacity and growth (Li et al., 2021). As water becomes trapped in plastic, the MPs provide a suitable habitat for breeding mosquitoes, which eventually increases the possibility of mosquito-borne diseases like dengue. The Covid-19 has also affected the waste recycling activity, which is usually performed to prevent pollution, save energy and conserve natural resources. Currently, the waste recycling operations in many countries have been ceased as these pose a risk to the workers in recycling centers who may get infected by the contaminated household or medical wastes.

3.2. Covid-19 driven PPE wastes: a threat to the aquatic ecosystem

The Covid-19 pandemic has resulted in the generation of a huge amount of PPE wastes which eventually impacts the aquatic ecosystem. Due to the lack of proper waste management, the PPE wastes (especially face masks) are found in every places such as roads, parks, drains, etc in the metropolitan area. The majority of these wastes are then drained to the Karnafully River via the open drainage system and internal canals or

Fig. 5. Indoor and outdoor PPE waste gathering and/or temporary dumping places.

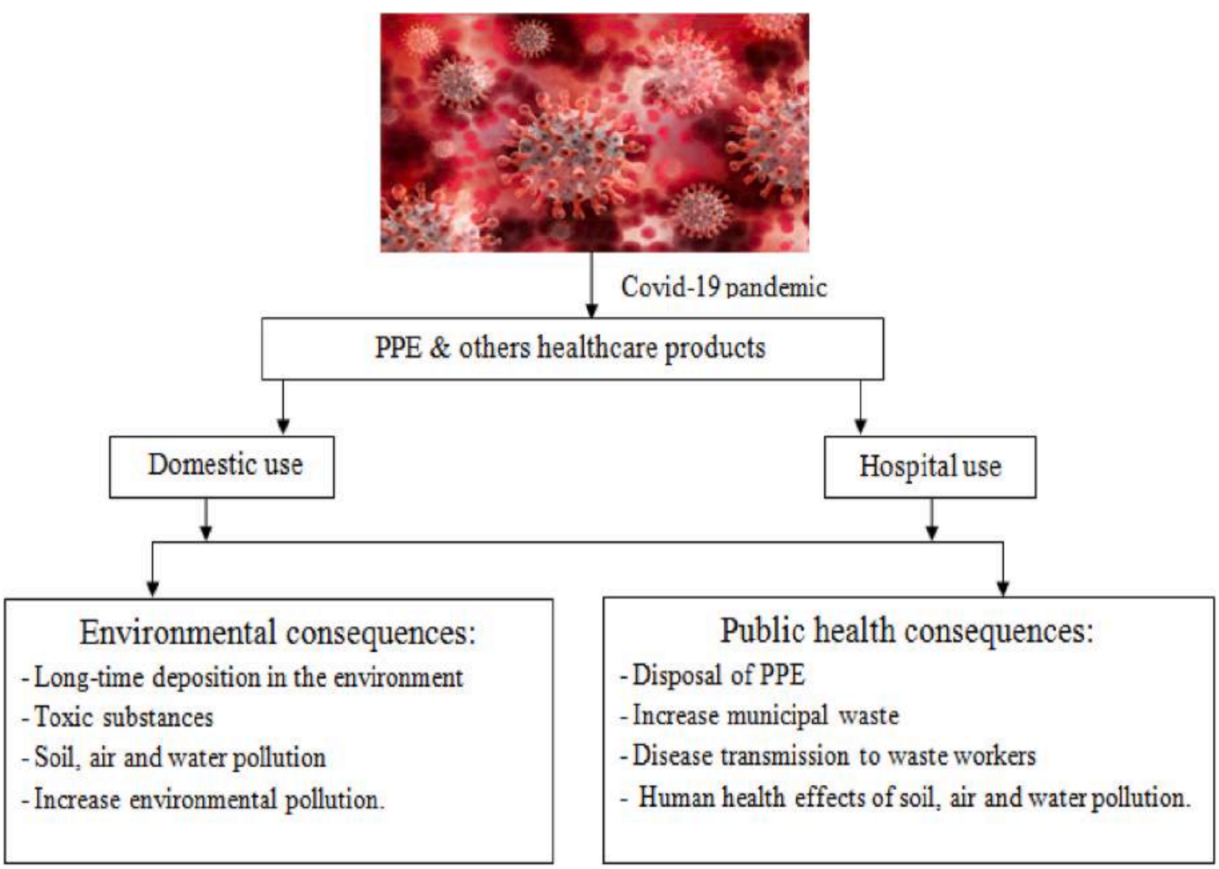

Fig. 6. Environmental and public health impacts of PPE wastes.

