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Research article

The use of Personal Protective Equipment (PPE) and associated environmental challenges: A study on Dhaka, Bangladesh

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ABSTRACT

The Covid-19 pandemic has caused health crisis and concerns worldwide. The use of Personal Protective Equipment (PPE) has been the primary behavioral and policy response to avert the infection of coronavirus. The emergence of the situation resulted in increased production of PPE, creating a surge in plastic pollution and carbon footprint. The consumption of PPEs is unavoidable; however, proper PPE waste disposal plays a vital role in lessening the associated environmental impacts. This study aims to provide an overview of the environmental challenges associated with Covid-19 pandemic faced in the households located at the heart of Bangladesh, Dhaka City Corporation (DCC) area. The study determines carbon footprint in terms of carbon emission equivalent and plastic pollution potential associated with PPEs. The study further implies that there is a gap in the 3R Strategy implementation in Bangladesh hindering the nation in achieving UN's SDG-12. The findings depict that the proper implementation of the 3R strategy is fundamental for ensuring more a resilient, sustainable and livable environment in the in-pandemic and post-pandemic era and further emphasizes that a strengthened policy framework, operational environmental policy tools, environmental education, and the society and stakeholders' spontaneous response to the plastic pollution challenge are essentially required.

1. Introduction

The COVID-19 pandemic has brought unprecedented challenges for the society. It has changed life as we know it and become the new normal (Johns Hopkins Medicine, 2020). In the first instance, it was assumed to be just another SARs epidemic, but by the time the World Health Organization (WHO) declared COVID-19 as a global pandemic, it had spread over 114 countries with over 118,000 cases (WHO, 2020). Within 21 months' span (March 2020 to December 2021) death tolls in 222 countries have reached 693.2 million (World meter, 2021). The sudden halt imposed by the pandemic has adversely affected the global economy with a lineup of reduced industrial productivity, trade disruption, business cessations, and annihilation of the tourism industry (Pak et al., 2020). Just at the verge of graduation from UN's Least Developed Countries (LDC) list, Bangladesh became a victim of the global economic meltdown, back drawn by 2.91% and 2.99% drop in Real GDP and Nominal GDP (FY2019-2020) (Siddiquee and Faruk, 2020). Bangladesh has had a hard economic comeback with a rebound in exports, financial flows, and the ongoing vaccination campaign (World Bank, 2021). Nevertheless, the inimical economic impacts are easily quantifiable; however, the far-fetched environmental impacts of the pandemic are often left unforeseen.

Consecutive lockdowns and travel restrictions have shown to cut down the daily global CO_2 emissions from 100 $MtCO_2$ per day in 2019 to 83 $MtCO_2$ per day in 2020 (Le Quéré et al., 2020). Forecast shows a probable peak of 26% reduction in carbon emissions in individual countries and interestingly, the only increase in CO_2 emissions during the global confinements of 2020 resulted from residential functions, with a mean and max increase of 2.8% and 6.7% respectively (Le Quéré et al., 2020). However, the estimates of carbon emissions reduction impacted by the pandemic are significantly underestimated in typical developing countries as China and India. The inter-annual comparison based conventional methods of measuring impacts on carbon emissions cannot accurately measure the actual decline and requires a shift to scenario simulation for better precision (Wang et al., 2022). Reductions have also been observed in case of NO_2 emissions during lockdown in South Asian countries India, Nepal, Bhutan, Sri Lanka, Afghanistan and Pakistan (Hassan et al., 2021). Notably, the NO_2 concentration of China has gone down to 50% that of the pre-pandemic scenario (Wang and Su, 2020). The Covid-19 lockdown and country shutdown have seemingly improved the Air Quality Index (AQI) in neighboring countries India (Dasgupta and Srikanth, 2020), Nepal (Baral and Thapa, 2021), Bhutan (Kuensel Online, 2020) and Myanmar (Aung et al., 2021). The initial lockdown of 2020

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has downscaled the AQI of Dhaka City, the capital of Bangladesh, approximately by 35% compared to the levels of the previous year (Islam and Chowdhury, 2021). The lockdown and shutdowns inevitably have had some direct impacts on cleaner air (Klemeš et al., 2020) and restrictions on urban transportation and industrial activities during the lockdown have cut down energy consumption (Wang and Su, 2020); however, air quality and energy consumption cannot be the sole measure for the assessment of environmental sustainability (Klemeš et al., 2020).

One hundred years apart, the global COVID-19 pandemic presents some similarities to the Spanish Flu Pandemic of 1918. Both are respiratory diseases, with asymptomatic to mild to severe illness and risks of death, spread through contact, droplets and fomites (WHO, 2021). The Spanish Flu teaches lessons on public health and awareness (Dowling, 2020; and Matta et al., 2020), quarantine, hand and surface washing, and mask-wearing (Rotondi, 2020); however, does not provide any insight into the environmental impacts of the healthcare and medical wastes of the pandemic. In the early 1980s, healthcare wastes were first acknowledged as an emerging major environmental issue (Prüss-Üstün and Townend, 1999) and after a few years, the concept of 'sustainability' was originated in 1980s, dating about 70 years from the pandemic (Du Pisani, 2006). Nevertheless, the only healthcare product people were bound to wear during the Spanish Flu pandemic was a mask (Hauser, 2020), that too made of cloth or gauze (Little, 2020) which was far more environment friendly than modern day masks (Liebsch, 2020). During the Covid-19 pandemic, modern-day safety equipment kits or Personal Protective Equipment (PPEs) have put huge pressure on the health sector supply chain. These kits include masks, gloves, face shields, disinfectant sprays, hand sanitizers, and alcohol hand rubs that yield microplastic pollution (Haddad et al., 2021) and increased carbon footprint (Karliner et al., 2019), creating spillover in environmental crisis which would lead to an uncontrollable environmental situation. The estimated daily plastic waste generated rounds about 1.6 million tons from 3.4 billion discarded single-use facemasks (Benson et al., 2021a). Alongside a massive surge in plastic pollution, the PPE wastes may also become disease vectors introducing new pathogenic virus or bacteria (Noman et al., 2021; and Andeobu et al., 2022).

In terms of Covid-19 healthcare and medical waste, Bangladesh generated approximately 927.81 tons of daily healthcare and medical waste in 2020. Dhaka alone accounted for 206 tons of daily medical waste (Sangkham, 2020). A study by the Environmental and Social Development Organization outlines that 14,165 tons of single-use plastic waste were generated countrywide between March 2020 and April 2020. The study further provided a breakdown into the category of waste, where gloves, surgical masks and sanitizer bottles attributed to 5,877 tons, 1,592 tons, and 900 tons respectively (ESDO, 2020). However, the findings of another study implies that Bangladesh generates approximately 1.2 million tons of daily plastic waste attributing to facemasks alone (Benson et al., 2021a), which points out a substantial underestimation by the other studies and requires further exploration. Several national policies and guidelines have been formulated to tackle the surge in PPE waste; however, there is no evidence of implementation (Barua and Hossain, 2021). The existing national environmental policies have the potential to address waste and pollution, however are seldom practiced (refer to Table 1).

