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Review

Personal protective equipment-derived pollution during Covid-19 era: A critical review of ecotoxicology impacts, intervention strategies, and future challenges

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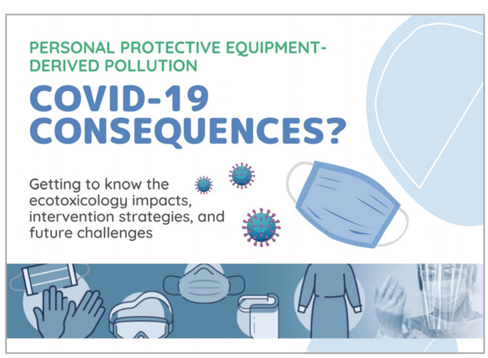
HIGHLIGHTS

- MPs from discarded PPE are a new threat to the long-term health of the environment.
- Excessive PPE use releases MPs into the ecosystem.
- Post-COVID-19 sustainability depends on proper intervention strategies for PPE waste.
- Impacts, strategies, and future challenges are discussed for BoB coastal regions.
- A gap is observed in the 5R strategy's implementation in the BoB coastal regions.

GRAPHICAL ABSTRACT



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ABSTRACT

During the COVID-19 pandemic, people used personal protective equipment (PPE) to lessen the spread of the virus. The release of microplastics (MPs) from discarded PPE is a new threat to the long-term health of the environment and poses challenges that are not yet clear. PPE-derived MPs have been found in multi-environmental compartments,

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e.g., water, sediments, air, and soil across the Bay of Bengal (BoB). As COVID-19 spreads, healthcare facilities use more plastic PPE, polluting aquatic ecosystems. Excessive PPE use releases MPs into the ecosystem, which aquatic organisms ingest, distressing the food chain and possibly causing ongoing health problems in humans. Thus, post-COVID-19 sustainability depends on proper intervention strategies for PPE waste, which have received scholarly interest. Although many studies have investigated PPE-induced MPs pollution in the BoB countries (e.g., India, Bangladesh, Sri Lanka, and Myanmar), the ecotoxicity impacts, intervention strategies, and future challenges of PPE-derived waste have largely gone unnoticed. Our study presents a critical literature review covering the ecotoxicity impacts, intervention strategies, and future challenges across the BoB countries (e.g., India (162,034.45 tons), Bangladesh (67,996 tons), Sri Lanka (35,707.95 tons), and Myanmar (22,593.5 tons). The ecotoxicity impacts of PPE-derived MPs on human health and other environmental compartments are critically addressed. The review's findings infer a gap in the 5R (Reduce, Reuse, Recycle, Redesign, and Restructure) Strategy's implementation in the BoB coastal regions, hindering the achievement of UN SDG-12. Despite widespread research advancements in the BoB, many questions about PPE-derived MPs pollution from the perspective of the COVID-19 era still need to be answered. In response to the post-COVID-19 environmental remediation concerns, this study highlights the present research gaps and suggests new research directions considering the current MPs' research advancements on COVID-related PPE waste. Finally, the review suggests a framework for proper intervention strategies for reducing and monitoring PPE-derived MPs pollution in the BoB countries.

Contents

1. Introduction

In the contemporary era, plastic/microplastic (MP) pollution has been one of the greatest environmental challenges in both developed and developing countries due to its huge impacts on the surface and subsurface waters (Ryan et al., 2020a, 2020b), sediments (Castro and Zermeño, 2020), and a wide range of taxa (De-la-Torre et al., 2022a; Santillán, 2020). Plastic polymers like polystyrene (PS), polyethylene (PE), and polypropylene (PP) will stay in the ocean for a long time because they are resistant to breaking down. This will cause plastic pollution in the marine environment (Rakib et al., 2021; De-la-Torre et al., 2021; Rahman et al., 2023). Researchers have found MP polymers in the hydrosphere, lithosphere, biosphere, and atmosphere (Gandara e Silva et al., 2016; Sanchez-Vidal et al., 2018; Ambrosini et al., 2019; Chen et al., 2021; Liu et al., 2019; Gallo et al., 2020). Researchers have found primary and secondary sources of MPs (Boucher and Friot, 2017; Crawford and Quinn, 2016). Primary sources include MPs in cosmetics, personal care products, and cleaning agents, and secondary sources include the breakdown of larger plastics into small pieces of MPs. Therefore, the research reports claimed the presence of higher synthetic fibrous particles in the environment, which come from textile industries and face masks (Ambrosini et al., 2019; Tiwari et al., 2019; Wang et al., 2019; Henderson and Green, 2020).

On January 30, 2020, the World Health Organization (WHO) declared a global health emergency (Saadat et al., 2020) due to the outbreak of the novel coronavirus disease (COVID-19) by the end of 2019 (S. Xu et al., 2020; Z. Xu et al., 2020). Most governments took decisive steps to stop the spread of the virus, such as short- and long-term lockdowns, the closing of borders, and the forced use of personal protective equipment (Siam et al., 2020; Alfonso et al., 2021). During the COVID-19 pandemic, using PPEs is one of the most efficient and affordable ways to prevent the transmission of the virus. Because of this, there has been a massive rise in the demand for and use of PPE, mostly face masks and hand gloves (Prata et al., 2020; Rakib et al., 2021), which makes PPE a type of marine litter that could be the most common (Ardusso et al., 2021).

Cordova et al. (2021) explained that human activities cause plastic trash in the ocean. During the COVID-19 pandemic, many PPEs were used, which worsened the problem (Dioses-Salinas et al., 2022; Pizarro-Ortega et al., 2022). On the one hand, there was a massive production and use of PPEs during the COVID-19 pandemic; on the other hand, their management got complicated by the sudden increment that has caused a global crisis in recent eras (Chowdhury et al., 2021; De-la-Torre et al., 2022a, 2022b; Mohammadi et al., 2022; Dai et al., 2022). E&T's editorial (2021) estimated that reusable PPEs, especially masks, could reduce plastic waste by 60,000 tons annually. Researchers have reported the existence of PPE, like face masks (87.7 %), followed by face shields (6.5 %), as MPs waste along the coastal sides (De-la-Torre et al., 2021). Although a considerable proportion of face masks were reported in the coastal sites, it should also be noted that surgical masks were also found in the ocean because of the synthetic polymers in the masks, which could lead to long-term environmental impacts (Aragaw, 2020). Researchers have also witnessed that the non-woven layer of surgical masks releases a considerable number of fibers (Chua et al., 2020), which cause environmental MP emissions (Nessi et al., 2022). Like surgical and face masks, other standard sets of PPEs, such as a surgical hat, shoe coverings, goggles or face shields, and gloves (El-Sokkary et al., 2021; WHO, 2021), were donned by healthcare workers and other citizens to protect them from exposure to the SARS-CoV-2 virus and cross-infection, which was the prime challenge of global health care systems.

The emergence of viral transmission during the COVID-19 pandemic disrupted PPE demands and supply. Therefore, the world faces concerns about the safety and efficacy of PPEs, which can be linked to the overuse of PPEs and their marine environment pollution (Jung et al., 2021). Consequently, developed and developing countries faced difficulties designing sustainable management systems for this unwanted PPE waste (Aragaw, 2020; Anastopoulos and Pashalidis, 2021; Patrício Silva et al., 2021; Rakib et al., 2021; Takdastan et al., 2021). Although several international authorities have adopted some policies for the safest disposal of PPE waste, their mass implementation has become a great challenge for the corresponding authorities (Van Fan et al., 2021; Dai et al., 2022). As a result, inadequately managed PPEs are thrown into the environment and act as a possible medium of transmission (Kampf et al., 2020; Klemeš et al., 2020a, 2020b; Sajorne et al., 2022). In recent studies by Fadare and Okoffo (2020) and Anastopoulos and Pashalidis (2021), it was reported that partial degradation of surgical face masks is composed of several polymers as raw products of plastics, i.e., polyester, polypropylene, polycarbonate, polyethylene, and polyacrylonitrile (Aragaw, 2020). When PPEs are released into the environment, they degrade into smaller particles (5 mm in size), which can then form new forms of MPs and pollute cities, beaches, coasts, rivers, and other water bodies (Ammendolia et al., 2021; Ardusso et al., 2021; Cordova et al., 2021; Thiel et al., 2021). Therefore, it is essential to know the abundance, distribution, and ecotoxicological impacts of PPEs in the Bay of Bengal off the coasts of India, Sri Lanka, Myanmar, and Bangladesh to develop efficient strategies for their sustainable management.

The sudden increment of PPE in the marine habitats and biota is not only a major environmental health hazard (Liu et al., 2019; Saliu et al., 2021; Dioses-Salinas et al., 2022; Mohammadi et al., 2022) but also they may act as carriers of hazardous chemicals in various compartments of the environment, affecting living organisms and subsequently food safety (Takada and Karapanagioti, 2019; Sarker et al., 2020; Islam et al., 2022). Studies by Boucher and Friot (2017) and Crawford and Quinn (2016) pointed out that the degradation of PPE into MPs has the potential to act as carriers for hydrophobic organic chemicals (HOCs) (Hartmann et al., 2017), antibiotics (Li et al., 2018), and heavy metals (Godoy et al., 2019; Wang et al., 2019). In this context, the fundamental importance of this study relates to the impacts of PPE on the marine environment and their interaction with other toxic substances (e.g., toxic metals, radionuclides, etc.) to understand the role of PPE and PPE-derived MPs in the environmental compartments and to perform related environmental impact assessments. With more PPEs being used and thrown away because of the COVID-19 pandemic, the problems caused by MP pollution have become a global issue. Since PPE could be a pollutant, it should be taken care of properly to avoid long-term effects that could be harmful (Wang et al., 2020). No attempt has been made yet to characterize PPE and PPE-derived MP's presence and eventual fate along the Bay of Bengal coasts (vital marine ecosystems of India, Sri Lanka, Myanmar, and Bangladesh).

Therefore, the present study is carried out with the following objectives: (i) critically analyze the presence and spatial behaviors of PPEs in the marine environment; (ii) present knowledge on the ecotoxicity impacts of PPEs on ecosystems; and (iii) illustrate the intervention strategies for policy evaluation for management, minimization, identification of research gaps, and future research needs for PPEs. This review is going to answer the following research questions:

- What are the main research gaps in the existing literature?
- What are the ecotoxicity impact, sources, and fate of PPE-derived MPs in BoB countries?
- What are the prospects for future research directions, and what intervention strategy can be implemented?

This research should offer a valuable viewpoint for comprehending the effects and destiny of PPEs in Southeast Asia's Bay of Bengal ecosystems.

2. Materials and methods

The research and publication of this study followed the criteria set by the preferred report items for the systematic reviews and meta-analyses (PRISMA) framework (Moher et al., 2015; Rakib et al., 2022). The PRISMA standards were decidedly followed throughout the review to guarantee thorough and open reporting of the methods and outcomes.

2.1. Search strategy

Observing PRISMA criteria, we conducted a review of aspects relevant to MP PPEs, face masks, and hand gloves in numerous environmental journal articles from diverse publishers, including Nature, Elsevier, Springer, Taylor & Francis, John Wiley & Sons, etc., and database management systems (Scopus, Web of Science, and Google Scholar) from pandemic situation 2019 to 2022, in close agreement with PRISMA guidelines (Moher et al., 2015). Our keyword phrases included "microplastics (MPs)," "COVID-19 19," "Bay of Bengal," "plastic waste," "PPEs," and "face masks." We then searched through the selected papers' references and relevant documentation to explore any additional relevant articles.