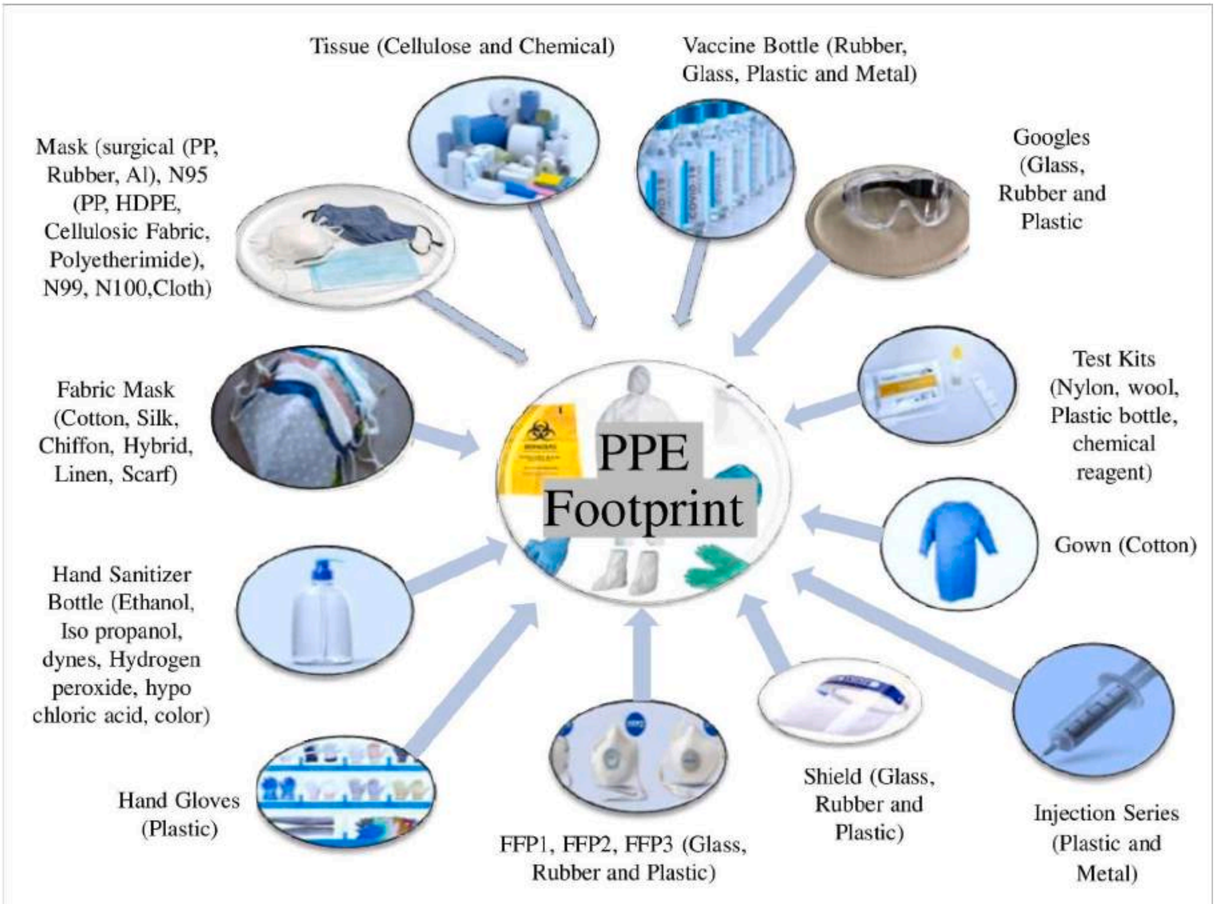

Fig. 7. Covid-19 driven PPE waste sources or PPE footprint.

Khals of the Chittagong city. It is well known that the face masks are made mainly by non-degradable plastic material, therefore causing a considerable pollution to the aquatic ecosystem.

It has been observed that the sudden usage of face masks, disposable gloves, and hand sanitizers by billions of people is producing an enormous amount of trash around the world, and the majority of them end up in the waterbody. Together with medical waste, this waste may cause deleterious effects on land and the aquatic ecosystem in the future (Hellewell et al., 2020). Generally, when MPs are mixed with the aquatic ecosystem, they have different fates and sink based on their characteristics of density. For instance, while the low-density ones ($\sim$1.03gcm^{-3}) float on the water, the high density ($>$1.03 gcm^{-3}) ones are sink and reach the bottom sediments. Then they react with the sediments and produce hazardous gases and components, and posing a significant risk to the aquatic ecosystems.