Given the deficiency of functional national policies and current waste management system in Bangladesh, these healthcare wastes are very unlikely to receive any special waste treatment; and either undergo uncontrolled incineration, releasing GHGs, heavy metals, dioxins, polychlorinated biphenyls and furans to the environment (Heidari et al., 2019), get stacked up for landfilling (Khan, 2018), or end up in drains, rivers and oceans, resulting in water-logging, and being mistakenly eaten by the marine creatures (Hossain et al., 2021; and McInturf and Savoca, 2021). Microplastic fragments from improperly disposed facemasks and surgical plastic items can cause severe injuries to marine organisms (Bansal and Sharma, 2021). The pollution issues arising from these wastes directly conform to Target 12.4 (achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment) and Target 12.5 (substantially reduce waste generation through prevention, reduction, recycling and reuse) under United Nations' (UN) Sustainable Development Goal (SDG) 12 (Sustainable consumption and production patterns). The SDGs tentative implementation timeframe indicates that the "Decade of Action" was supposed to elapse from 2020; however, the COVID-19 pandemic has disrupted alignment with the SDGs as well as National Priority Indicators (NPIs). Nonetheless, global stakeholders are now determined to re-launch a "Decade of Recovery and Action" with a strengthened global SDGs framework (Schmidt-Traub, 2020). Despite the negative impacts, the pandemic has brought some opportunities for the SDGs, especially SDG-12 in terms of creating scope for working on sustainable consumption transformation, and protection against environmental degradation (Wang and Huang, 2021). This opens a new window for Bangladesh to reinforce its commitment to the agenda 2030 by placing waste management and environmental sustainability at the core of its recovery strategies, enabling a circular economy and promoting healthier natural environment, more resilient cities and more frequent ecological restoration cases.

Scientists around the world are predicting that the coronavirus is highly unlikely to go away any time soon, rather become an endemic (Phillips, 2021). Since, the pandemic may not end in the near future; the environmental aspects of the pandemic should no longer be sidelined amidst containment actions. In terms of sustainability, the recent literatures focus either on the negative environmental impacts of COVID-19 fighting equipment used by medical or healthcare staff, or grossly by the whole population, and by far, there is no literature on any study carried out in Bangladesh to measure the associated carbon footprint of PPEs. This creates a massive new scope to study the environmental

Table 1. Existing environmental policies and specific indicators for waste and pollution.

Name of the Policy	Waste and Pollution Specific Indications
Draft National Environmental Policy (2018)	Setting standards and policies for domestic pollution
Solid Waste Management Rules (2010)	Suggested use of 3R practice
National 3R Strategy for Waste Management (2010)	The 3R strategy for cleaner production, product life extension, emissions reducing technologies and waste as resource
Draft Solid Waste Management Rules (2018)	Segregation of waste at primary source
Draft SRO on Plastic Waste Management (2019)	Circular economy and extended producer responsibility (EPR)
National Sustainable Development Strategy (2010–2021)	Environmental protection of humans and ecosystem, pollution control, and efficient utilization of natural resources
City Corporation Act (2009)	The city corporation will be responsible for all wastes generated in public places and labelled waste bins will be provided
Bangladesh Environment Conservation Act (1995)	Control measures for environmental pollution and remedial measures for injury to ecosystem
Bangladesh Environment Conservation Rules (1997)	Standards for emission (air, water, effluent, industrial or projects waste, etc.)

impacts exerted solely by households, especially in a developing country like Bangladesh.

The presented study intends to provide an overview of the environmental impacts of Personal Protection Equipment (PPE) used at households of Dhaka City Corporation (DCC), Bangladesh. The primary focus is to determine the carbon footprint and plastic pollution potential of frequently used PPEs such as masks, gloves, face shields, disinfectant sprays, hand sanitizers, and alcohol hand rubs at the household level and present a footprint and pollution intensity map of DCC that empirically portrays the environmental challenge scenario of the different zones of the study area. The study further points to the current scenario of the 3R Strategy implementation in Bangladesh, shedding light on the malfunction of the implementation system, which is often times sidelined during the analysis of the environmental scenario of Bangladesh. This manuscript suggests that the practice of 3R strategy is a substantial parameter of environmental management, especially during the pandemic situation. This work provides a new perspective of inspecting the environmental scenario during the COVID-19 pandemic and identifies a loophole in the current waste management system that could further be explored in future works.

2. Materials and methods

2.1. Material search

2.1.1. The plastic contents in PPEs and associated pollution

PPEs are mostly made of plastic materials (Khoo et al., 2021) and act as a source of microplastic pollution (Haddad et al., 2021).

Between the year 2016 and 2040, 710 million metric tons of plastic waste will have entered the marine and terrestrial ecosystem (Lau et al., 2020), and Covid-19 fighting PPEs will contribute significantly to the waste flow, exacerbating the pollution scenario (Shams et al., 2021). PPEs consist of different plastics, shown in the following Table 2.

These PPEs are seldom recycled (Kahlert and Bening 2020). In case of Dhaka, less than half of the wastes are collected by open truck and hauled container system and the rest are littered on the streets, dumped into drains and water-bodies, or burned. Such indiscriminate open dumping gives rise to not only plastic pollution, but also a series of drainage and waterlogging problems (Alam and Qiao, 2020). The Covid-19 pandemic has augmented such waste generation by multiple folds, scaling up the plastic pollution in aquatic, atmospheric and terrestrial ecosystems (Lau et al., 2020).

2.1.2. The carbon footprint values of PPEs

Prior to the Covid-19 pandemic, the global healthcare sector was already responsible for 4.4% of global net emissions equivalent to 2 giga tons of CO_2 (Karliner et al., 2019). The pandemic crisis has ignited the situation by putting immense pressure on the healthcare sector. Panic buying emerged as a feature of the virus outbreak (Islam et al., 2021), emptying current stocks of PPEs and surging the demand for PPE production. The sudden surge in demand increased global production of PPE (OECD, 2020), significantly upscaling the production of gloves by 11% in 2020 (Reuters, 2020). The annual production of N95 masks by 3M increased to 2.5 Billion, a fourfold increase from their production in 2019 (Kapadia, 2021). Face shields production by 3M has increased tenfold. The International Financial Corporation (IFC) has determined that the demand for PPE by non-healthcare workers and general mass has increased 300%–400% between 2019 and 2020, and forecasted this demand to continue throughout 2021 (IFC, 2021). The CO_2 equivalent of the different PPEs are extracted from literature and presented in Table 3.

Table 2. Types of plastic consisting in PPEs.

Item	Plastic Type
Surgical, N95 and KN95 mask	Polypropylene (PP) (Chan, 2021; Health Desk, 2021; and Sherman, 2021)
Polyethylene Glove	Polyethylene (PE) (Glove Nation, Retrieve on 2021.)
Face Shield	PET (TAPR, Retrieve on 2021.)
Disinfectant Spray Bottle Cap	HDPE and PP (Blaxhall, 2020)
Sanitizer Bottle	PET (Kahlert and Bening 2020)
Hand Rub Bottle	HDPE (estimated by author)

2.2. Study area selection

Dhaka (Figure 1), the capital of Bangladesh, is one of the utmost urbanized cities in the world (Lansat, 2018). Dhaka houses 44.26% of the nation's urban population every year (World Bank, 2007). Apart from high urbanization, high population density, socio-spatial divisions, Dhaka is an abode of disaster vulnerability, air pollution, noise pollution, deficient green spaces and unhygienic living conditions (Roy et al., 2019). During the Covid-19 pandemic, Dhaka has generated a bulky portion of the country's total PPE waste (ESDO, 2020), henceforth, this study explores the environmental impacts of Personal Protection Equipment (PPE) used at households within the peripheries of the City Corporation area.