2.2. Exclusion and creating criteria

For the present study, a collection of inclusion and exclusion criteria was designed to enable a systematic, comprehensive, and robust analysis. No limitations on time, language, or study were successfully implemented. Studies had to be original and published to satisfy the inclusion criteria. They had to emphasize quantitative and scientific research concerning, among other things, the abundance, footprint of PPEs, distribution, mechanism of impact, and management strategy of MPs. Study that used FTIR (Fourier Transform Infrared Spectroscopy) techniques, visualization techniques, trustworthy datasets, and the included system was mainly, and variations of data in the specific region of the study were specifically considered eligible for inclusion. The study area's current status of MP pollution, its effects on aquatic, terrestrial, and human health, and MP management options in rural and coastal habitats were all to be highlighted in the results' required quantitative and illustrative descriptions. Studies that did not meet the inclusion above requirements, such as non-original research or duplicate work, conference papers, journal pre-proofs, and manuscripts, were, on the other hand, disqualified.

The study also did not include studies that dealt with the Bay of Bengal or PPEs, face masks, or hand gloves unrelated to MP. Fig. 1 shows further information on the selection and retention procedures. A total of 809 research publications underwent screening before being added to our review.

2.2.1. Type of outcome

This study monitors outcomes and circumstances relevant to the footprint of PPEs, the abundance and distribution of MPs, face masks and their effects on aquatic, terrestrial, and human health, and policy proposals to control the high incidence of MPs in the marine environment are all included in this review.

2.2.2. Study selection

A comprehensive and systematic search mechanism was used to pick and choose studies directly relevant to the subject for this review article. To conduct the initial search, relevant keywords were used in well-known databases, including Scopus, Web of Science, and Google Scholar. In addition, because they provide unlimited access to relevant material, the Sci-Lit and Google Scholar databases were also searched. After being exported in CSV format and imported into Mendeley v1.19.8 for duplication removal and manual review, the studies that came up in the search were the results of the search. The papers were then scrutinized for inclusion in the review based on their title, abstract, and complete text in accordance with the review's purpose.

2.2.3. Screening

The research screening criteria were applied to the article titles and abstracts during the initial screening step. An in-depth analysis of the full text was done to resolve any conflicts of interest or ambiguities. We removed preprints from books, preprints from government reports, and preprints from journals to preserve the data's reliability and integrity. Also, this review only considered peer-reviewed journal publications into consideration for inclusion. The selected papers were appropriate for inclusion in this review because they met the strictest standards for scientific research due to the careful methodological approach used.

2.3. Data eligibility

The stages of data eligibility, which include identification, screening, eligibility, and inclusion, are shown in Fig. 1. At first, we identified 809 total outcomes that matched our search parameters. We filtered out 97 duplicate articles and then looked at the titles and abstracts of 712 papers. Of those, 553 papers, including review papers, were disqualified because they failed to adhere to our selection criteria. We looked over 159 full-text papers to ensure that research articles were included. Ultimately, 24 research articles were selected to create our review article.

2.4. Data extraction

A data extraction file was generated to extract the information from the chosen research articles. The sampling strategy, the study's gap, future perspective, limitations, and proposed framework were all extracted, together with information about the first author, country, and the year of publication. The first author independently carried out the initial title and abstract screening, full-text review, and data extraction. Using Mendeley and Microsoft Excel, duplicate papers were found and eliminated during the title and abstract screening process.

3. Results and discussion

3.1. Personal protective equipment derived microplastics pollution trend in the Bay of Bengal

In recent years, more articles have been published on PPE pollution in the Bay of Bengal (Fig. 2A). With ten articles, the year 2021 has the most publications, according to the dataset, and nine publications will follow this in 2022. With only three articles, the quantity of publications in 2020 is relatively low. However, it is essential to note that this dataset only contains articles published through 2023, and it is conceivable that additional research will be conducted and published in the future. Over the past few years, the increase in publications suggests that PPE contamination in the Bay of Bengal is a developing concern among academics and researchers. These studies' findings and recommendations could help develop policies and strategies to mitigate the adverse effects of PPE pollution on the environment and human health.

Researchers from many countries are interested in the problem of PPE pollution in the Bay of Bengal because it is a great threat to the terrestrial and aquatic ecosystems. Bangladesh has the greatest number of publications, with 11 articles among the countries included in the dataset (Fig. 2B). India comes second with eight publications. Sri Lanka and Myanmar have relatively fewer articles published, with two and one,

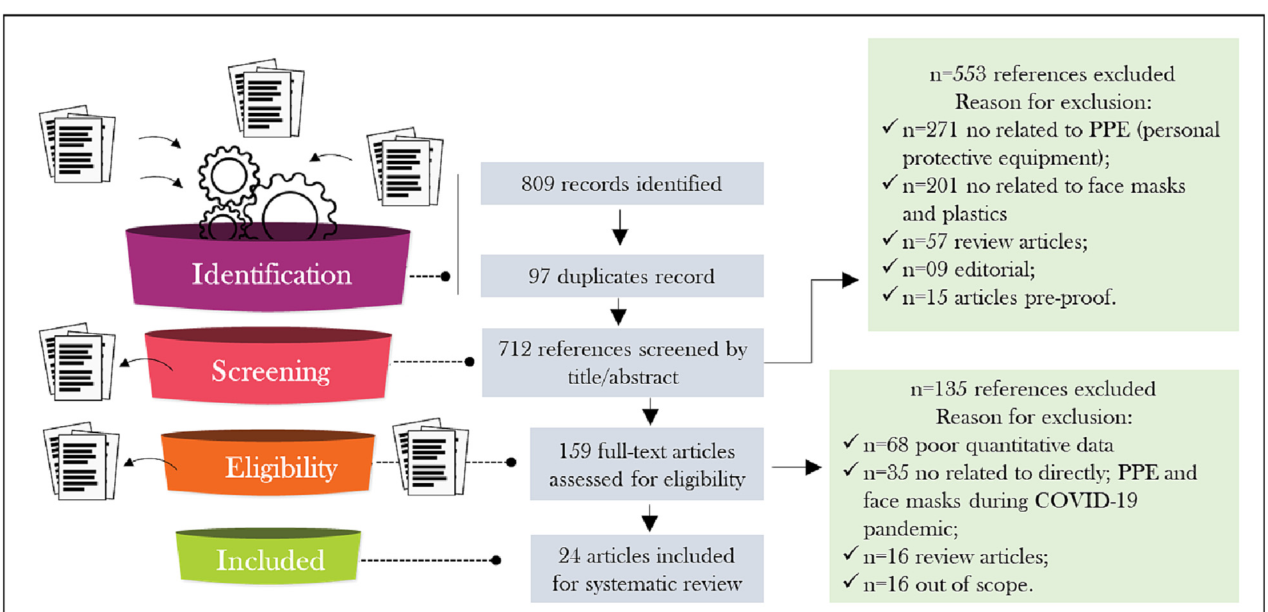

Fig. 1. PRISMA flow diagram for the paper selection process.

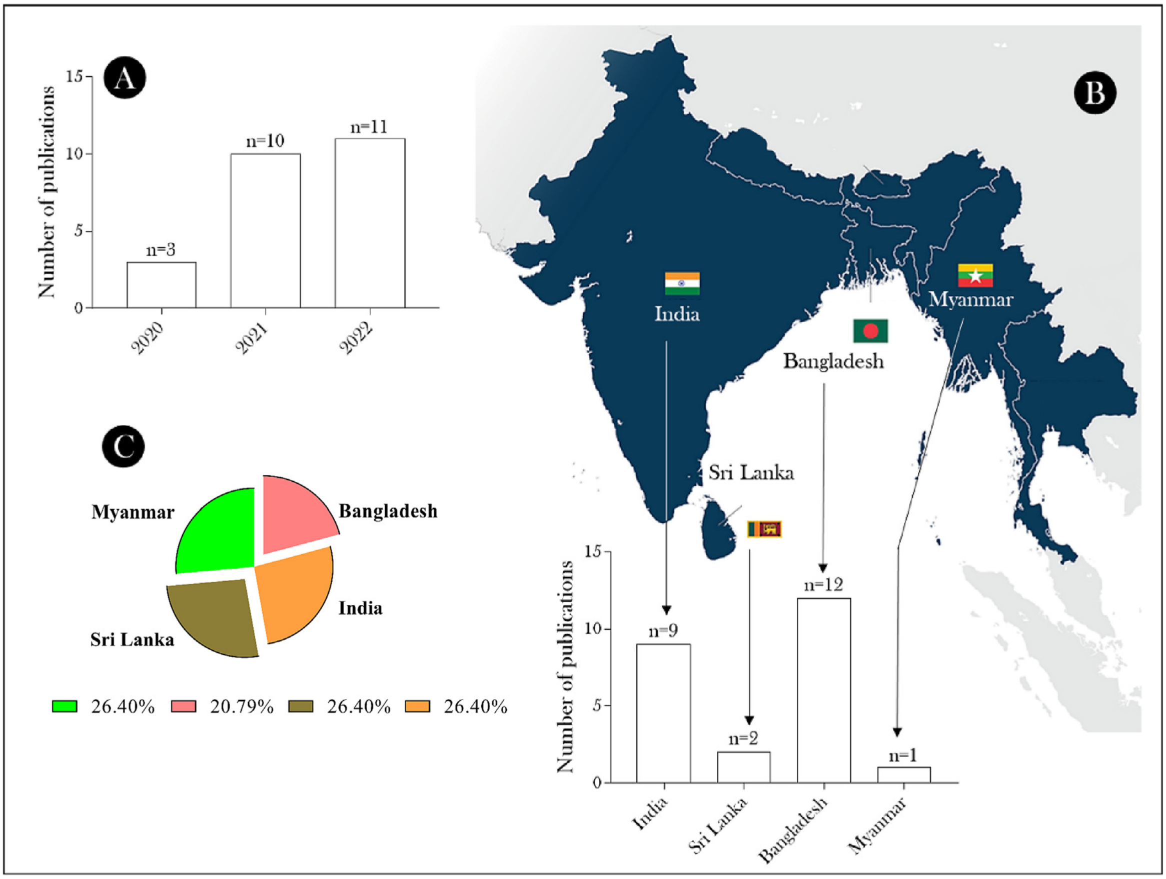

Fig. 2. (A) Year and number of publications in this review, (B) spatial distribution of the number of publication trends in the Bay of Bengal, and (C) face mask acceptance rate.

respectively. This dataset may include only some publications from these countries, and there may be other researchers and organizations in these nations studying PPE pollution in the Bay of Bengal.

Bangladesh and India are doing a good job of dealing with PPE pollution and actively researching ways to reduce its harmful effects on the environment and people's health. This is clear from the large number of publications they have put out. As neighboring countries share the Bay of Bengal, collaborative efforts between these nations may be necessary to combat PPE pollution in the region. Acceptance of face masks has been a significant factor in preventing the spread of COVID-19 and decreasing PPE contamination. Bangladesh has the lowest approval rate for face masks, at 63 %, while India, Sri Lanka, and Myanmar all have acceptance rates above 80 % (Fig. 2C).

The high adoption of face shields in India, Sri Lanka, and Myanmar may have contributed to the lower levels of PPE pollution in these nations compared to Bangladesh. Acceptance of face shields demonstrates individuals' willingness to take precautions and embrace practices that promote public health. Notably, cultural and socioeconomic factors may affect acceptance rates of face masks. Thus, additional research is required to comprehend the reasons for the disparities in face mask acceptance rates between these nations and to develop strategies to promote the adoption of face masks in regions with lower acceptance rates. Overall, the high approval rates of face masks in India, Sri Lanka, and Myanmar could be an encouraging sign for reducing the adverse effects of PPE pollution. Additional efforts could be made to promote face mask acceptance in countries with lower acceptance rates, such as Bangladesh.