Plastic waste generation in Asian countries is reported to be much higher (1.51 million tons) than in Europe (0.48 million tons) due to the higher acceptance of face masks as well as the population density. Accordingly, the amount of mismanaged waste is also higher in Asian countries because of the lack of enough waste management facilities compared to Europe (Chowdhury et al., 2021). The MPs entering the aquatic environment may remain for a very long period due to slow biotic decomposition and then fragmented to smaller size microplastics or nano plastics ($<$1 μm) via the various mechanical and photochemical processes (Jeong and Choi, 2019; Rakib et al., 2021). The presence of such a small size MPs in the aquatic environment is uptake via a wide range of aquatic species, thus undergoing disturbance to their physiological functions through the food web and ultimately reach to human body and creates adverse effects to human health (Espinosa et al., 2016). Moreover, floatable and sinkable MPs in the aquatic environment act as a carrier for the transfer of pollutants (Thushari and Senevirathna, 2020) to the aquatic organisms (Rodrigues et al., 2019; Cozar et al., 2014) that potentially cause various detrimental and cytotoxic effects. Since the inhabitants of Chittagong city and other nearby areas are the ultimate consumers of Karnafully river fish where a high rate of MPs contamination is suspected, therefore the probability of transfer of significant amount of MPs to human health can't be overlooked (Yang et al., 2020; Frias and Nash, 2019). Therefore, unplanned waste disposal may endanger the ecology of the riverine habitats of the Karnafully river.

3.3. Covid-19 driven PPE wastes impact on public health

Although almost all people are using PPEs (especially face masks) to protect the Covid-19 transmission, the PPE wastes pose severe environmental and public health threats. Cong et al. (2020) reported that a person's discomfort increases significantly by wearing face mask for a long time in a warm environment. Moreover, there is an increase in the mean skin temperature and heart rate, a decrease in the blood oxygen saturation level, all ultimately lead to a decline of health and comfort levels. In Bangladesh, two types of healthcare wastes are produced-hazardous and non-hazardous. Hazardous waste, including pathological, viral, sharps, and chemical wastes, are usually produced in hospital wards, operation rooms, labs, etc. Non-hazardous medical waste is typically common waste that has no specific guideline for handling or environmental issues.

A rapid increase of toxic wastes and plastic-based products has disrupted the standard recycling capability as well as other waste management methods, and also the fear of coronavirus infection has forced the industry to stop the recycling activities, which in turn, increased the waste volume. Due to the lack of proper disposal facilities, the healthcare waste could pose a higher risk to the health care staff, informal waste collectors, and the citizens who live close to the waste collection areas. Potentially hazardous heavy metals Cd and Pb, and organic chemicals and additives such as surfactants, plastic oligomers, and dye-like molecules are leachates from the low-quality face masks produced by illegal/unauthorized companies that create various respiratory diseases. Infectious PPE wastes contain viruses, bacteria, fungi, or parasites and can cause disease in liable hosts. The existence of micro or nano size of PPEs debris are reported in air, soil, water, living organisms, processed food, and even in drinking water (Cowger et al., 2020; Prata, 2018; Mohammad et al., 2019; Amato-Lourenço et al., 2020). Exposure to pollutants from PPE debris can occur via both direct and indirect pathways such as inhalation, dermal contact, and ingestion. It has been reported that a person inhales between 26 and 130 MPs/day (Rahman et al., 2020). The ingestion of MPs impacts blood, bodily fluids, organs tissues, and can cause lung inflammation leading to cytotoxic effects in the respiratory system (Dris et al., 2016; Rahman et al., 2021; Thompson, 2015).

4. Recommendations to minimize the PPE's pollution

The following steps may be applied to minimize the PPE's pollution in this Covid-19 pandemic.

4.1. Covid-19 driven infectious waste: challenges and management

Many public health specialists has already prescribed some feasible solutions for the proper management of PPE wastes to prevent the spread of the virus. For instance, public health experts Dr. Kiattisaksiri and Mr. Amornyut from Thailand emphasized the use of autoclaving for the management of infectious waste under the law governed by the respective country. They suggested performing a spore test to check the waste's biological standards. They also stated that the infectious waste management in field hospitals and waiting areas should not be different from the management in hospitals that focus on hygiene and safety, collection method, infectious waste transportation procedures, materials and disposal methods. Those who isolate at home, should dispose of the infectious waste inside the garbage bag, close tightly the bag with the disinfectant spray, then put it into another garbage bag, gather them in the safe spots suggested by the relevant responsible units, such as local administrative organizations, private companies, community hospitals, etc. (CWT, 2021). As for the disposal by incineration, the temperature of the incineration chamber must be controlled as prescribed by law. On the other hand, bioplastics or biodegradable polymers can be produced by using polylactic acid, starch, and protein (Scheer, 2007; Shen et al., 2020). Adequate number of composting centers supported by UV degradation or hydrolysis processes should be built and disseminated worldwide for the biological degradation of such products (Luyt and Malik, 2019). To produce the biomaterials and nontoxic compounds at a low cost, the respective government should reduce the taxes, and provide subsidies and incentives in R & D to combat the pandemic and the adverse environmental effects.