2.3. Population forecast

The current population of Dhaka City Corporation was forecasted by means of the geometric increase method (Field and MacGregor, 1987) employing the Bangladesh Bureau of Statistics' (BBS) Population Census of 1981, 1991, 2001 and 2011. The population censuses were directly collected from BBS. The population of 2021 was estimated by use of the following equation.

$$P_n = P\left(1 + \frac{I_g}{100}\right)^N$$

Where,

P_n = Population of n^{th} year
I_g = Geometric mean (%)
P = Present population
N = Number of decades

The population of 2021 was forecasted to be 14 million. The forecast was crosschecked and validated by an officer of the Bangladesh Bureau of Statistics and therefore deemed as reasonable for determining a sample size.

2.4. Sample

The survey was conducted in a combination of web-based survey (7 July 2021 to 31 August 2021) and in-person questionnaire interview (01 September 2021 to 15 November 2021). The population of DCC was classified into nine residential zones and the sample size (N = 423) was determined using the stratified random sampling method. The participating households consisted of 2055 individuals.

Table 3. PEEs' Carbon Footprint in Kg eqCO2.

PPE Type	Kg eqCO_2
N95	0.05/single use (Liebsch, 2020)
KN95	0.05/single use (estimated by author)
Surgical Mask	0.059/single use (Klemeš et al., 2020)
Cloth Mask	0.06/single use (Liebsch, 2020)
Glove	0.21/piece (Usubharatana and Phungrassami, 2018)
Face Shield	0.35/piece (Usubharatana and Phungrassami, 2018)
Disinfectant Spray Bottle (Aluminum)	0.28–0.74/kg Aluminum (Green, 2007)
Sanitizer Bottle (PET)	1.36/kg polyethylene (Blue, 2018)
Hand Rub Bottle (HDPE)	1.58/kg polyethylene (Dormer, 2013)

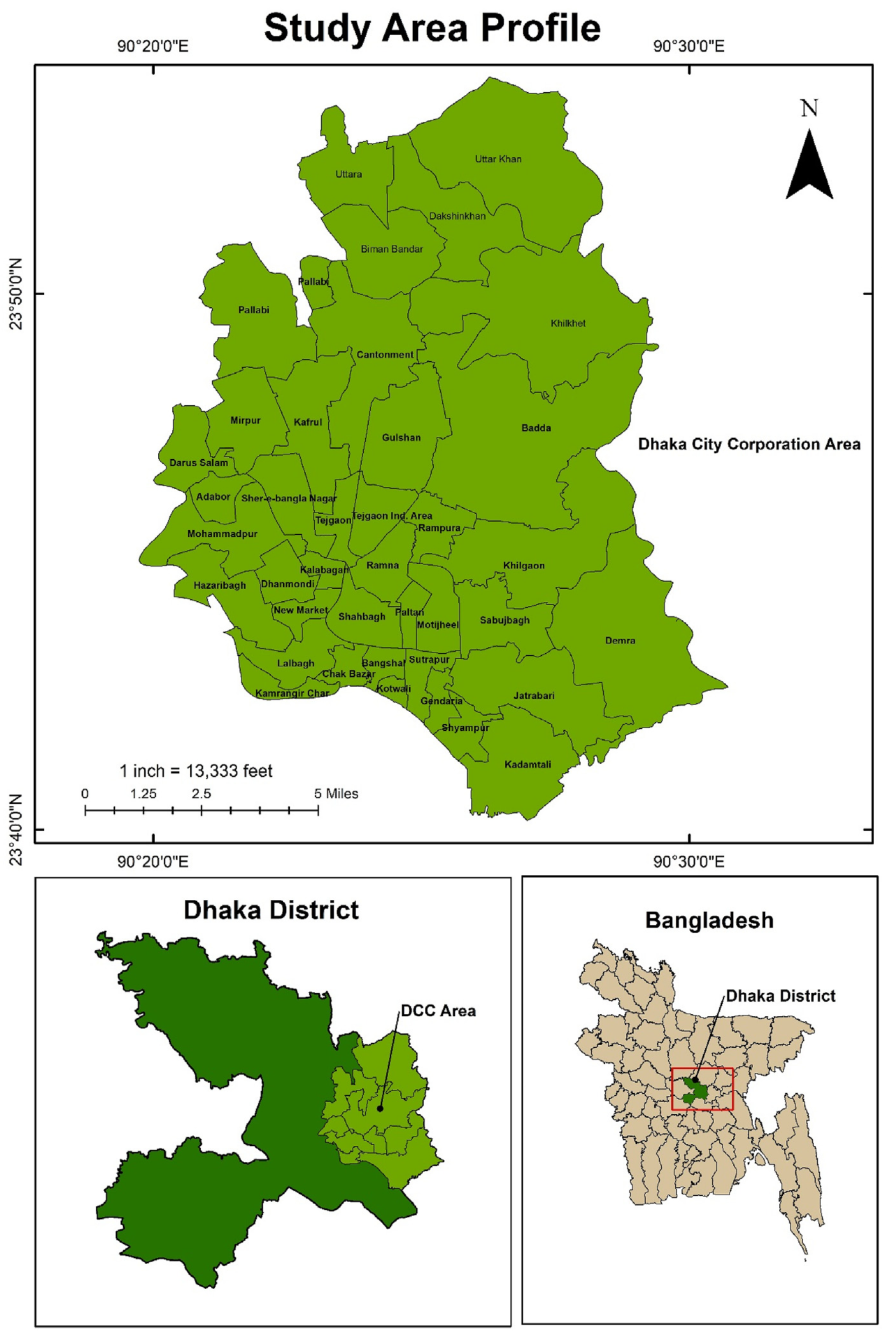

Figure 1. Location map of study area Dhaka City Corporation (DCC).

The survey was anonymous, and confidentiality was assured beforehand. No monetary rewards were associated in completing the survey.

Data were collected from nine residential zones. The zones were declared based on data availability and data detectability and created by grouping adjacent residential areas. The zones were sequentially numbered. The following Table 4 entails the zones and the areas covered under each zone.

2.5. Survey questionnaire

The survey questionnaire inspected the monthly consumption of PPEs such as masks, gloves, face shields, disinfectant sprays, hand sanitizers, and alcohol hand rubs after the Coronavirus outbreak in 2020. The questionnaire consisted of separate parts for each type of PPE, categorized by type (surgical mask, N95 mask, KN95 mask, cloth mask, rubber gloves, and polyethylene gloves) size (50 mL, 100 mL, 150 mL, 250 mL, 300 mL, 500 mL, 1000 mL, 2000 mL and 5000 mL) and the frequency of purchase. Additional questions were prepared to gather insights of reuse and recycle methods practiced at the household levels.

2.6. Data calculation and analysis

The corresponding weight of each PPE was determined using a digital scale. A variety of designs of each PPE is available in the market, therefore the most commonly used designs and sizes were examined for this study. The mean value of weights corresponding to the same size was considered for calculation. The carbon footprint value of each PPE (masks, gloves, face shields, disinfectant sprays, hand sanitizers, and

Table 4. Areas under different zones.