Researchers and academics from many fields, such as oceanography, ecology, climate science, and others, are very interested in the area around the Bay of Bengal. We analyzed the number of publications from India, Bangladesh, Sri Lanka, and Myanmar to understand better the Bay of Bengal-related research output (Fig. 2B). In addition, the spatial distribution of publications reveals that most Bay of Bengal-related publications is centered in India and Bangladesh, with fewer originating from Sri Lanka and Myanmar. The concentration of research output in India and Bangladesh may be attributable to their larger populations, economies, and extensive coastlines bordering the Bay of Bengal. Our analysis indicates that the Bay of Bengal region interests researchers and academics, with Bangladesh and India contributing the most to the research output. Nonetheless, there is space for additional research and collaboration in the region, particularly from Sri Lanka and Myanmar.

The outbreak of COVID-19 has led to a surge in demand for personal protective equipment (PPE) and face masks worldwide, including in the Bay of Bengal region (Shammi and Tareq, 2021; Gunasekaran et al., 2022). Proper disposal of these materials is essential for preventing environmental pollution (Gunasekaran et al., 2022) and protecting the marine ecosystem (Bhat et al., 2022). Identifying the sources of PPE and facemask waste in the Bay of Bengal region is crucial to address this issue for proper PPE waste management.

Healthcare facilities, such as hospitals, clinics, and medical laboratories, are the region's primary generators of PPE waste (Sangkham, 2020; Maalouf and Maalouf, 2021; Rajak et al., 2022). The increased use of PPE by healthcare professionals and patients during the pandemic has increased medical waste, including used PPE and face masks. Inadequate waste management practices and infrastructure in some areas of the region permit the unlawful disposal of medical waste, exacerbating the problem (Sangkham, 2020; Manupati et al., 2021).

Another significant source of PPE and facemask waste in the Bay of Bengal is individual consumers (Mayilvaganan, 2020; Abedin et al., 2022a, 2022b; Gunasekaran et al., 2022). As people look to defend themselves and others from COVID-19, they purchase and dispose of vast quantities of PPE and face masks for single use. The improper dispersal of these items, such as dumping them in open areas or waterways, contributes to environmental contamination in the region (Chowdhury et al., 2021; Cudjoe et al., 2022). In addition, the PPE and facemask waste generated by the Bay of Bengal's fishery industry is an essential source of pollution (Abedin et al., 2022a, 2022b). Fishermen, whose livelihoods rely heavily on the ocean, use PPE and face masks while fishing and improperly dispose of them (Bhar et al., 2022).

However, Chand et al. (2021) highlighted the alarming issue of improper disposal of personal protective equipment (PPE), which can lead to severe land, air, and water pollution (Fig. S1). Birds or animals pick up the PPE materials, thus becoming carriers of the virus and spreading it to humans. This phenomenon can also contribute to the transfer of used PPE into water streams and seas, causing a great threat to marine life. Fig. S1 also portrays human negligence in the disposal of used PPE by various entities like medical staff, the general public, business communities, and waste management departments, which results in a polluted environment and significantly hinders health safety. Thus, it exhibits the harsh reality of disposable PPE ending up in our marine ecosystem, thus posing a grave danger to marine life and the overall safety of the water body. Overall, healthcare facilities, individual consumers, and the fishing industry account for most PPE and facemask detritus in the Bay of Bengal region. To reduce the environmental impact of these materials, proper waste management practices, such as using biodegradable PPE and face masks, are essential. In addition, increased public education and awareness campaigns are required to promote responsible waste disposal and sustainable waste management in the Bay of Bengal region.

3.2. Personal protective equipment derived waste abundance and mechanistic insights

The impact of PPE pollution on the marine environment is a growing concern, with the Bay of Bengal being particularly vulnerable due to its high population density and increasing PPE usage. A total of 22 articles were reviewed to gain insight into the abundance, size, and mechanism of PPE pollution in the Bay of Bengal (Table 1).

The articles that were looked at showed that surgical masks, gloves, and face shields were the most common types of PPE in the marine environment (Shammi and Tareq, 2021; Monolina et al., 2022). These items are primarily made of fiber materials, which can take a long time to degrade and pose a significant threat to marine life (Gunasekaran et al., 2022; Mehtab et al., 2022). The size of PPE debris varied from small particles to more oversized items; for instance, Rakib et al. (2021) found the density to be 6.29×10^{-3} PPE m^{-2}, whereas Haque et al. (2021) included 0.89–0.91, 0.93–0.98, and 0.91–0.94(g cm^{-3}) respectively.

Therefore, the study mechanism to extract PPE materials was mainly FTIR spectroscopy and the point count method (Marnn et al., 2021; Kannan et al., 2023). However, there is a need for methodological advancements to improve the efficiency and accuracy of PPE material extraction. Country-specific articles revealed that Bangladesh and India are actively researching PPE pollution, with 11 and 7 publications, respectively (Table 1). However, Myanmar and Sri Lanka require more attention to address this issue and develop strategies to sustain contamination-free environmental conditions. It is also worth noting that investigations have primarily focused on coastal or aquatic environments, with only Bangladesh and India emphasizing the terrestrial connection to marine environments for PPE contamination.

Overall, the reviewed articles highlight the urgent need to address PPE pollution in the Bay of Bengal. To lessen the damage that PPE waste does to marine ecosystems, it is essential to have good waste management practices, develop new ways to get materials out of waste, and do more research. All stakeholders must work together to address this growing environmental threat and ensure a sustainable future for our planet.

3.3. Total waste generation and face mask in the Bay of Bengal

Plastic waste pollution is one of the most significant problems in Bangladesh and is expected to increase significantly over time. The Bay of Bengal is a potential marine source that produces 6 million tons of fish annually, contributing nearly 4 % of the total fish caught globally (Islam, 2019). Approximately 400 million people in this region have fulfilled their demand for animal protein from the Bay of Bengal. However, this possible source has become very polluted in the past few years with plastic. Plastic particles have been found on the seabed, along the shore, and floating in the water column.

Moreover, 2 lakh tons of plastic waste go through the Bay of Bengal from Bangladesh. Before the COVID-19 pandemic, data showed that 87,000 tons of single-use plastics were made yearly, while >1 million tons of plastic waste were produced annually. Of this waste, nearly 73,300 tons went to the Bay of Bengal through several rivers in India. Plastic waste is disposed of randomly in landfills and dustbins (Environment and Social Development Organization-ESDO Global Plastic Treaty). Environment and Social Development Organization-ESDO (n.d.-a, n.d.-b) reported that during the first month of the COVID-19 lockdown, 14,500 tons of plastic waste were produced, and most of this amount was PPE (Environment and Social Development Organization-ESDO, ESDO's Online Press Briefing on COVID-19 Pandemic Outbreak, 14,500 Tons of Hazardous Plastic Waste in a Month). Eriksen et al. (2018) reported that 500–20,000 items/km^2 of MPs were found in the surface water of the Bay of Bengal near Nicobar Island, while the amount exceeded 100,000 items/km^2 in some regions. Ryan et al. (2009) found that 95.5 % of the trash was made of plastic, while 4.5 % was made of wood, paper, tin, and glass. They also found that 4.1 % of the trash comprised user items, 6.3 % of fishing and boating elements, 30.5 % of plastic fragments, and 54.6 % of packaging items (Fig. 3).

Prokić et al. (2019) reported that 700 marine species directly interacted with plastic waste, and the presence of such plastic waste in the stomachs of fish is an alarming problem nowadays (Ory et al., 2018; Strungaru et al., 2019). As a result, the marine environment, including the Bay of Bengal, must have a strict monitoring system to protect the marine ecosystem from the noxious influences of MPs (Savoca et al., 2019). Lebreton et al., 2017 (River Plastic Emissions to the World's Oceans Nature Communications) reported the Ganges River as the second largest plastic disposer that emits massive plastic waste into marine environments. Their study also conducted comparisons of the South Pacific and the Bay of Bengal and found that the samples collected from the Bay of Bengal carried ten times more plastic particles than the South Pacific. These findings of such plastic particles represented the population density in the coastal area of the Bay of Bengal and the massive use of plastic bags. India's National Centre for Coastal Research sampled the surface water of the Bay of Bengal to determine the presence, distribution, types, and sources of MP contamination by collecting samples from 21 sites along 1200 km of the east coast (Sahana., 2022). They reported that the abundance of MPs three kilometers from the coast was lower than 10 km farther into the Bay of Bengal. In a study titled 'From source to sea,' a team consisting of some women scientists and researchers from around the world collected 56,000 plastic samples from the Padma River across the Bay of Bengal, and they reported that 300 different types of plastic waste entered the Bay of Bengal from the Padma River. These plastic wastes contained polythene, cosmetics wrappers, soft drink bottles, and some plastic wastes produced regularly (Tutul, 2023). Prothom Alo, a national newspaper in Bangladesh, reported in 2020 that 92 % of the used masks and gloves were disposed of in a nearby river, from which a large amount of these wastes ended up in the Bay of Bengal. In the same year, the World Wildlife Fund reported in August that every month starting in April, 129 billion marks and 6600 gloves ended up in the Bay of Bengal through the rivers (Islam, 2019). In the previous years, 800 million tons of plastic waste would be disposed of in the rivers that finally ended up in the Bay of Bengal. This pollution caused noxious influences that resulted in 1 million seabirds and 1 million fish deaths annually.

3.4. Ecotoxicity impacts of personal protective equipment derived microplastics and fate during the COVID-19 era on the Bay of Bengal

The rapid rise in plastic waste can potentially suppress waste disposal and recycling systems by overloading the current facilities. Due to the

Table 1
PPE-derived MPs waste, facemask abundance, size, composition, density, and methodology in the Bay of Bengal countries.

Article references	Abundance				Methodology	Country	Environment
	Sample type	Composition	Sample size	Concentrations (mean ± SD)			
Abedin et al. (2022a, 2022b)	Face masks and PPEs	Fiber and microfibers	21 locations	$2.8 \times 10^{-3} \pm 1.7 \times 10^{-3}$ items/m^2	Disposal methods, PPE density, and different waste estimation methods	Bangladesh	Chittagong metropolitan area
Abedin et al. (2022a, 2022b)	PPEs and face masks	LDPE, PP, PU, PC, PS, and PET	30 locations	$1.6 \times 10^{-2} \pm 1.16 \times 10^{-2}$ items/m^2	Different waste estimation methods and PPE density methods	Bangladesh	Rural and urban
Chowdhury et al. (2021)	N95 masks and surgical masks	PP, PS, PC, and PET	46 countries	4.77 ± 1.2 million	Estimating coastal population methods,	Bangladesh	Coastal region
Dehal et al. (2022)	Biomedical waste, plastic waste, and PPE	LDPE, PP, PU, PC, PS, and PET		-	Deep burial methods and waste disposal methods	India	Urban/State
Gunasekaran et al. (2022)	Face masks and gloves	Fiber, HDPE, and PET	Six beaches and counted 496 PPE	1.3×10^{-4} (PPE m^{-2})	Pyrolysis method and PPE density	India	Coastal area
Hantoko et al. (2021)	Face masks, Gloves, and other protective stuff	LDPE (low-density polyethylene), PP, PU, PC, and PS	219 countries	-	Plasma method, disposal method, and waste treatment or final disposal	India	City/State
Hasan et al. (2021)	Face masks	Fiber	30 locations	-	Different waste estimation methods and improper disposal	Bangladesh	Aquatic environments
Haque et al. (2021)	Face masks, hand gloves, and gowns	Face masks, HDPE, PP, PS, PVC, PET	Plastic particles <0.50 mm	0.89–0.91, 0.93–0.98, and 0.91–0.94 g/cm^3	Disposal, dominant methods, and different waste estimation methods	Bangladesh	Coastal area
Haque and Fan (2022)	PPE	PET PP HDPE	193 countries	1.13×10^{-5} PPE/m^2	Scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FT-IR)	Bangladesh	Coastal area
Islam et al. (2020)	Face mask and hand gloves	Fiber	1303 adult residents	-	PPE waste disposal methods	Bangladesh	Online survey on adult residents
Jayasinghe et al. (2021)	Plastic waste, PPE and drinking bottles	PET, PC, Fiber	620 respondents	-	Waste disposal method and different waste estimation methods	Sri Lanka	Online survey
Kannan et al. (2023)	PPE, masks, and gloves	Fiber, LDPE, PP, PU, PC, PS, and PET	Ten sites and 1154 PPE items	4×10^{-3} PPE/m^2	FT-IR, chemical analysis techniques, and PPE density	India	Coastal area and marine beach
Mallick et al. (2021)	Plastic products	Fiber and PET	-	-	Plastic waste footprint (PWF)	India	Coastal area
Marnn et al. (2021)	Mask and waste	Fiber, PET, and PP	50,000 mask items	-	The point count method and population index methods	Myanmar	Bago River and Bago City
Mehtab et al. (2022)	PPE and face mask	Fiber, PET, and PP	-	-	-	Bangladesh	Coastal areas
Monolina et al. (2022)	PPE	PET PP HDPE	432 Participants	-	Population forecasted using the geometric increase method and carbon footprint of PPE	Bangladesh	Dhaka City Corporation (DCC) area
Parveen et al. (2022)	PET		30	-	Spectroscopy	India	Coastal area
Rakib et al. (2021)	Face masks, Bouffant caps, and Gloves	Fiber, fragment, HDPE and PC	13 sites	$3.3 \times 10^{-4} \pm 2.6 \times 10^{-4}$ (Cox's Bazar beach)	PPE density methods, Shapiro-Wilk normality test, and Kruskal-Walli's test	Bangladesh	Coastal area
Rakib et al. (2022)	Microplastics (MPs)	PET, PS, and PE	30 locations	22.29–59.5 items kg^{-1}	FT-IR and ATR (attenuated total reflection	Bangladesh	Karnaphuli River Estuary
Ray et al. (2022)	Face masks, PPE,	PBT and PET	-	-	SEM, FTIR, and chromatographic methods	India	Coastal area
Shammi and Tareq (2021)	Gloves, medical masks, goggles, or face shields	Fiber	-	-	Disposal methods	Bangladesh	Urban area
Shukla et al. (2022)	Face masks and PPE	Fiber, PET, and PP	36 countries	-	Annual mask usage (AMU) estimation and estimated weight of masks	India	Rural and urban areas
Siwal et al. (2021)	PPE, face mask and gloves	Fiber, PET, and PP	11 coasts and 138 PPE items	0–7.44×10^{-4} PPE/m^{-2}	Amino lysis, hydrolysis, and pyrolysis	India	Coastal area