4.2. Incineration and other processes

The PPE-driven medical wastes are classified as bio-hazard plastic products and pose a growing problem worldwide. In this regard, incineration has been adopted all over the world as the most cost-effective technique to kill pathogens. However, to reduce the negative impacts generated by the combustion process, a better gas emission control system capable of capturing 99.9% of chemical pollutants (Jose et al., 2021) must be introduced. For example, a highly efficient incineration system is used in cement plants, which can reduce dioxin emissions significantly (Richards and Agranovski, 2017). In this manner, a similar system can be adopted to reduce toxic emissions generated by burning plastics. Some countries already have waste-to-energy incinerators; such a system should be adopted for the incineration of PPE-driven plastic wastes. Moreover, biodegradable PPEs such as bioplastics should be introduced as a long-term action to reduce the environmental impacts of medical waste, and these wastes may not emit persistent toxic chemicals while incinerated.

To ensure proper handling, storage, disposal, and treatment of wastes, several options such as autoclaves, incinerators, microwave sterilization, and sanitary landfills are identified as the preferred process. The authority may adopt the most reliable treatment process for PPE waste known as pyrolytic incineration, which is also called controlled air incineration or double-chamber incineration. Fig. 8 shows a sustainable green management system for mitigating the PPE waste disposal during the Covid-19 pandemic. The various steps demonstrated in Fig. 8 are designed to ensure the conversion of waste-to-energy and industrial materials that will be added economic value.

5. Limitations, weaknesses and strengths of this study

The major limitation is that it was not possible to survey the whole Chittagong district and also for the whole period from April 2020 to September 2021. This is because, the government had imposed a countrywide lockdown several times, also the overall use of PPEs by rural and sub-urban populations was relatively lower, hence the survey was focused only on the city area. The main weakness was due to not able to collect any PPE-derived MPs from the bottom sediment or river bed of the Karnafully river as well as not collecting and analyzing any fishes for the concentrations of MPs. Such an analysis is important to understand the transfer of MPs to human health via the food chain. On the other hand, the main strength of this study is to provide a clear picture of the PPE derived wastes produced in CMA, the overall scenario on the source and fate of the PPE wastes, produce brief information on the current waste management practices by CMA authority, and finally show the pathways for viable waste management in light of international standards.

6. Conclusion and future outlook

This study has focused on the impacts of PPE waste disposal on the environment and aquatic ecosystem. It has been observed that the PPE-derived organic pollutants and microplastics are responsible for contaminating the environment and pose a significant threat to public health. It has also been found that the responsible authorities in the city have not adopted a proper process for handling, storage, disposal, and treatment of PPE wastes; instead, these are dumped into open spaces for landfills. Furthermore, the lack of awareness about environmental pollution as well as poor municipal waste management practices is identified as the root causes for the contamination of the dwelling environment by PPE wastes. Although this study has compiled several opinions and suggestions on the efficient management of solid wastes, however, further research should be conducted by addressing knowledge gaps on the environmental health risks due to PPE-derived MPs pollution. Currently, only a little information is available on the phase partitioning of microplastics and associated contaminants in the aquatic ecosystem and concomitant effects. The degradation and fate of MPs along the transfer pathway from the source to the human food chain are yet to be investigated, and finally, the sinking of microplastics in sediments due to physical or biological phenomena requires detailed future study.