Zone No.	Covered Areas
1	Uttara, Bimanbandar, Uttarkhan, Dakshinkhan and Khilkhet
2	Mirpur, Darussalam, Pallabi and Cantonment
3	Gulshan, Badda, Rampura, Tejgaon, Tejgaon Industrial Area and Sher-e-Bangla Nagar
4	Mohammadpur and Adabor
5	Dhanmondi, Kalabagan, New Market, Hazaribagh and Shahbagh
6	Ramna, Motijheel and Paltan
7	Sabujbagh and Khilgaon
8	Sutrapur, Gendaria, Kotwali, Shyampur, Jatrabari, Kadamtali, Demra, Bangsal and Chawkbazar
9	Lalbagh and Kamrangirchar

alcohol hand rubs) was determined by means of multiplication of respective Kg eqCO_2 in Table 4 with the plastic waste weight values obtained from the calculation incorporating the surveyed data. Similarly, plastic waste generation was calculated for every six months (Refer to Appendix).

2.7. Geospatial mapping

Datasets in ArcGIS were generated by merging thana shapefiles from the population and housing census of 2011 (BBS, 2011) according to corresponding zonal features. The PPEs' carbon footprint and plastic-made PPE consumption data were attributed to the corresponding shapefiles and proper color ramps were selected for data visualization, yielding the study maps. Here Figure 2 represents the methodological flow diagram of this study.

3. Analysis & findings

3.1. Zonal carbon footprints of PPEs in Dhaka City Corporation

The healthcare system has been under immense pressure during the global pandemic. PPEs are massively produced and consumed by the public to prevent SARs-Cov-2 infection. In this study, the Dhaka City Corporation area is divided into nine residential zones (refer to Table 4) to better elucidate the household consumption of the most commonly used PPEs and the carbon footprint (CF) associated with these. The Table 5 encompasses the Kg eqCO_2 values of these PPEs used in every six months.

The cloth masks attribute to the highest carbon footprint value of 57858.12 kg eqCO_2 with consideration of washing. As each mask can be used up to 183 times, it holds the carbon footprint value of 6.92 kg eqCO_2 per mask. Surgical mask comes in second, followed by polyethylene and rubber gloves attributing to carbon footprint values of 5594.40 kg eqCO_2 and 5375.16 kg eqCO_2 respectively. The total carbon footprint of PPEs used in every six months is equivalent of 79071.77 kg eqCO_2.

To better delineate the PPE carbon footprints of the nine zones, a GIS map was prepared. The GIS map (refer to Figure 3) portrays the carbon footprint scenario in the nine study zones through a combination of six colours. The lightest beige colour represents a low carbon footprint, whereas the crimson red represents extreme carbon footprint.

According to Figure 3 and Table 5 the northern zone 3 and 2 hold the highest values of carbon footprint. Other than the high attributing carbon footprint of cloth masks, a significant carbon footprint value of polyethylene gloves, rubber gloves, surgical masks and disinfectant spray is observed in zone 3. On the other hand, besides the cloth masks, substantial amount of carbon footprint is associated with the amount of

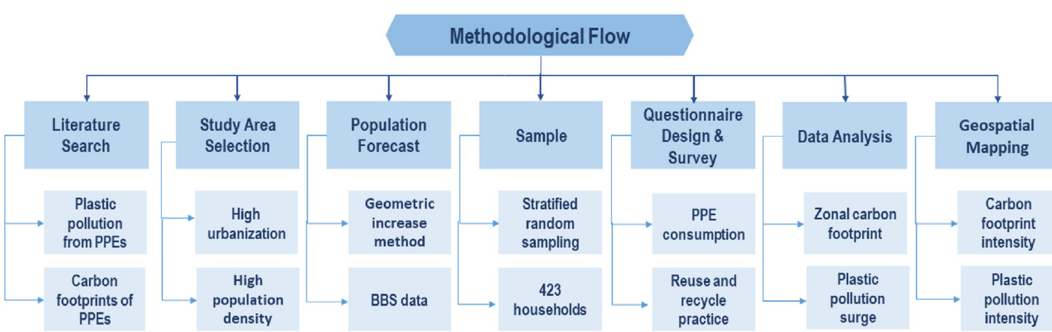

Figure 2. Methodological flow process.

Table 5. Carbon footprint values of PPEs used every six months.

Zones	Items (Kg eqCO_2)										
	Surgical Mask	N95 Mask	KN95 Mask	Cloth Mask	Rubber gloves	PE gloves	Disinfectant Spray	Face Shield	Hand Sanitizer	Hand Rub	Zonal Total
1	1356.19	24.40	15.40	9812.56	1028.16	1257.48	115.39	30.80	29.75	22.69	13692.82
2	1494.23	60.50	29.70	13507.84	957.60	635.04	101.74	23.10	34.88	22.66	16867.29
3	2362.24	51.40	25.30	13300.24	1123.92	1829.52	168.39	21.00	36.59	24.15	18942.75
4	274.00	8.60	4.40	3660.68	287.28	430.92	26.58	4.90	19.35	4.72	4721.42
5	540.91	19.40	18.70	1411.68	572.04	176.40	28.81	4.20	13.13	9.75	2795.01
6	276.83	8.70	16.50	567.44	292.32	70.56	50.45	12.60	11.03	7.84	1314.27
7	697.73	3.70	5.20	3017.12	335.16	420.84	58.43	7.70	12.38	6.41	4564.68
8	1661.32	25.30	20.40	9487.32	584.64	509.04	49.64	17.50	16.13	24.39	12395.68
9	195.05	3.50	3.20	3093.24	194.04	264.60	13.26	3.50	5.58	1.86	3777.84
Total	8858.50	205.50	138.80	57858.12	5375.16	5594.40	612.69	125.30	178.82	124.47	79071.77

*Details of the zones are given in Table 4.

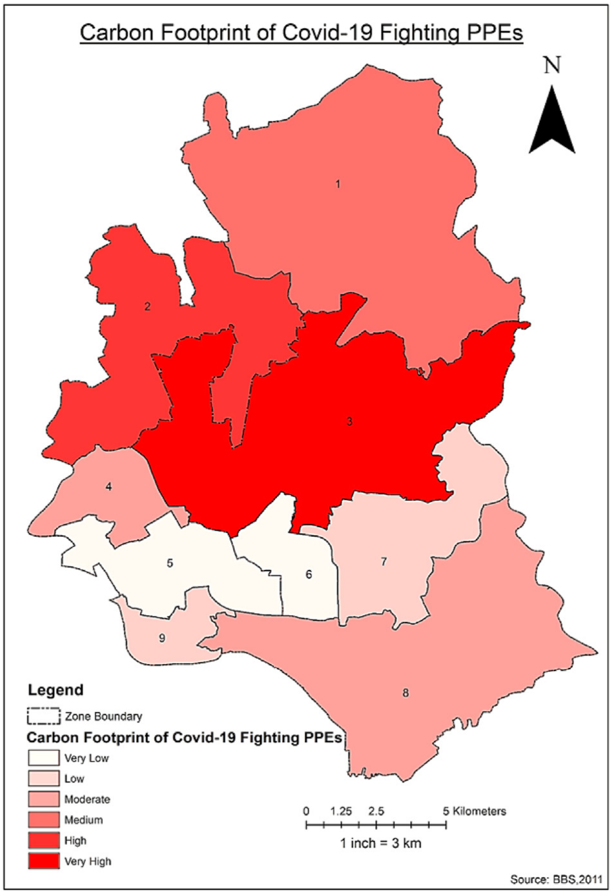

Figure 3. Carbon footprint map of Covid-19 Fighting PPEs of DCC area.

surgical mask, polyethylene glove, rubber glove and disinfectant spray use is observed in zone 2, making it the second highest scoring zone. Zone 1 exhibits high carbon footprint contributed by cloth masks, surgical masks, polyethylene and rubber gloves, and disinfectant spray. Zone 4 and 8 fall into the medium category, where cloth masks, surgical masks and polyethylene gloves add most to the corresponding carbon footprint. Zone 7 and 9 fall into the moderate category, however, cloth masks contribute an unparalleled amount to the corresponding footprint of zone 7, whereas carbon footprint of zone 9 is associated with cloth masks, surgical masks, polyethylene gloves and rubber gloves. Zone 5 and 6's carbon footprint comprises mostly that of cloth masks, surgical masks and rubber gloves; zone 5 holds a high value of footprint corresponding to polyethylene gloves as well, securing a low footprint category. In comparison with zone 5, zone 6 holds a substantially low carbon footprint value, with the lowest footprint value of cloth masks and polyethylene gloves among all zones.