Note: "-" putted on several fields without information.

COVID-19 pandemic, hazardous PPE waste is deposited in landfills without prior treatment or effective management, resulting in environmental pollution. The production of disposable PPE emits greenhouse gasses that can react with municipal waste to produce MPs, which are deposited in the living environment, and contribute to environmental pollution (Shruti et al., 2020). Illegal dumping sites located primarily on tourist or recreational beaches are the primary source of PPE pollution, with face masks accounting for most items (97.9 %) and a mean PPE density of 6.29×10^{-3} PPE/m^2 across various sites (Rakib et al., 2021). Consequently, the mismanagement of plastic waste (MMPW) may result in its release into various environmental components such as streets, rivers, soils, marine coastlines, and oceans. This could lead to a swelling of MPs in the environment (Akarsu et al., 2021; Okuku et al., 2021; Rakib et al., 2021). In addition to creating significant environmental issues (Hiemstra et al., 2021), PPE could generate secondary MMPs and NPs that may pose a more substantial threat if they fracture into smaller fragments (Fadare and Okoffo, 2020; Ma et al., 2021). PPE and container boxes are composed predominantly of plastic polymers like polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), or polyester (Du et al., 2020; Fadare and Okoffo, 2020; Liu et al., 2021; Ma et al., 2021) gradually decompose in the environment through weathering, photolysis, microbial degradation, erosion, or mechanical water forces to generate MPs and NPs (Aragaw, 2020; Parashar and Hait, 2021). MPs and NPs exist in water and air and infiltrate land ecosystems and food chains (Chen et al., 2020a, 2020b; Kwak and An, 2021), potentially leading to toxic accumulation in humans due to increasing plastic waste from household and industrial sources,

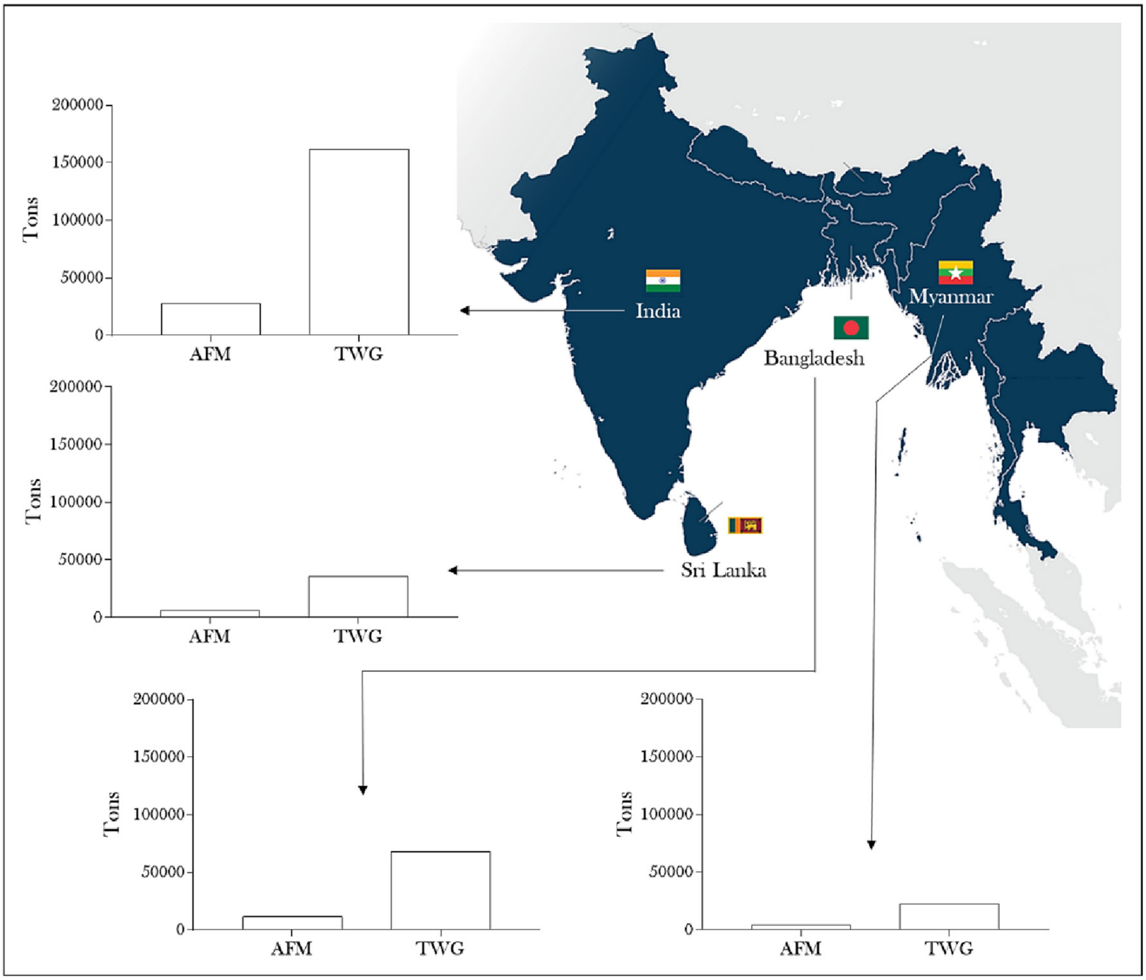

Fig. 3. Total waste generation (TWG) and annual face mask (AFM) (tons) by Bay of Bengal countries.

exacerbated by the pandemic. MPs and NPs in the soil can affect the ecosystem of plants and soil microorganisms and can be moved through the food web while consumed by farm animals. Likewise, in marine environments, fish can ingest MPs and NPs, which humans can eventually consume through contaminated plant and meat consumption (Fig. S2). Researchers investigated the plastic waste deposition in the Ganges River. Their results revealed that 3 billion pounds of plastic waste were deposited in the Ganges and ended up in the Bay of Bengal. As a result, 655 million people living near this region are being negatively influenced (Nishat, 2021). Plastic wastes have several offensive effects on the Bay of Bengal ecosystem, which includes different marine inhabitants, organisms, economies, and human health (Hinojosa and Thiel, 2009). For instance, MPs, like jellyfish, can cause turtle mortality while mistakenly eating single-use polythene (SUPs) bags. Table 2 presents the ecotoxicity impacts of PPE wastes associated with MPs during the COVID-19 era in Bay of Bengal countries.

3.4.1. Impacts of personal protective equipment on marine ecosystems

The practice of PPE amid the COVID-19 pandemic has the potential to save lives. Still, the inappropriate disposal and mismanagement of plastic rubbish generated by various sources can impede waste management systems. These PPEs have emerged as a significant cause of plastic pollution in marine environments, which may cause excessive environmental pollution on both land and aquatic ecosystems. As an outcome of the COVID-19 pandemic, PPE has become a newly emerging contaminant that pollutes the marine environment, as evidenced by various studies that have found different types of PPE on coastlines (De-la-Torre and Aragaw, 2021; Okuku et al., 2021), beaches, and underwater locations in remote and uninhabited islands (Oceans Asia, 2020), causing harm to the ocean ("How to face masks, gloves, and other coronavirus waste is polluting our ocean," 2020). The result of PPE in oceanic conditions is determined by the different characteristics of the plastic materials it is composed of, such as highly-densified polymers like polyvinyl alcohol (PAV), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) that sink on the ocean floor. In contrast, low-density polymers like polystyrene (FACE MASKS) and polypropylene (PP) may waft in marine water for extended periods of years (De-la-Torre and Aragaw, 2021). Sun UV radiation and breaking waves have the potential to fragment COVID-19 PPE into numerous microplastic particles, resulting in widespread and nearly everlasting contamination of the marine environment (Fig. 4).

Recent research has indicated that the number of MPs in the ocean is significantly higher than previously thought, with over 125 trillion microplastic particles present, and researchers have now estimated that the ocean floor holds a minimum of 14 million tons of MPs (Barrett et al., 2020; Brandon et al., 2020; Lindeque et al., 2020). The pollution of ocean floors with microplastics from PPE deserves significant attention because the vast majority of PPE, including face masks, gloves, and safety goggles, will sink into the sea floor. Only 1 % of plastic will remain on the sea surface. MP accumulation is also found in freshwater systems, similar to that observed in oceans. The excessive use of PPE for protection during the COVID-19 pandemic results in plastic and MP pollution in freshwater systems. From March to April 2020, the researchers witnessed an unusual amount of PPE, such as medical masks, gloves, and PPE kits, which comprised 16.67 % of the debris collected from Jakarta Bay.

Research conducted in Kenya revealed that the waste produced during the COVID-19 pandemic accounted for approximately 17 % of the total waste observed along coastlines. Notably, the bulk of this waste consisted

Table 2
Ecotoxicity impacts of PPE wastes associated MPs during the COVID-19 era in Bay of Bengal coasts.