Author contributions

Mayeen Uddin Khandaker: Conceptualization. Md. Jainal Abedin and Md. Ripaj Uddin: methodology. M. Shahab Uddin Ahamad and Md. Ariful Islam: software. Mayeen Uddin Khandaker and A. Sulieman: validation. Md. Jainal Abedin, Syed Md. Minhaz Hossain and Abu Mohammad Arif: formal analysis. Md. Jainal Abedin, M. Shahab Uddin

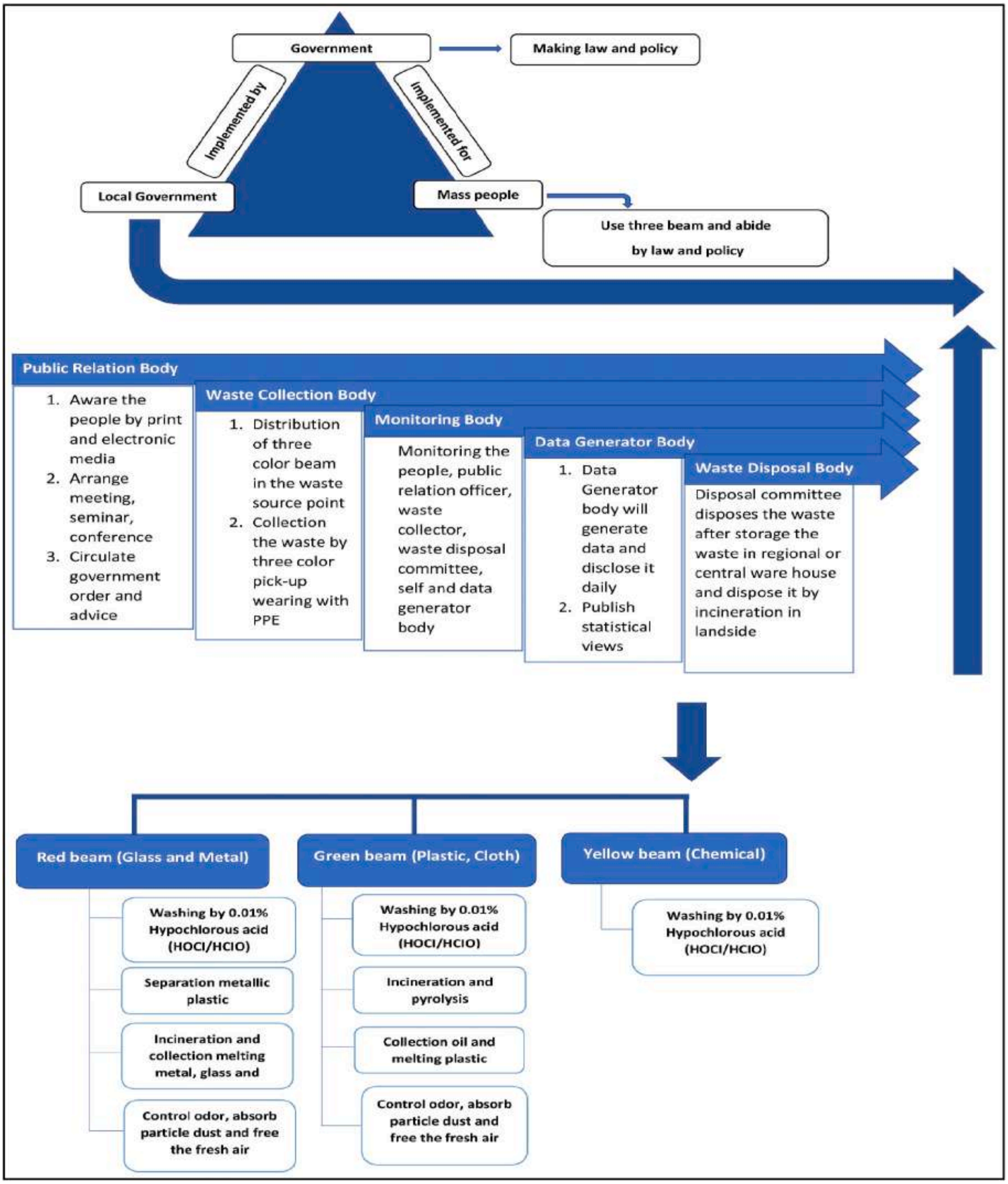

Fig. 8. Sustainable green management system for mitigating the PPE waste disposal. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Ahamad and Md. Ariful Islam: investigation. Md. Ariful Islam, Md. Rezaul Karim and Abu Mohammad Arif: resources. Md. Jainal Abedin, Syed Md. Minhaz Hossain and MRI: data curation. Md. Jainal Abedin and Md. Ripaj Uddin: writing—original draft preparation. Mayeen Uddin Khandaker, Abubakr M. Idris and Md. Rezaul Karim: writing—review and editing. A. Sulieman: visualization. Mayeen Uddin Khandaker: supervision. Md. Jainal Abedin and Abu Mohammad Arif: project administration. Abubakr M. Idris and Mayeen Uddin Khandaker: funding acquisition.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

All authors are agreed to this submission, and publish in

Chemosphere if accepted.

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Availability of data and materials

All data are available in the manuscript.

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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