During the questionnaire survey, only one out of the 2055 individuals stated that they use a cloth mask only once and dispose afterward. Others shared that they use the cloth masks, as well as N95 and KN95 masks multiple times before disposing. However, none of the respondents recycles those. In case of the surgical masks, rubber gloves, and polyethylene gloves all respondents make single-use of these items and do not recycle or reuse. One of the 400 households reuse the disinfectant spray bottles at home. Only a handful of households use face shields, especially those who are over 50 years old. Hand sanitizer and hand rub bottles are the only items that are broadly reused, however, not recycled. None of the households was found to recycle any of the PPEs. Majority of the households are unfamiliar with the concept of reduce, reuse and recycle. They reuse the hand rub and sanitizer bottles that are of smaller size (50 mL and 100 mL) for travel and carrying convenience, and the medium sized ones (250 mL, 500 mL) as those are easier to use when refilled from a larger bottle. The respondents were not reusing the bottles from an environmental point of view, rather based on convenience.

3.2. Plastic containing PPE and waste generation

In reference to Table 2, apart from cloth mask and rubber gloves, the other PPEs contain a significant amount of plastic. The surveyed 423 households purchase 1241.44 kg of plastic made or plastic containing PPEs every six months. Surgical masks are the highest purchased product among all with a total number of 150072 pieces purchased every six months. Polyethylene gloves come in second with a total number of 12354 pieces or 6177 pairs purchased every six months. Hand sanitizers are the third highest purchased product, followed by disinfectant sprays, N95 masks, hand rubs, KN95 masks and face shield. The following Table 6 exhibits the order of the PPEs in terms of amount purchased and the zones that hold the highest number of purchase score of corresponding PPEs.

Figure 4 depicts the variation in plastic-made PPE consumption within the study area through six colours. Zone 4 and 9 fall into the low consumption category represented through light red; contrarily, zone 3 falls into the highest consumption category visualized through a deep red color.

These PPEs are made of different plastic materials, and when improperly disposed can cause plastic pollution. Some of these PPEs can remain in the environment for more than 400–500 years (Lambden, 2020). Due to the current healthcare emergence of Covid-19 pandemic, PPE production has boomed ten-folds, generating bulks of PPE waste. These PPEs contain a significant amount of plastic materials, as plastics are comparatively easier and economical to make (Kramer, 2016). The plastic contents are promoting PPE wastes as a potential source of plastic pollution. The PPEs used by the study population are made of polypropylene (PP), polyethylene (PE), high density polyethylene (HDPE), polyethylene tetraphthalate (PET) and a combination of HDPE and PET The bulky portion (86%) of the plastic contents in PPE waste constitute of HDPE (Figure 5), which has an estimated half-life of 58 years, meaning that it may take over 100 years for the HDPE molecules to degrade (Chamas et al., 2020).

The existing literatures on PPE generation in Bangladesh discuss about the plastic waste grossly, rather than breaking down the percentage of different plastic contents that contribute to different carbon footprint values. The rise in carbon footprint associated with PPE use has not been explored in previous studies conducted in Bangladesh, leaving a major scope for studying the carbon footprint aspects of the plastic-made PPEs. This study elucidates that PPE and its improper disposal account for rise in carbon footprint and result in a surge of plastic pollution. Insights into the reuse and recycling practice and environmental challenges associated with PPEs reflect on the importance of adopting a circular system for closing the loop to utilize maximum value of the PPEs, eliminate waste and pollution, and regenerate natural resources. The findings of the study in terms of 3R Strategy implementation, indicate that the general mass is unfamiliar

Table 6. PPE purchases and zones with highest purchase scores.

PPE Item	Pieces/Six Months	Zone with highest purchase score
Surgical Mask	150072	3
Polyethylene Gloves	12354	3
Hand Sanitizer	5093	3
Disinfectant Spray	4344	3
N95 Mask	4110	2
Hand Rub	3659	3
KN95 Mask	2776	2
Face Shield	358	1