References	Pollutant type	Country	Impacts of PPE, face masks, and other microplastics during the COVID-19 era			
			Aquatic	Terrestrial	Atmosphere	Health impact
Abedin et al. (2022a, 2022b)	PPEs and face mask	Chittagong, Bangladesh	The chemical compositions of PPEs react with the sediments and water, producing hazardous gasses and components in the aquatic ecosystem, polluting the water body and sediment.	Decreased soil fertility, landfill pollution	PPEs may react with air particles, become a source of hazardous exposure, and release greenhouse gasses into the environment.	Infection, impacts blood, bodily fluids, organs, and tissues.
Abedin et al. (2022a, 2022b)	PPE and face mask	Bangladesh	Impact on ecosystems and organisms.	Decreased soil fertility	Solar UV oxidation, low rate of biodegradation	Oxidative stress
Chowdhury et al. (2021)	Face masks		Coastal population and face mask acceptance rates are responsible for higher plastic debris that enters the oceans	Countries with a higher coastal population and higher mismanaged waste percentages produced a higher amount of mismanaged plastic waste	-	-
Dehal et al. (2022)	Biomedical waste and plastic waste	India	Risk on aquatic animals	Land pollution	Air pollution	Secondary impacts on health and the environment
Gunasekaran et al. (2022)	PPEs	India	The marine ecosystem undergoes degradation processes, including temperature fluctuations, ultraviolet radiation, physical abrasion, chemical oxidation, increased humidity, and biodegradation. Juvenile turtles are among the most threatened by plastic entanglement. An ecological risk to the marine environment	This richness of biodiversity, like mangrove forests, could be threatened by pollution from PPE.	PPE can absorb and concentrate contaminants from the surrounding environment, posing risks of contaminant transfer to animals through different trophic levels	Nasal cavity
Haque and Fan (2022)	PPE	Bangladesh	Plastic waste poses a significant threat to the terrestrial and marine environment due to its non-biodegradable nature.	Plastic waste moves to the oceans in the form of macro-plastic (>200 mm), microplastic (1 μm–5 mm), and nano plastic (<1 μm) particles, which produce severe toxic effects on both terrestrial and marine animals.	Greenhouse gas emission	Affect public health through further infection and (micro and nano) plastic pollution
Haque and Fan (2022)	PPEs		Wastewater discharges	Imposes detrimental effects on organisms and the environment. Significant threats to ecological integrity and environmental sustainability.	-	The global online food delivery service market increased, demonstrating different toxic levels to organisms at various food chain hierarchies and accumulating in the biological tissues through biomagnification.
Hasan et al. (2021)	Face mask	Bangladesh	Changing in Microbiome, water quality deterioration, micro gel formation, and ecosystem alteration	Reproduction hamper, structural damages, and growth inhibition	Oxidative stress	Cancer, neurotoxicity, immuno-suppression, physiological burdens, and hormonal disruption
Jayasinghe et al. (2021)	Plastic waste	Sri Lanka	-	-	-	Human health impacts
Kannan et al. (2023)	PPE, masks, and gloves	India	Pathogen and chemical contamination	Ecotoxicological problems	Non-native species	Health impact
Mallick et al. (2021)	Plastic products	India	Plastic additives release contaminated chemical matter into ambient soil that percolates into the groundwater and negatively impacts the aquatic environment (rivers, lakes, oceans) with terrestrial ecosystems	-	-	Infectious to diseases and resulted in health risks and pollution
Marnn et al. (2021)	Waste masks	Myanmar	Death of aquatic animals, threatening wildlife animals, aquatic animals.	Loss of ecosystem	Air pollution	-
Mehtab et al. (2022)	PPE	Bangladesh	-	-	-	Endangering the health and safety of waste collectors, waste collectors' occupational health and safety concerns are completely ignored
Monolina et al. (2022)	PPEs	Dhaka, Bangladesh	-	Restrictions on urban transportation and industrial	The lockdown and shutdowns inevitably	It does not provide any insight into the

(continued on next page)

Table 2 (*continued*)

References	Pollutant type	Country	Impacts of PPE, face masks, and other microplastics during the COVID-19 era			
			Aquatic	Terrestrial	Atmosphere	Health impact
				activities during the lockdown have cut down energy consumption	have had some direct impacts on cleaner air	environmental impacts of the healthcare and medical wastes of the pandemic.
Rakib et al. (2021)	PPEs	Cox's Bazar, Bangladesh	Fishing activity contributed to PPE pollution at a lower level and illegal dumping	Decreased land-based activity	Waste burning lack of environmental awareness	Change humans in natural habitats
Rakib et al. (2022)	PPEs	Cox's Bazar, Bangladesh	Marine litter is threatening urban drainage and natural lake, respectively, consisting of polypropylene (PP) and high-density polyethylene (HDPE)	Massive production, use, and incorrect disposal, mismanagement have turned plastics into one of the most challenging environmental issues. The ongoing COVID-19 pandemic exacerbated plastic pollution due to the increase in demand for plastic-based PPE and constraints to efficient waste management	Plastic pollution in the environment.	-
Ray et al. (2022)	Face masks and PPE		Particulate plastic contamination of seawater is increasing. Marine crustaceans, and even in the stomachs of fish.	Panic buying results in the overuse of single-use plastic bags and food packaging. Environmental exposure to MPs can cause a variety of problems	Harm aquatic organisms and increasing NaCl concentration	Chemical effects on the health of living organisms
Siwal et al. (2021)	PPEs		Ecological asymmetry	-	Potentially raising the risk of infection, high processing heat, and nonwoven fibers have a below-melting point	Breathe problems

Note: "-" putted on several fields without information.

of items that had been discarded due to their association with COVID-19 (Okuku et al., 2021). Until August 2021, the extent of plastic waste related to the pandemic generated globally by 193 countries was estimated to be 8.4 ± 1.4 million tons (Peng et al., 2021). Because of the mismanagement of PPE litter, research on the Agadir coastline in Morocco revealed a PPE density of 1.13×10^{-5} PPE m^{-2} (Haddad et al., 2021). During the COVID-19 pandemic, a biomonitoring study in Songkhla Lake, Thailand, revealed the existence of MPs, specifically PE and polyester fibers, in the stomachs of commonly consumed marine species (catfish, spear shrimp, and yellow shrimp), with a total of approximately 170 MP pieces found in the guts of the 47 tested creatures (Pradit et al., 2021). In marine ecosystems, the potential impact of PPE may result in various adverse outcomes, including the creation of MPs, the unintentional conveyance of likely nuisance species, and the ensnarement or consumption by extensive organisms (Rakib et al., 2021).

According to a study by Haque and Fan (2022), the chronic toxicity of MPs released from surgical masks, mainly consisting of particles smaller than 10 m, affects the marine copepod (*Tigriopus japonicas*), which is a crucial component linking primary producers to higher marine consuming organisms as copepods are the primary food source for these organisms and an essential part of the food chain (Sun et al., 2021). The findings revealed that copepods consumed the MPs, leading to a notable decrease in their reproduction ability. As a result, there would be a depletion in the food reserves for the copepods' higher consumers, which could ultimately lead to

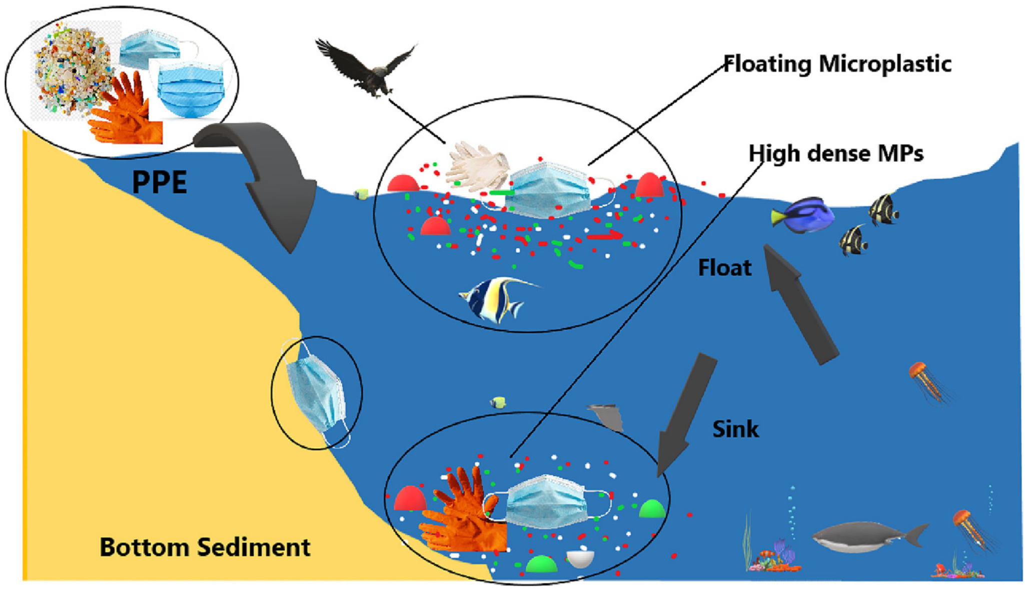

Fig. 4. Schematic representation of the potential fate of PPE in the marine ecosystem on the Bay of Bengal coasts.

disequilibrium in the aquatic ecosystem. The fluorescence imaging technique confirmed the presence of ingested MPs and their distribution within the guts and bodies of organisms. This research illustrated that MPs could accumulate within these organisms by utilizing copepods as a model. It was established that they could aggregate in higher marine organisms with processes such as bioaccumulation and biomagnification.

3.4.2. Impacts of personal protective equipment on terrestrial ecosystems

During the COVID-19 pandemic, the increased production and use of PPEs have caused a large amount of plastic waste to build up on land, polluting the environment and worsening it. During the COVID-19 pandemic, plastic wastes were thrown away incorrectly, leading to many MPs and nano plastics (NPs) entering the terrestrial environment (Fig. 5). When MPs are released into the environment, they may pose a health risk to living things. MPs can absorb chemical pollutants like hydrophobic organic chemicals (HOCs) (Hartmann et al., 2017), antibiotics (Li et al., 2018), and heavy metals (Oz et al., 2019), which can then be transported through the terrestrial environment. This can hurt agricultural production. Investigation shows the harmful effects of discarded face mask filters (MB fillers) on soil invertebrates, which can hinder reproduction, growth, and spermatogenesis, negatively impacting the soil ecosystem (Kwak and An, 2021). The accumulation of MPs resulting from the degradation of PPE plastics in anaerobic environments can diminish soil fertility and hinder the growth of plants and other species because it secretes toxic chemicals (Shruti et al., 2020). Microbial activities in open dump areas can accelerate the transformation of PPEs into MPs faster than in soil.

3.4.3. Impacts of personal protective equipment on human health

When MPs enter a person's body, they can cause oxidative stress, increasing the risk of mortality and hurting growth and reproductive organs. Most slum inhabitants utilize water from lakes, rivers, estuaries, and ponds containing more PPE waste. Due to the entrapment of water in waste plastic items, MPs generate a conducive breeding environment for mosquitoes and many waterborne infectious diseases, resulting in an increased incidence of illnesses like dengue among individuals in recent times.