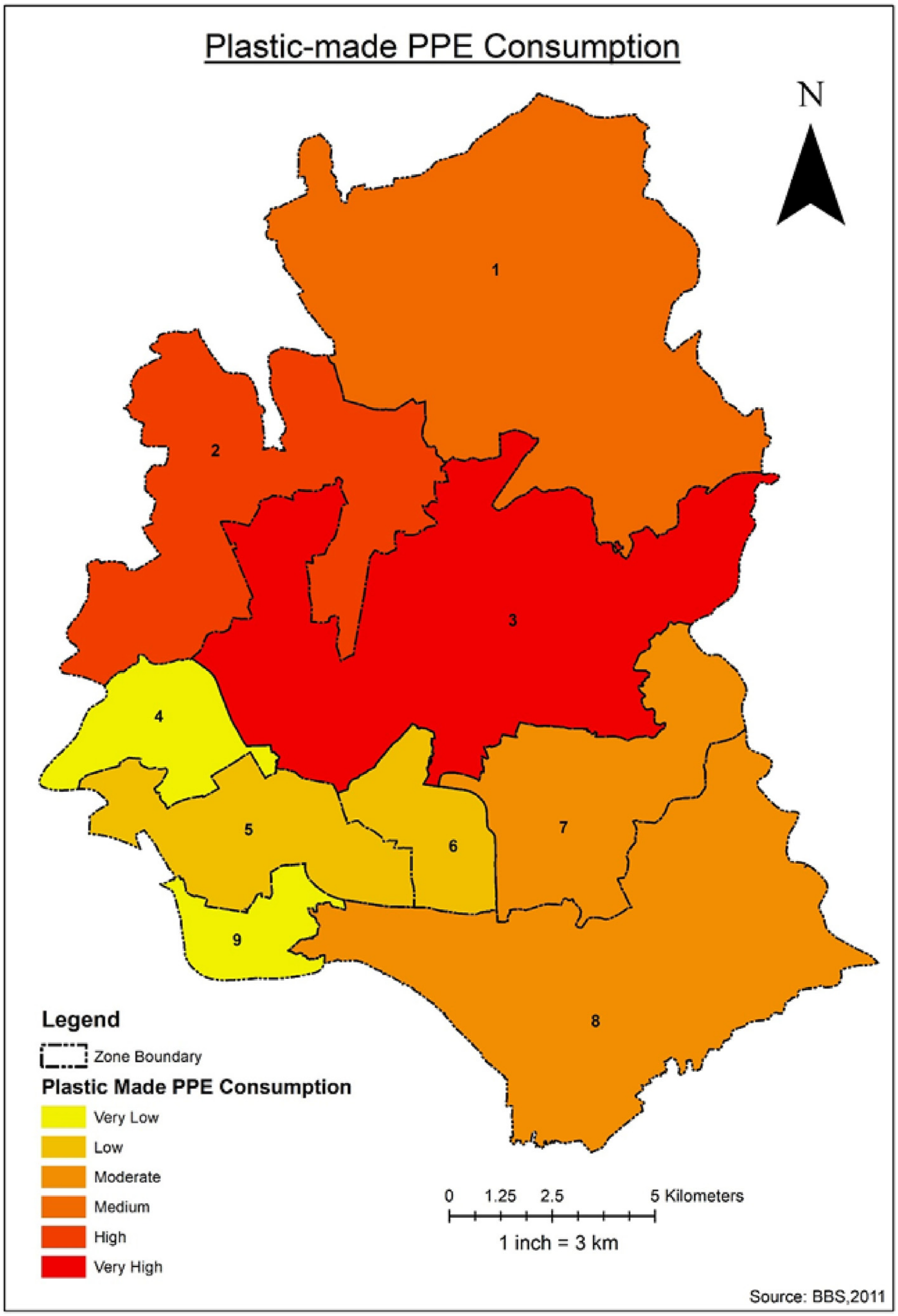

Figure 4. Plastic-made PPE consumption map of DCC area.

with this policy and therefore do not adhere to it. The inadequate practice of the existing 3R Strategy points out the need for its effective implementation and operation for waste management, particularly during the pandemic situation to tackle the environmental pollution scenario. The practice of 3R Strategy at the household as well as municipal level can be considered as an important parameter of assessing the municipal waste management system in both developing and developed countries. The identified gaps in waste management policy implementation and the associated carbon footprint aspects are additions to existing literature for future exploration and the outputs of the study may act as notable aspects of the environmental challenges associated with Covid-19 pandemic for strengthening the SDGs framework (refer to Figure 6).

4. Discussion

At the advent of the Covid-19 pandemic in Bangladesh, the Directorate General of Health Services (DGHS) has imposed directives on the proper disposal of PPE; including disposal in color-coded bins, securely sealed, and labeled. However, these regulations are seldom followed; the PPE wastes are neither segregated nor disposed in a proper manner, rather disposed at random places, mixed up with normal waste and openly piled up in streets (Barua and Hossain, 2021). The convictions of this manuscript imply that the unfamiliarity of the general mass with the 3R Strategy is associated with the improper disposal of PPE wastes. Familiarization with national environmental policies and regulations play a significant role in influencing environmental behavior of people,

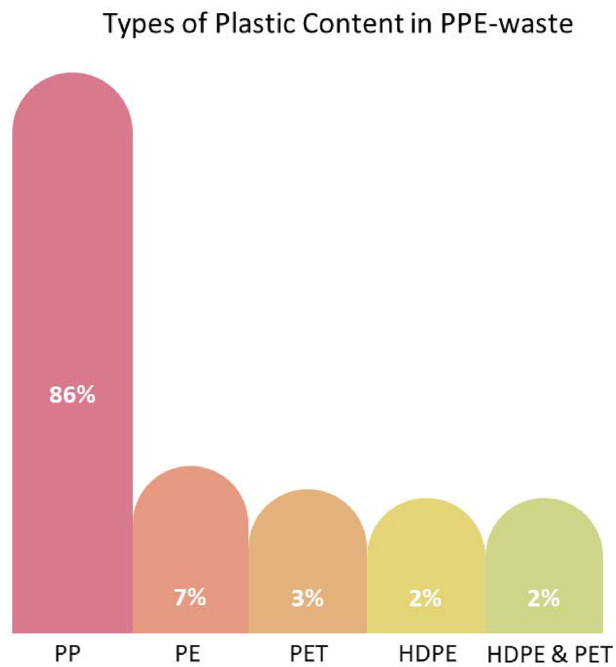

Figure 5. Types of plastic content in PPE waste of DCC area.

however, the dysfunctionality of the policy implementation and practice system in Bangladesh is partly responsible for the mismanagement of wastes.

Wuhan City of China has set an exemplary example of Covid-19 medical and healthcare waste management. The waste was generally disposed of in sanitary landfill or incinerated as waste to energy recovery. During the pandemic, Wuhan's waste management shifted to centralized, regular, and non-incineration disposal technologies such as autoclave steam, dry heat, chemical disinfection or microwave. Internet of Things (IoT) was employed to keep real-time tracking and controlling of the waste to make the whole waste management system automated and synchronized (Singh et al., 2020).

In the Philippines, there are registered transporters, treatment, storage, and disposal (TSD) facilities that handle the healthcare wastes (EMB, 2020). Jordan's Government imposed three principles under their healthcare waste management system; cut down unnecessary healthcare waste, isolate regular waste from hazardous waste, and properly treat waste to reduce risks to the people and society (ISWA-Jordan, 2020). Waste management strategies adopted around the world during this pandemic are all based on regular management. In order to advert environmental crisis spillover in Bangladesh, waste needs to be collected, segregated, stored with specific labels, transported, treated and disposed of properly (Das et al., 2021). In addition, public education on sustainable waste management methods is required (Benson et al., 2021b).

5. Recommendations

5.1. Future measures for zero plastic pollution and environmental sustainability

The surge in plastic pollution resulting from PPE wastes is becoming a major challenge, especially for a developing nation as Bangladesh. The findings of this study point that the improper disposal and treatment of PPE wastes are gradually turning Bangladesh in to a plastic pollution hotspot, necessitating immediate actions. Addressing the plastic pollution challenge requires partitioning the reduction strategies into preconsumption and postconsumption measures. A coordinated combination of these two measures could gradually avert environmental pollution. The preconsumption solutions focus on a reduce and substitute scenario, where the volume of plastic is reduced, less disposed in to waste streams, and alternative compostable materials are used (Lau et al., 2020). Microalgae based bioplastics are increasingly becoming a sustainable choice of plastic alternative, which are composed of biosynthesis materials and are energy efficient. Microalgaes can produce biopolymers polyhydrobyalkanoates (PHAs), polyhydroxybutyrates (PHBs) polylactic acids (PLAs), which commonly go by Biopol, Nodax, Degr Pol and Biogreen in the market (Khoo et al., 2021). The postconsumption solutions entail collection and recycling of plastic-made items (Lau et al., 2020). In terms of collection and recycling, segregation and sorting plays a vital role, since the availability of recycling options often increase when the plastic waste is either segregated or sorted (Fang et al., 2020).

5.2. Circular economy and the 3Rs strategy

Amidst the climate change era, plastic pollution has become an emerging global challenge. In recent years, the concept of circular economy has gained massive momentum among scholars, industries, policymakers and practitioners. The concept of circular economy can grossly be defined as a combination of reduce, reuse, recycle and recovery activities involving any necessary systematic change (Kirchherr et al., 2017). In other words, circular economy is a regenerative system where resource, waste, emission and energy leakage are minimized to the maximum possible extent by slowing, closing and narrowing material and energy loops through sustainable design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling (Geissdoerfer et al., 2017). The 3R strategy under the circular economy concept has been introduced in Bangladesh in 2010. The National 3R Strategy for Waste Management (2010) focuses on the principles of reducing waste, reusing and resources and products. Reducing refers to using items in a careful manner in order

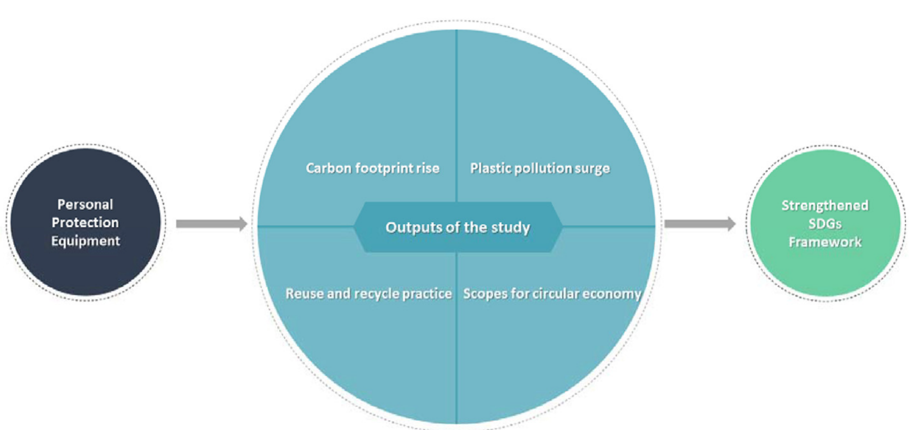

Figure 6. Linkage between study outputs and SDGs framework.

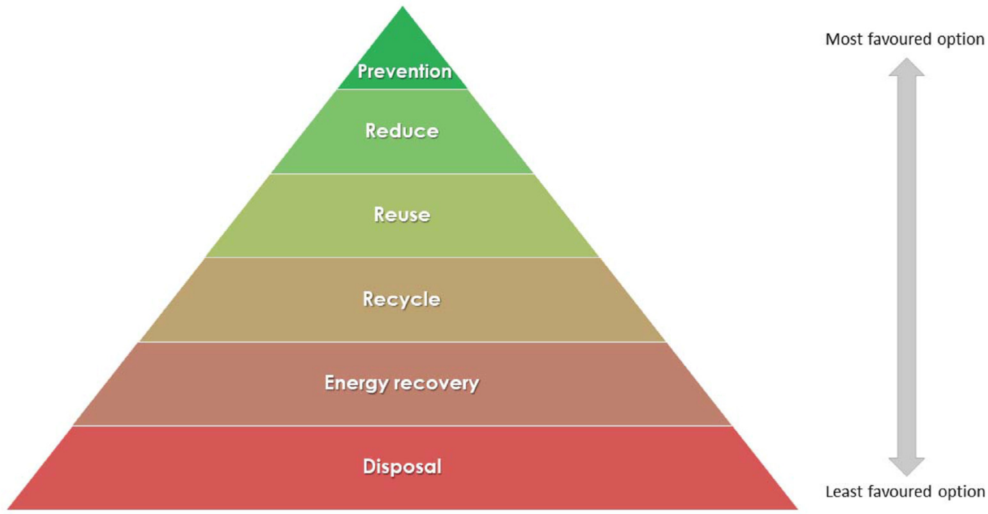

Figure 7. Waste hierarchy.

to reduce waste generation. Reusing implies to repeat the use of items or parts of items that are still useable. Recycling refers to use the waste itself as resource. The 3Rs follow a hierarchy of importance, recycling being at the bottom of the hierarchy and reducing at the top (National 3R Strategy for Waste Management, 2010).

Figure 7 waste hierarchy has a total of six principles, however, only the 3Rs are reflected in 2010's National Waste Management Strategy of Bangladesh. The government of Bangladesh has introduced a mix of policy instruments for waste management, including the 3R Strategy, however, they are hardly practiced (Azizuddin et al., 2021). The 3R strategy mandates local authorities to promote recycling through mandatory waste segregation at source, waste treatment facility development and commercialization of recyclable materials (Yousuf, 2014). The findings of Alam and Qiao portray a scenario where majority of wastes are openly dumped in the environment and the minimal amount of waste collected from households are either collected by open truck or hauled container system, leaving segregation at source out of question. Other than the open dumping disposal, wastes are often landfilled; as these landfills are neither engineered nor sanitary, the wastes can stay in earth for an eternity, adversely impacting the environment. The recycling market is slowly growing, acting as the means of breadwinning of 0.5 million people who save disposal cost of USD15.29 every year. In terms of waste treatment methods, incineration has caught the attention and been validated as applicable technology, however, it is still at the primary stage (Alam and Qiao, 2020). The findings of this study depict that most of the surveyed households are unaware of the 3R principles, and therefore they do not practice them, which in lines with the convictions of Azizuddin et al. and Alam and Qiao. The results of this study also indicate that there is a massive scope for Bangladesh to shift to a circular economy by reducing, reusing and recycling plastic wastes. The Covid-19 pandemic brings opportunities for Bangladesh to effectively manage the environmental crisis associated with PPE use, close the loop to conquer the plastic circularity challenge and achieve UN's SDG-12 through a strengthened framework. In this backdrop, it becomes crucial to follow the 3R strategy in collaboration with external sectors. Reducing plastic usage requires a change in consumer behavior. Environmental education can play a vital role in habit formation of reduction, reusing and recycling and achieving eco-consumerism (Khoo et al., 2021). Public awareness education plays a vital role in bringing behavioral change to reduce plastic pollution (Benson et al., 2021b). A strengthened legislative framework, operational environmental policy tools, education on the adverse effects of plastic waste, advantages and methods of the 3Rs, and the society and stakeholders' spontaneous response to the plastic pollution challenge (refer to Figure 8), altogether can bring Bangladesh under the umbrella of circular economy (Khoo et al., 2021).

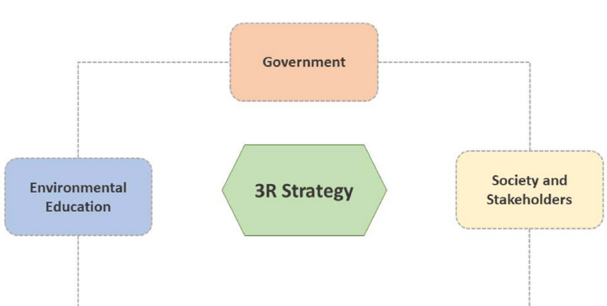

Figure 8. Collaboration of 3R strategy, environmental education, government, society and stakeholders.

6. Conclusion

The Covid-19 pandemic situation has become the new normal. The pandemic has put the healthcare sector under immense demand for PPEs. PPEs are essential to prevent or reduce the infection of the coronavirus, however, yield a great amount of healthcare waste when disposed improperly. The findings and insights offered in this study point to the overarching impacts of Covid-19 fighting PPEs used at the household level. Plastic pollution and carbon footprint are highly associated with the PPEs that are being used worldwide. The single-use of PPEs such as surgical mask, N95 mask, KN95 mask, rubber gloves, polyethylene gloves, face shields, disinfectant sprays, hand sanitizers, and alcohol hand rubs is not only increasing carbon footprint but also escalating the plastic pollution surge. The only PPE that is deliberately used multiple times by the majority of households is the cloth mask, which may initially deem as an eco-friendly alternative to the other masks, nevertheless, when washed with detergent it attributes to a much higher carbon footprint than that of any other single-use PPEs. These household PPEs are disposed openly in streets, drains and the environment, yielding to a greater amount of plastic waste than the pre-pandemic scenario. There are several national policies to tackle the environmental crisis, however seldom practiced. The convictions of this study implies that there is a better need to strengthen the policy implementation and practice system in order to retain Bangladesh from becoming a major plastic pollution hotspot in the near future. The pollution scenario is becoming surged with plastic and microplastic wastes amidst the pandemic situation and requires to be immediately addressed to avoid future spillovers.