Evidence has verified that patients' airborne viruses or respiratory droplets can accumulate on PPEs and stay active for over three days (Liu et al., 2020; Ryan et al., 2020a, 2020b; Van Doremalen et al., 2020). For the first time, after analyzing 47 human tissue samples comprising lungs, blood, breast milk, livers, spleens, and kidneys in 2018, researchers were able to identify the existence of MPs in human organs, followed by the subsequent detection of MPs in the human colon and placenta (Eco Watch, 2020; Ibrahim et al., 2021; Ragusa et al., 2021). Researchers recently discovered that the composition of MPs found in adult and infant stool samples showed little difference. However, infants displayed microplastic levels up to 20 times higher than adults, suggesting the spread of these particles to

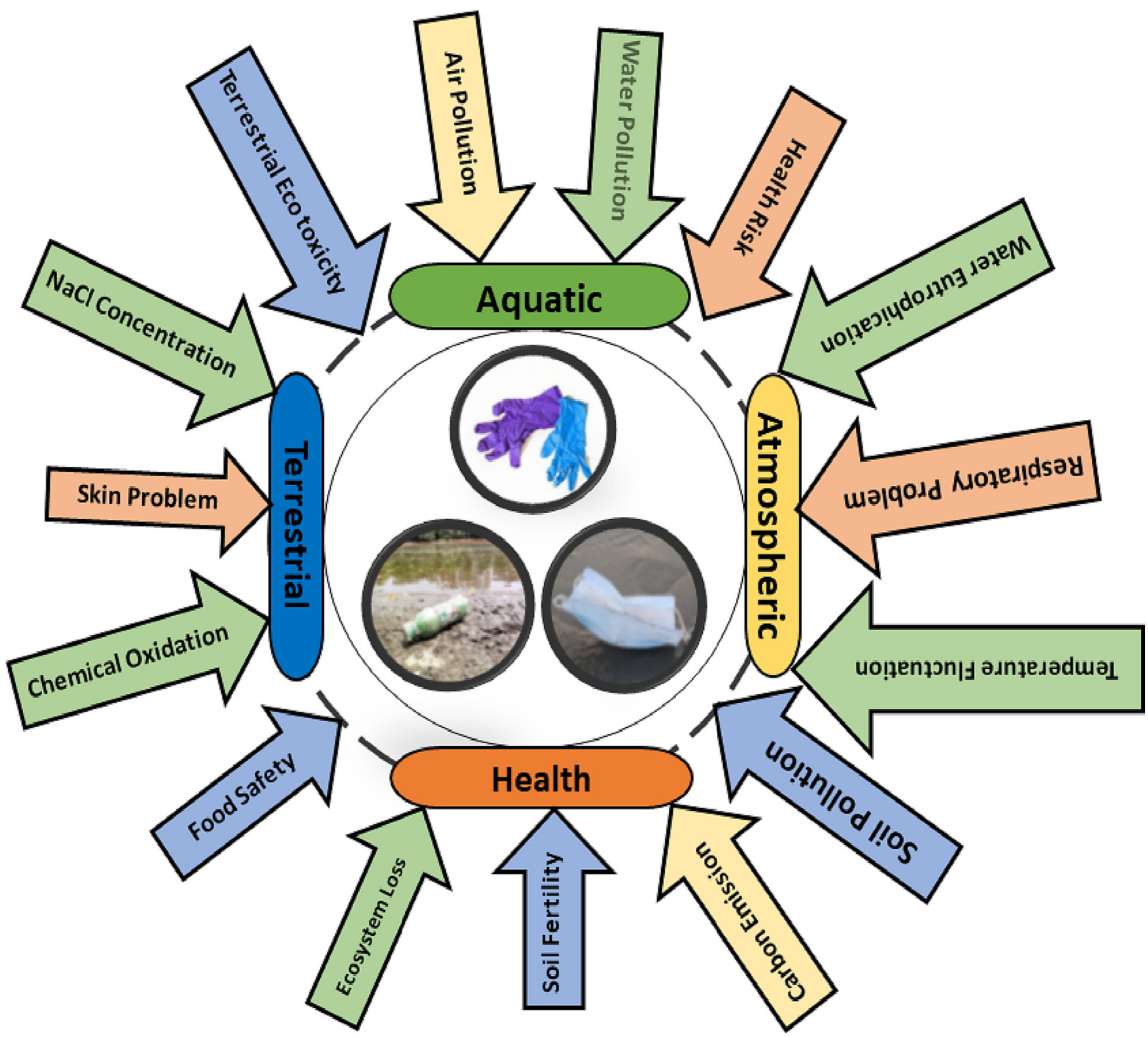

Fig. 5. Ecotoxicity impacts of PPEs face mask pollution on aquatic, terrestrial, human health, and atmospheric environment.

infants (Zhang et al., 2021). Consuming MPs may interact with the gut flora, altering the intestinal milieu and perhaps damaging the intestinal barrier through oxidative stress and inflammation. (Huang et al., 2021). Thus, PPE wastes can potentially increase the danger of MPs to the human body by serving as an origin of MPs in the environment (Fig. 5).

Infectious microplastic waste contains disease-causing pathogens like viruses, fungi, bacteria, and parasites that threaten vulnerable hosts, Smaller PPE debris (5 mm) is ubiquitous. It can be found in the atmosphere, water, ground, animals, packaged food, and mineral water. An emerging class of air pollutants is the potential effects of MPs on human respiratory health (Hossain et al., 2019; Cowger et al., 2020). MPs can adversely affect bodily fluids, organs, tissues, and henceforth and researchers have noted that lung MPs can cause respiratory system inflammation and cytotoxic consequences (Dris et al., 2016; Prata et al., 2019). Airborne MPs, posing a risk of inhalation exposure, are widely dispersed in the atmosphere, and PPE wastes are becoming an increasingly recognized source of airborne MPs (Chen et al., 2021). The lung toxicity of airborne MPs is increasingly uncovered in vivo and in vitro studies, indicating that they can induce oxidative stress, inflammation, and epithelial barrier destruction (Di Dong et al., 2020; Lim et al., 2021; S. Yang et al., 2021), potentially leading to respiratory and cardiovascular diseases and even cancers (Prata, 2018). Wearing PPE can defend individuals from infectious viruses, including the COVID-19 virus; however, individuals who use lesser-quality face masks or reuse disinfected masks may face a greater risk of breathing MPs generated from the masks (Li et al., 2021; Ma et al., 2021). Even though these face masks can be recognized as having organophosphate ester, safety calculations may not consider the potential interaction between organophosphate ester and MPs. Studies have shown that people inhale 26–130 MPs daily; thus, choosing the appropriate mask is crucial in preventing microplastic inhalation during the COVID-19 pandemic. The generation of infectious waste and PPEs due to COVID-19 has become a global concern for the well-being of humans and the environment. The mismanagement of PPE waste could exacerbate coronavirus transmission, so it is crucial to manage and dispose of such waste properly.

3.4.4. Impacts of personal protective equipment on animals

Animal sightings during the COVID-19 lockdown increased due to reduced human activity, but improper disposal of PPE is worsening plastic pollution and posing risks to animals through entrapment, ingestion, and entanglement. Researchers often report that creatures can become trapped in plastic garbage, such as hermit crabs in plastic containers (Lavers et al., 2020). A fish in the Netherlands was the first victim of COVID-19 waste after becoming trapped in a latex glove (Hiemstra et al., 2021). PPE items used during COVID-19, like PPE kits, face masks, and gloves, discarded randomly in the outside environment, may cause an increase in the frequency of such entrapments in the future.

After discovering that sea turtles are attracted to the scent of marine plastics and subsequently ingest them, causing plastic accumulation in their stomachs, a semblance has been drawn between this behavior and the possibility of other marine animals mistaking COVID-19 PPE for food; tragically, this concern has been confirmed with the first recorded case of a penguin's death resulting from the ingestion of COVID-19 protective equipment that resembles and smells like prey to marine life (Gallo Neto et al., 2021; Rosane, 2020). Aragaw et al. (2022) gathered photographic proof of the various PPE-biota interactions, such as the absorption of face masks or gloves and entrapment and entanglement. Similarly, Mghili et al. (2022) observed a seabird picking up a face mask, posing a significant entanglement risk. A face mask has also been discovered in the stoma of a deceased Magellanic penguin (*Spheniscus magellanicus*), and its cause of death has been determined (Gallo Neto et al., 2021). Given their apparent threat to aquatic biota, investigating how PPEs affect the most vulnerable species is essential. The act of long-tailed macaques chewing on PPEs and pet animals such as cows, dogs, horses, etc., consuming COVID-19 litter is a cause for concern that animals feeding in landfills may consume food contaminated with discarded PPE waste, resulting in both immediate and long-term negative consequences (Seif et al., 2018). The absorption of PPE waste by animals can harm their health, including changes in blood chemistry parameters and leading to a decline in biodiversity (Lavers et al., 2019). MPs, found in various aquatic and terrestrial organisms worldwide, modify the bacteria in the gut, lessen mucus production, and cause gut dysbiosis through interaction with microbes (Wang et al., 2021), and can accumulate in organisms through their food source, leading to transfer to higher consumers and ultimately threatening human health.

PPE pollution may cause entanglement and subsequent sudden death by suffocation, but not all exchange with PPE litter has adverse outcomes. PPE deteriorates animals, impairs their ability to move around and feed, and causes wounding, infections, and severe infections that have long-lasting damage. Various wildlife species, such as American robins, swans, mallards, gulls, bats, hedgehogs, pufferfishes, shore crabs, and octopuses, are at risk of entanglement in COVID-19 PPE, and in addition to this, it has been observed that plastic is being more commonly used to construct nests; furthermore, the latest findings reveal that common coots and sparrows are now also using COVID-19 PPE as nesting materials (Jagiello et al., 2019; Hiemstra et al., 2021). The integration of plastics into nests can alter the drainage and thermal characteristics, heighten the chances of penetration or entrapment, and thus possibly negatively impact the wildlife's nutritional needs and reproductive achievements.

MPs can cause physiological hazards and sublethal effects by distributing to other organs besides the gastrointestinal tract (S. Xu et al., 2020; Z. Xu et al., 2020), as demonstrated by the presence of MPs in 67 % of sharks sampled, which suggests that they may also be present in other organs and tissues across various species (Parton et al., 2020). The hepatopancreas of crabs and the organs of scallops, including kidneys, gills, and muscles, accumulate MPs (Wang et al., 2021), and MPs can injure animals at the tissue and cellular levels. Exposure to MPs from COVID-19 PPEs can impede growth and reproduction in young animals and reduce intracellular esterase activity and spermatogenesis in earthworms (Kwak and An, 2021). COVID-19 protective equipment indicates a potential danger to animals through entrapment, entanglement, and ingestion. In contrast, MPs associated with this equipment may amass in animal organisms and result in harmful impacts throughout the ecosystem via the food chain. Further studies must focus on reducing ecotoxicological effects.

3.4.5. Impacts of personal protective equipment on the atmospheric environment

The COVID-19 pandemic lockdown positively affected greenhouse gas emissions and air quality. Still, the production and disposal of plastic-based protective equipment, which emits over 850 million metric tons of greenhouse gases annually, presents a hidden crisis that could exacerbate climate change. Plastics' cumulative greenhouse gas emissions will surpass 56 billion tons in 2050, constituting 10–13 % of the remaining carbon budget, hindering the possibility of limiting global temperature increment to under 1.5 °C (Abedin et al., 2022a). The production and utilization of plastic-based PPE involve the expulsion and transportation of fossil fuels; additionally, the management and disposal of PPE waste result in the release of GHG at every stage of the life cycle (COVID-19: Creating another problem? Sustainable solution for PPE disposal through the life cycle analysis (LCA) approach (Rodríguez et al., 2021) The usage of disposable masks, with a greenhouse gas footprint of 0.05 kg CO_2 eq/single-use (excluding transportation), could potentially worsen climate change by ten times higher compared to reusable masks, with greenhouse gas footprints of 0.059 kg CO_2 eq/single-use (including transportation) and 0.036 kg CO_2 eq/usage (including washing) (Klemeš et al., 2020a, 2020b; Patrício Silva et al., 2021). Several countries have evaluated the environmental influence of PPE throughout the pandemic, verifying that it has generated substantial greenhouse gas emissions. Additionally, disposing of PPE waste through landfill and incineration can release toxic substances like dioxins and furans, contributing to air pollution (Mejjad et al., 2021; Patrício Silva et al., 2021; Rizan et al., 2021; Vanapalli et al., 2021).