Bangladesh has employed a 3R strategy with a vision of transitioning to circular economy; however, the mass people are utterly unfamiliar with the practices and principles of the 3R strategy. The findings of this study indicate that there is a gap in the 3R Strategy implementation. The strategy is neither properly functional at the municipal level nor the household level, and requires a strengthened framework of implementation and a series of public awareness programs to familiarize people with the positive outcomes of the principles. Responses on the reducing, reusing and recycling practices can be incorporated in future assessment of environmental management in Bangladesh to thoroughly understand the prevailing situation.

The pandemic has brought a variety of environmental challenges for the society, and as this situation is highly unlikely to change in the near future, Covid-19 fighting measures must still be in place. As circular economy is no longer just a concept, rather the future, waste management system and solutions should be designed based on the concept of the circular economy. A reinforced legislative structure, operational environmental policy tools, environmental education and spontaneous participation of society and stakeholders in addressing the environmental challenges of the global pandemic is essential. The observations of this study enrich the existing researches in the context of the increase in plastic pollution and carbon emission, and the 3R Strategy implementation in Bangladesh. Future works incorporating a greater sample and ease of data collection may pave way for a developing country like Bangladesh in building a strengthened legislative framework to achieve UN's SDG-12 and create a more sustainable environment and society in the in-pandemic and post-pandemic era.

Declarations

Author contribution statement

Prokriti Monolina: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Mozammel Hasan Chowdhury: Analyzed and interpreted the data; Wrote the paper.

Md. Nazmul Haque: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Appendix

Carbon Footprint (CF) Calculation:

$$CF_{Surgical\ Mask} = N_{SM} \times V_{SM} \times 6$$

$$CF_{N95} = N_{N95} \times V_{N95} \times 6$$

$$CF_{KN95} = N_{KN95} \times V_{KN95} \times 6$$

$$CF_{Cloth\ Mask} = N_{CM} \times V_{CMW} \times 6$$

$$CF_{Rubber\ Gloves} = N_{RG} \times V_{RG} \times 6$$

$$CF_{Polyethylene\ Gloves} = N_{PG} \times V_{PG} \times 6$$

$$CF_{Disinfectant\ Spray} = \{(N_{SDS} \times W_{Al} + N_{LDS} \times W_{Al}) \times V_{Al} + (N_{SDS} \times W_P + N_{LDS} \times W_P)\} \times V_{DS} \times 6$$

$$CF_{Face\ Shield} = N_{FS} \times V_{FS} \times 6$$

$$CF_{Hand\ Sanitizer} = \{(N_{SHS} \times W_{SHS}) + (N_{MHS} \times W_{MHS}) + (N_{LHS} \times W_{LHS}) + (N_{XLHS} \times W_{XLHS}) + (N_{XXLHS} \times W_{XXLHS})\} \times V_{HS} \times 6$$

$$CF_{Hand\ Rub} = \{(N_{SHR} \times W_{SHR}) + (N_{MHR} \times W_{MHR}) + (N_{LHR} \times W_{LHR}) + (N_{XLHR} \times W_{XLHR}) + (N_{XXLHR} \times W_{XXLHR})\} \times V_{HS} \times 6$$

Plastic Waste (PW) Generation Calculation:

$$PW_{Surgical\ Mask} = N_{SM} \times W_{SM} \times 6$$

$$PW_{N95} = N_{N95} \times W_{N95} \times 6$$

$$PW_{KN95} = N_{KN95} \times W_{KN95} \times 6$$

$$PW_{Polyethylene\ Gloves} = N_{PG} \times W_{PG} \times 6$$

$$PW_{Disinfectant\ Spray} = \left(N_{SDS} \times W_P + N_{LDS} \times W_P\right)\} \times 6$$

$$PW_{Face\ Shield} = N_{FS} \times W_{FS} \times 6$$

$$CF_{Hand\ Sanitizer} = \{(N_{SHS} \times W_{SHS}) + (N_{MHS} \times W_{MHS}) + (N_{LHS} \times W_{LHS}) + (N_{XLHS} \times W_{XLHS}) + (N_{XXLHS} \times W_{XXLHS})\} \times 6$$

$$CF_{Hand\ Rub} = \{(N_{SHR} \times W_{SHR}) + (N_{MHR} \times W_{MHR}) + (N_{LHR} \times W_{LHR}) + (N_{XLHR} \times W_{XLHR}) + (N_{XXLHR} \times W_{XXLHR})\} \times 6$$

Where,

N_{SM} = Number of Surgical Masks
N_{N95} = Number of N95 Masks
N_{KN95} = Number of KN95 Masks
N_{CM} = Number of Cloth Masks
N_{RG} = Number of Rubber Gloves
N_{PG} = Number of Polyethylene Gloves
N_{SDS} = Number of Small Sized Disinfectant Spray Bottles
N_{LDS} = Number of Large Sized Disinfectant Spray Bottles
N_{FS} = Number of Face Shields
N_{SHS} = Number of Small Sized Hand Sanitizer
N_{MHS} = Number of Medium Sized Hand Sanitizer
N_{LHS} = Number of Large Sized Hand Sanitizer
N_{XLHS} = Number of XL Sized Hand Sanitizer
N_{XXLHS} = Number of XXL Sized Hand Sanitizer
N_{SHR} = Number of Small Sized Hand Rub
N_{MHR} = Number of Medium Sized Hand Rub
N_{LHR} = Number of Large Sized Hand Rub
N_{XLHR} = Number of XL Sized Hand Rub
N_{XXLHR} = Number of XXL Sized Hand Rub
V_{SM} = Carbon Footprint Value of Surgical Masks
V_{N95} = Carbon Footprint Value of N95 Masks
V_{KN95} = Carbon Footprint Value of KN95 Masks
V_{CMW} = Carbon Footprint Value of Cloth Masks with Consideration of Washing
V_{RG} = Carbon Footprint Value of Rubber Gloves
V_{PG} = Carbon Footprint Value of Polyethylene Gloves
V_{DS} = Carbon Footprint Value of Disinfectant Spray
V_{FS} = Carbon Footprint Value of Face Shield
V_{HS} = Carbon Footprint Value of Hand Sanitizer
V_{HR} = Carbon Footprint Value of Hand Rub
W_{SM} = Weight of Surgical Masks
W_{N95} = Weight of N95 Masks
W_{KN95} = Weight of KN95 Masks
W_{RG} = Weight of Rubber Gloves
W_{PG} = Weight of Polyethylene Gloves
W_{Al} = Weight of Aluminum bottle
W_{FS} = Weight of Face Shield
W_P = Weight of Plastic Cap
W_{SHS} = Number of Small Sized Hand Sanitizer
W_{MHS} = Number of Medium Sized Hand Sanitizer
W_{LHS} = Number of Large Sized Hand Sanitizer
W_{XLHS} = Number of XL Sized Hand Sanitizer
W_{XXLHS} = Number of XXL Sized Hand Sanitizer
W_{SHR} = Number of Small Sized Hand Rub
W_{MHR} = Number of Medium Sized Hand Rub
W_{LHR} = Number of Large Sized Hand Rub
W_{XLHR} = Number of XL Sized Hand Rub
W_{XXLHR} = Number of XXL Sized Hand Rub

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