A study on air sample monitoring performed in a hospital complex in Sao Paulo, Brazil, discovered the presence of MPs in the form of airborne particles varying from zero to 0.9 units/m^3, along with fibers ranging from 9 to 24 units/m^3. These MPs in the air possess the possibility of being carriers for the virus, such as SARS-CoV-2 aerosols, which can ease the virus's entry into the human body (Amato-Lourenço et al., 2022). Therefore, it is crucial to analyze the fate of MPs discharged from plastic waste related to the pandemic, not just in terrestrial or oceanic environments but also in the atmosphere. Various MPs, such as polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride (Enyoh et al., 2019) that constitute PPE spread worldwide via air and aggregate in the air, ocean, and land (Peeken et al., 2018; G. Chen et al., 2020; Y. Chen et al., 2020); but the ocean does not serve as the ultimate sink for these particles as they can return to humans through the sea breeze (Allen et al., 2020). Researchers suggest that the annual release of 136,000 tons of MPs into the atmosphere from the sea is expanded by additional sources such as wastewater sludge, compost spreading, surface sediment of soil, and ash from solid waste incinerators, emphasizing the vital role of the atmosphere in the PPE-linked microplastic cycle and its active involvement in the process of MPs infiltrating various environments (Sridharan et al., 2021; S. Yang et al., 2021; Z. Yang et al., 2021). In addition, to acting as repositories for harmful chemicals, MPs may be vectors for transporting bacteria and viruses in aquatic and soil environments (Fig. 5). Experts suggest that contaminated surfaces of airborne MPs might be a possible transmission route for COVID-19, particularly those released from improper disposal of PPE, underscoring the harmful effects of PPE-associated MPs on human health (Liu and Schauer, 2020). The significant increase in energy consumption, environmental footprint, and air pollution is a direct result of the large production and use of PPE, and the atmosphere's involvement in the microplastic cycle contributes to the deterioration of air quality, climate influence, and absorption of harmful chemicals from plastic and microplastic waste.

3.5. Proposed intervention strategies for implication

Reduce, Reuse, Recycle, Redesign, and Restructure -5R is a suitable and effective mitigation measure that can be taken to reduce PPE pollution (Mazahir and Al Qamari, n.d.). Proper PPE waste management was necessary during the COVID-19 outbreak, as PPE use and production sharply increased during this pandemic (Abedin et al., 2022a, 2022b). Pandemic waste will harm the future environment and human health (Dehal et al., 2022). To handle microplastic pollution from PPE, integrated and comprehensive approaches are useful that prioritize the reduction of pollution (Ray et al., 2022). During the COVID-19 pandemic, hazardous PPE wastes are deposited in landfills without being adequately managed or pre-treated (Abedin et al., 2022a, 2022b). After the pandemic, world leaders must take several steps to address the plastic crisis (Vaughan, 2020). Microplastic pollution from PPE needs to be reduced substantially to keep aquatic and terrestrial environments safe. An integrated and well-developed management strategy is a must to handle the associated pollution from PPE. An integrated management strategy has been shown in Fig. 6 that comprises all necessary and impactful stages together. This proposed strategy consists of monitoring, policy, and legislation associated with the aquatic, tourism, and urban environments. Monitoring includes PPE identification and face masks. Skilled personnel conducting aerial surveys in aquatic, terrestrial, and atmospheric environments must ensure monitoring systems. Plastic material recovery facilities adjacent to an aquatic harbor are also necessary.

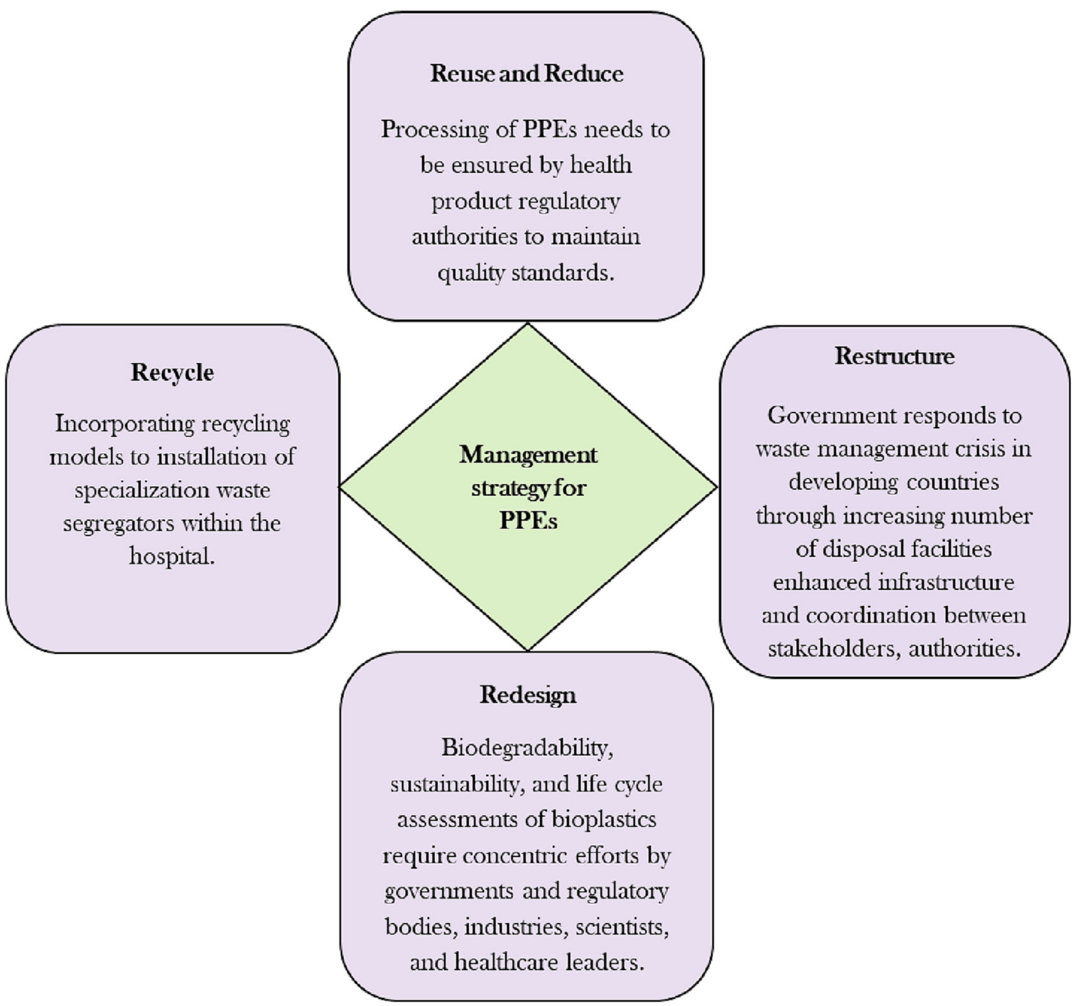

Fig. 6. 5R strategy for managing PPEs intervention.

Regarding PPE pollution, reuse, reducing, recycling, redesigning, and restructuring can be effective methods. Policy and legislation are key elements of the PPE management strategy. A few existing policies, such as the solid waste management rule 2016 and the plastic waste management rule 2016, the national 3R strategy for waste management (2010), the city corporation act 2009, and so on, focus on plastic pollution control (Fig. 7). To reduce microplastic pollution from PPE during the pandemic period, digital technologies must be utilized to monitor and demonstrate plastic leakages in a targeted ecosystem. Artificial intelligence (AI) can be used to handle PPEs, medical waste, and trash more efficiently. Sustainable design and quality materials are necessary to build a safe model and plan for PPE waste reduction. Tourist sites are characterized by high usage of plastic (hand gloves, face masks). Implementing a plastic recycling unit near tourist attractions can be helpful. Public–private collaboration and sustainable city planning regarding pollutant management are ways of managing PPE-associated pollution. The use of green and eco-friendly waste disposal systems is also a concern.

3.6. Future challenges for personal protective equipment derived waste management

Researchers and scientists have been paying much attention to plastic waste pollution in Bangladesh over the past few years. However, the available scientific research regarding plastic pollution, its impacts, and mitigation approaches is very limited. Hossain et al. (2021) said there would be only 18 peer-reviewed journal papers about plastic waste until 2020, and only three papers would be about MPs. The main reason may be a lack of lab facilities, money, and knowledge, an imbalance in funding, locational barriers, etc. Even today, the behavior of nanoplastics in this region is unknown due to a lack of research laboratories and funding opportunities. To minimize the substantial threat of plastic wastes such as PPEs to the environment, repurposing, recycling, and reusing approaches must be well-developed for brief periods of waste management. Incineration is the most common method for plastic waste management due to its simplicity and effectiveness. However, this approach is limited by its negative impact on the environment as it causes massive emissions of greenhouse gases and particles (Parashar and Hait, 2021). As a widely employed approach, the application of incineration is much more challenging as it causes great harm to human and animal health and causes serious diseases that can have further consequences, including the death of humans and animals (Table 3). Therefore, researchers and scientists should conduct further research to enhance the effectiveness of the incineration process by improving its capacity, maximizing its purification ability, and minimizing toxic environmental pollutants. Decontamination of PPFs can be a possible way to assist with proper plastic waste management. Removing MPs from PPEs is also challenging, requiring further sorption and separation advancements. Novel materials like nanosheets, membranes, nanotubes, and other chemical elements must be developed to get high accuracy for sorption, filtration, and removing MPs from waste plastics (Rakib et al., 2021). However, these advancements mainly focus on wastewater treatment and treating water for consumption. Researchers should carefully focus on territorial plastic waste management systems, and due to a lack of awareness, the plastic waste management system becomes more challenging. The disposed face musk and other PPE components get mixed with soil, and when humans and animals get touched with these, they become contaminated with the adverse effects of different viruses that come from PPEs. Therefore, volunteers who would raise awareness among people should be employed by hanging posters and banners, collecting PPEs that are disposed of in random places, and then delivering those to nearer plastic waste management services.

Publications in the past have shown that PPEs can be found in water and urban areas. However, knowing how much PPE contamination is in a particular area is hard. For this reason, it becomes challenging for waste management systems to predict the amounts of PPE and MPs in a specific area. To overcome these challenges, a proper monitoring plan must be executed in different regions to determine whether PPE contamination increases or decreases over time. A proper understanding can be made to attribute appropriate legislation. With a substantial increase in PPE use and disposal during COVID-19, plastic waste management has become challenging due to its lack of capacity, control, and potential management processes. MPs in human blood, the placenta, and deep lung tissues have been recently investigated and reported in different studies (Ragusa et al., 2021; Jenner et al., 2022; Leslie et al., 2022). These research works have revealed the consumption of MPs by human beings. However, the load and influences of these consumed MPs still need to be improved within the human body. Properly understanding the consumed MPs from PPE will make investigating and analyzing the negative impacts of randomly disposing of PPE easier. Processing PPEs by applying several approaches is challenging as there is a strong possibility of being infected by the viruses in PPEs.

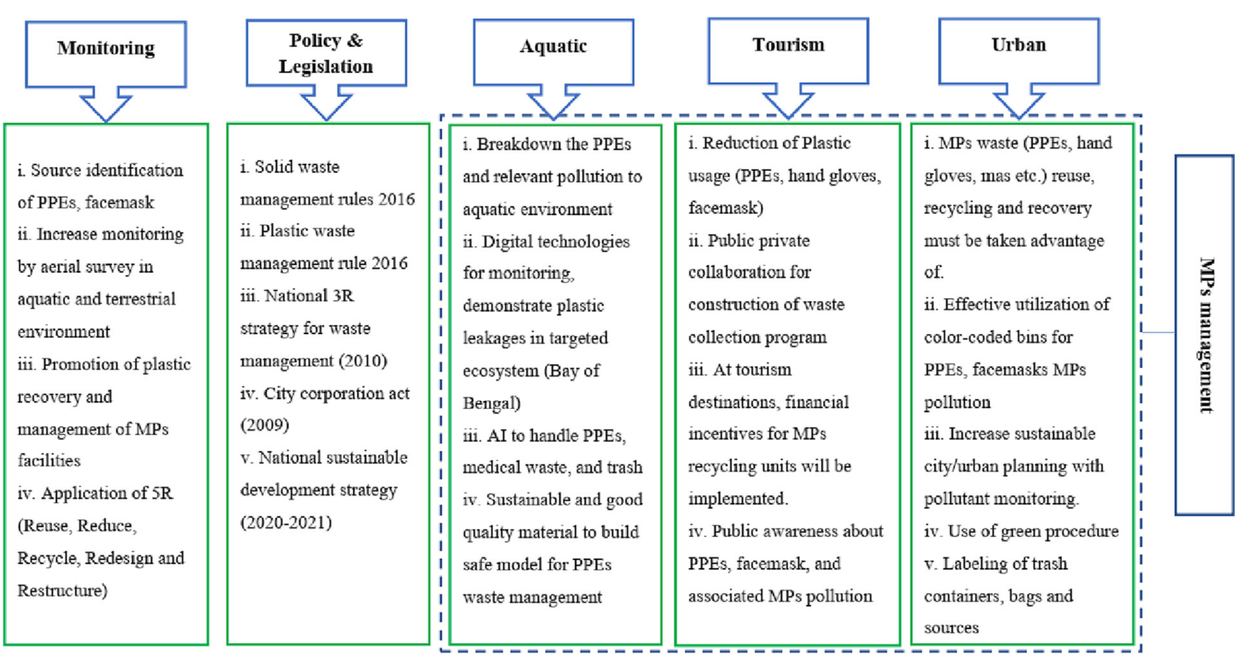

Fig. 7. Proposed management intervention strategies to reduce PPE-derived MPs pollution.

Table 3
Key findings of the PPE-derived MPs, and focus of the study, gap highlighted, future challenges and limitations during the COVID-19 era.

References	Focus of the study	Method identified	Gap highlight	Future challenges	Limitations
Abedin et al. (2022a, 2022b)	Indiscriminate disposal of personal protective equipment (PPEs) and environmental contamination.	Survey with photography and records	Observed PPE wastes must be lower than normal because there was a 2-week lockdown.	Increase public perception of the use and subsequent disposal of PPEs, especially face masks.	With the increase of inappropriate disposal of PPEs, the possibility of virus transmission increases.
Monolina et al. (2022)	A major scope for studying the carbon footprint aspects of plastic-made PPEs.	Population forecast and random sampling method	Proper waste management	Study about carbon-footprint	The notable aspects of the environmental challenges associated with the COVID-19 pandemic for strengthening the SDGs framework
Dharmaraj et al. (2021)	This study focuses on thermochemical processes, particularly pyrolysis, to treat Covid-19 waste, its sources, and collection and management strategies.	Disinfection technologies	Lack of an effective technique for decomposing the COVID-19 waste.	Study the factors influencing the pyrolysis of COVID-19 plastic waste, such as temperature, Pressure, Reactors, Plastic materials, etc.	Great challenge for the government. to handle the pandemic situation with the prevailing infrastructure Facilities and waste management.
Ray et al. (2022)	To cater a comprehensive perspective on the effect of a pandemic on MPs pollution during Covid-19	SEM (scanning electron microscopy), SEM-EDS (SEM-energy dispersive X-ray spectroscopy), and FTIR (Fourier transform infrared spectroscopy)	The gap in the origin and distribution of MP pollution in water bodies and the environment to the related studies of disposal face masks and PPE kits.	More research and development are needed on the effect of MP pollution on human health.	Proper management of single-use plastics (including PPE kits)
Haque and Fan (2022)	The main scope of the studies associated with a micro plastic release due to pandemic-associated plastic waste (PPEs, Face masks, etc.)	Retrieving the research	The little work published on the ecotoxicological/toxicological effect of MPs.	Future research should focus on human health and ecosystem stability during and after the COVID-19 pandemic.	It is necessary to Collaborate with government, policymakers, waste managers, and researchers to solve the problems of mismanaged plastic waste.
Rakib et al. (2021)	The most notorious source of face masks was illegal dumping sites in most touristic/recreational beaches.	Shapiro-Wilk normality tests, Kruskal-Wallis test, and Statistical tests	Researchers have better ideas of the intensity and impact of PPE and Face mask pollution across various environmental compartments and organisms.	Study about the impact of MPs	There are very few articles to report PPE pollution in coastal environments.
Dehal et al. (2022)	The intervention helped minimize the general waste treatment during the second pandemic.	Deep burial methods	Identifying "critical areas" that need BMW management may not be possible.	Study regulatory mechanisms and increase management where it is weak.	The regulatory framework and the institutional capacity to manage the unpredictable volume of BMW generation during the COVID-19 pandemic.
Hasan et al. (2021)	The long-term accumulation of microplastic pollution in aquatic environments.		Slow degradation of mask-derived polypropylene and polyethylene fibers creates large reservoirs of microplastic pollution.	The study of MPs pollution effect on the aquatic environment.	A new challenge for waste management.
Siwal et al. (2021)	Focus on the recycling strategies of PPE	Value addition methods	The complications of plastic trash management and disposal	Efficient recycling of PPE kits (used and faulty) using different technologies.	We have limited technology and funds for the study of recycling of PPEs and face masks.
Gunasekaran et al. (2022)	The abundance of PPE (face masks and gloves) was discharged on six beaches along the coast of India.	Transect visually scanning recognition	The lack of awareness of environmental pollution The negligence of the population; mismanagement of municipal waste.	Future studies must quantify the impact of PPE (face masks and gloves) waste on marine animals. Chemical Composition of PPEs	The challenge of environmental remediation and PPE management can be converted into opportunities by producing oil and gas. It was not possible to perform a long-term survey as in previous studies.
Abedin et al. (2022a, 2022b)	We are focused on the impacts of PPE waste disposal on the environment and aquatic ecosystem.	Walkways Visual observation Photographing Recording	The environmental health risks due to PPE-derived MPs pollution.	Need critical study on PPE waste production, management, and consequences.	Challenges have emerged in solid waste management following an appropriate waste management strategy.
Haque et al. (2021)	Focus on the waste generation scenario	Disposal methods	Lack of plastic waste management	Artificial intelligence-based plastic waste management	Few papers about sustainable waste management.
Chowdhury et al. (2021)	Focus on annual face mask utilization and plastic pollution from mismanaged face masks in coastal regions of 46 countries.		The weakness in waste management infrastructures	We are improving the waste management facilities for better disposal of masks and solid waste.	Challenges in plastic waste management, especially for developing countries.
Marnn et al. (2021)	Emphasizes waste pollution in Bago River and Bago City, Bago Division, Myanmar	Photographs Table Graphs Histograms	Myanmar does not have to use modern technology because of insufficient budgets and poor technicians.	The pyrolysis technique and microwave technique	The mask wastes and plastic debris will transform into microplastic.

Developed countries like the USA invested nearly $14.5 million in managing single-use plastics (SUPs) to further improve their technologies to cut waste, reuse, and minimize the energy waste to recycle the SUPs (DOE Announces $14.5 Million to Combat Plastics Waste and Pollution). China, Germany, and Italy are also investing a massive amount of money in protecting their environment from the negative impact of plastic waste by developing their research laboratories and investigations. However, there are limited facilities to do such research despite being one of the most polluted countries in the world. More investment must be made to cut waste, establish technologies for plastic recycling approaches, and further manage, control, and monitor it. Otherwise, plastic waste control will be more challenging in the upcoming years.

According to the Bangladesh Environmental Conservation Act (BECA) of 1994, Section 6 (A), there is a section that states the ban on polythene bags that are <55 μm in thickness; however, the collected samples of plastic waste from several regions have revealed the massive use of this type of bag. People's unconsciousness regarding plastic waste management and their negligence to follow the implemented legislation make it challenging for the government to control pollution caused by plastic waste.

4. Limitations and future research direction

4.1. Limitations

- To get a comprehensive view of the environmental effects of COVID-19-driven PPE pollution, more research and development are required regarding dumping chemicals and MPs and elucidating the consequences of ecotoxicology.
- The constant pollution of beaches by PPEs, face masks, and other things has adverse effects. Only a few articles discuss PPE pollution in coastal areas.
- MPs pollution during COVID-19 must be reduced and recycled; hence, effective waste management techniques must be used. Yet, there are limited resources and technology for recycling PPEs and face masks.
- The public must be concerned for trash management to be done correctly. Yet, the general public lacks sufficient environmental awareness regarding handling single-use plastics, particularly PPE kits.
- Due to low resources and inadequate technicians, some coastal parts of the Bay of Bengal, such as Myanmar and Bangladesh, do not adopt current technologies.
- In earlier PPE studies in the Bay of Bengal countries, research on the hotspot of PPE-made MPS pollution was overlooked.

4.2. Future research direction

✓ Future studies should therefore concentrate on human health, the environmental impact of PPEs, ecotoxicity, regulatory mechanisms, the effects of MPs, and ecosystem stability before, during, and after the COVID-19 pandemic.

✓ Face masks and their plastic polymer components have not been seriously investigated, and it deserves further investigation.

✓ To better comprehend the scope and effects of PPE pollution on various environmental compartments and creatures, significant study efforts must be displayed.

✓ The consequence of MP pollution on human health requires additional research and innovation for the future.

✓ Demand for a long-term treatment Artificial intelligence-based (AI) management of plastic waste

✓ Pyrolysis and microwave techniques must be apparent for future studies to reduce pollution from plastic waste.

✓ The load and impacts of MPs via PPE on human bodies should be thoroughly investigated. Although the sustainable management of plastic-made PPE is challenging, more research studies on using green materials are essential.

5. Conclusions and final considerations

In summary, this review critically highlighted the impact of ecotoxicity, intervention strategies, and future challenges of PPE-derived MPs pollution along the BoB countries, especially in India, Bangladesh, Sri Lanka, and Myanmar. Several issues about COVID-19-induced PPE waste, including how PPE-derived MPs pollute the aquatic ecosystem (e.g., source and fate in the ecosystem and the potential threats to ecosystems in the BoB countries), have been addressed in this review. Given the lack of scientific knowledge regarding the ecotoxicity impact of PPE-derived, we propose some research insights that must be addressed immediately to clarify the post-COVID-19 PPE-associated environmental issues. Many studies have been done on the PPE-derived MPs pollution of aquatic environments in the BoB coasts. Still, assessing the MP's pollution load before and during the COVID-19 era is overlooked in the literature. To address the issues of improperly managed PPE waste, it is crucial for all stakeholders, including the government, policymakers, waste managers, and researchers, to work together. The most essential elements of minimizing single-use PPE waste are garbage management, required restrictions, and environmental awareness. To address the problem of PPE-derived MPs pollution, the government, academics, the general public, and businesses must work combinedly.

Furthermore, the main reasons for the contamination of the aquatic environment by PPE wastes are poor municipal waste management techniques and a lack of understanding about MPs pollution. Although this study has established a variety of viewpoints and interventions for the effective management of PPE-derived wastes, more research is needed to fill research gaps related to the risks to the environment's health posed by the pollution of MPs derived from PPE. The current data about MP loads concerning PPE-derived pollution needs to be more reliable and necessitates further research. Finally, a thorough future investigation is required into how MPs degrade along the transfer pathway from the source to the human food chain and how they sink to the bottom of sediments due to physical or biological phenomena.

CRediT authorship contribution statement

Mehedi Hasan: Methodology, Investigation, sample collections, and preparation. **Most. Mastura Munia Farjana Jion, and Md. Naimur Rahman**: Methodology, Validation, **Abu Reza Md. Towfiqul Islam**: Conceptualization, Writing - original draft preparation, Writing - reviewing and editing, Supervision. **Md. Saiful Islam, Arnob Das, and Susmita Datta Peu**: Sample analysis, data curation, and interpretation. **Md. Refat Jahan Rakib, Tasrina Rabia Choudhury and Abubakr M. Idris**: Original draft preparation, reviewing, and editing. **Guilherme Malafaia, A.B.M. Mainul Bari, Subodh Chandra Pal** and **Aznarul Islam**: Reviewing, and editing. All authors read and approved the final manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial in the subject matter or materials discussed in this manuscript.

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Appendix A. Supplementary data

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