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Microplastics waste in environment: A perspective on recycling issues from PPE kits and face masks during the COVID-19 pandemic

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A B S T R A C T

During the COVID-19 pandemic, the extensive use of face masks and protective personal equipment (PPE) kits has led to increasing degree of microplastic pollution (MP) because they are typically discarded into the seas, rivers, streets, and other parts of the environment. Currently, microplastic (MP) pollution has a negative impact on the environment because of high-level fragmentation. Typically, MP pollution can be detected by various techniques, such as microscopic analysis, density separation, and Fourier transform infrared spectrometry. However, there are limited studies on disposable face masks and PPE kits. A wide range of marine species ingest MPs in the form of fibers and fragments, which directly affect the environment and human health; thus, more research and development are needed on the effect of MP pollution on human health. This article provides a perspective on the origin and distribution of MP pollution in waterbodies (e.g., rivers, ponds, lakes, and seas) and wastewater treatment plants, and reviews the possible remediation of MP pollution related to the excessive disposal of face masks and PPE kits to aquatic environments.

Contents

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1. Introduction

Plastics are emerging as the dominant material causing marine pollution and are currently used to produce many products because of their low cost, light weight, and high durability. However, compared to the high demand for plastics, problems arise owing to their improper disposal (Teuten et al., 2009; Ritchie and Roser, 2018; Rhodes, 2018). The wide presence of plastic debris (<5 mm in diameter) has become an emerging environmental concern (Horton and Dixon, 2018; Derraik, 2002; Audrézet et al., 2021). These so called microplastics (MPs) can be either primary or secondary MPs; primary MPs are manufactured at this small size and are often found in cosmetic goods, while secondary MPs are the breakdown products of larger plastic items (Pico and Barcelo, 2019). Although the intentional addition of primary MPs to non-essential products has been banned in a number of countries (Anagnosti et al., 2021), it is nearly impossible to control the increasing amount of secondary MPs. For example, the marine system receives an estimated 4.8–12.7 $\times$ 10^6 t of plastic waste each year due to improper waste management (Alfaro-Nunez et al., 2021; Eriksen et al., 2014).

Conventional and commercial plastics are not susceptible to degradation, and it is estimated that they may take a few hundred years to degrade in the environment. The degradation process may vary depending on numerous factors, such as mechanical stress, heat intensity, chemical composition, ultraviolet (UV) radiation, biodegradation, and bio-disintegration. However, the degradation process occurs at a very slow rate, which leads to the breakdown of plastics into smaller molecular products, fragments, and MPs (PlasticsEurope, 2016). After degradation, MPs are highly dispersed and can either settle out to the seabed or enter the food chain. Although the penetration mechanism of these alien particles through the epithelium of living organisms after being inhaled or ingested is unclear, plastic fragments with a diameter of 5–10 μm have been found in the placentas of pregnant women (Ragusa et al., 2021; Alfaro-Núñez et al., 2021). Moreover, the concern regarding MPs also relates to the remaining additives used in plastic manufacturing processes, which are often known as endocrine disrupting chemicals and can have severe effects on the health of living organisms (Chen et al., 2019).

The global production and disposal of face masks and medical materials, as well as the existence of plastic laboratories, have increased dramatically (Fadare and Okoffo, 2020; Ray et al., 2020). Before the COVID-19 pandemic, it was predicted that the amount of plastic debris would double by 2030, regardless of the numerous efforts of governments worldwide to reduce single-use products (Silva et al., 2021; Vanapalli et al., 2021). During the pandemic, a precautionary measure has been the use of personal protective equipment (PPE) to avoid virus transmission. Most PPE is used for single-use purposes and disposable PPE (e.g., surgical gowns) are often made of nonwoven fabrics containing polyethylene, polypropylene, and polyethylene terephthalate (Prata et al., 2021). The negative effect of plastic waste generated from PPE kits, single use face masks, gloves and other equipment has disturbed the environment globally. Typically, improper usage of PPE kits, disposal of biomedical waste and increased plastic wastes from domestic households continuously endangers environment. Some research indicated that there is a long-term impact on the environment as well as human health (Bansal and Sharma, 2021). In this regard, various researches have illustrated numerous solutions to tackle the increase waste generated by PPE kits and reduce their long-term impact on human health and environment. The recommended N95 mask capable of filtering up to 95% of air particles with a size of <0.3 μm is made of plastics such as polypropylene and polyethylene terephthalate, although a cloth mask can provide sufficient protection for general purposes (C.e.a. Abrar, 2020). Recently, Xiang et al. has demonstrated the decontamination of facemasks and N95 respirators via dry heat pasteurization technique that retains the filtering ability. These techniques could be valuable in order to minimize the quantity of generated facemasks (Xiang et al., 2020). As the number of polymer-made masks and other types of PPE being produced and used increased due to COVID-19, the number of emissions also increased (Hu et al., 2021a).

This review article aimed to cater a comprehensive perspective on the effect of pandemic on MPs pollution. Therefore, high scientific discussions on MPs pollution, particularly considering over consumption of single-use plastics (including PPE kits), must initiate soon with involvement with plastic producers and scientific community to be prepared for the near future. Furthermore, the main challenges and mitigation measures are discussed in order to overcome the waste generation during this COVID-19 pandemic.

2. Sources of microplastic pollution

During the COVID-19 pandemic, high amounts of biowaste and medical waste contributed to the sudden increase in plastic pollution. The persistence of plastics within single-use face masks and PPE kits will probably lead to the prevalence of these materials in the environment for many years (Schnurr et al., 2018). Plastic wastes from urban areas, wind and runoff, inadequate disposal of biowaste and medical waste, and mismanagement of dumped plastic waste are prominent sources of aquatic plastic pollution. Consequently, owing to the effects of wind, current, solar UV radiation, and other natural factors, MPs disintegrate into smaller microparticles (usually <100 nm to 5 mm). The major sources of MPs during the COVID-19 pandemic are illustrated in Fig. 1.

As synthetic polymers are generally highly resistant to environmental factors, they undergo relatively low degradation and can reside in the environment for a long time. Meanwhile, synthetic polymers are transformed into smaller molecular

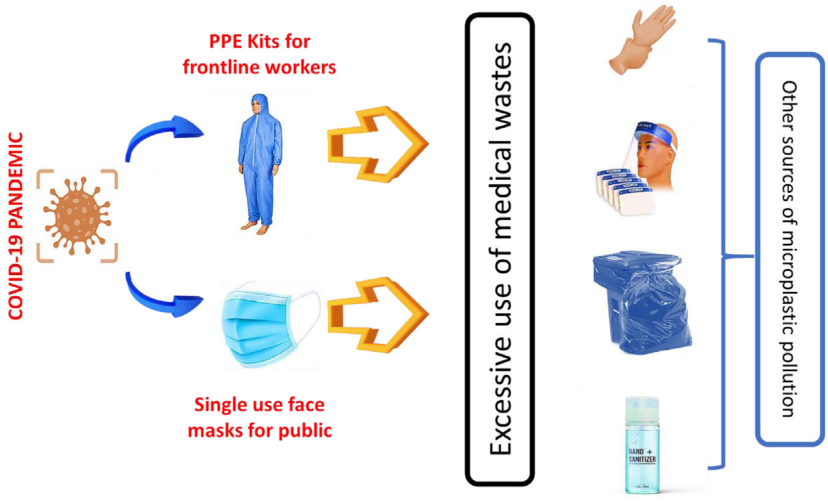

Fig. 1. Major sources of microplastics during the COVID-19 pandemic.

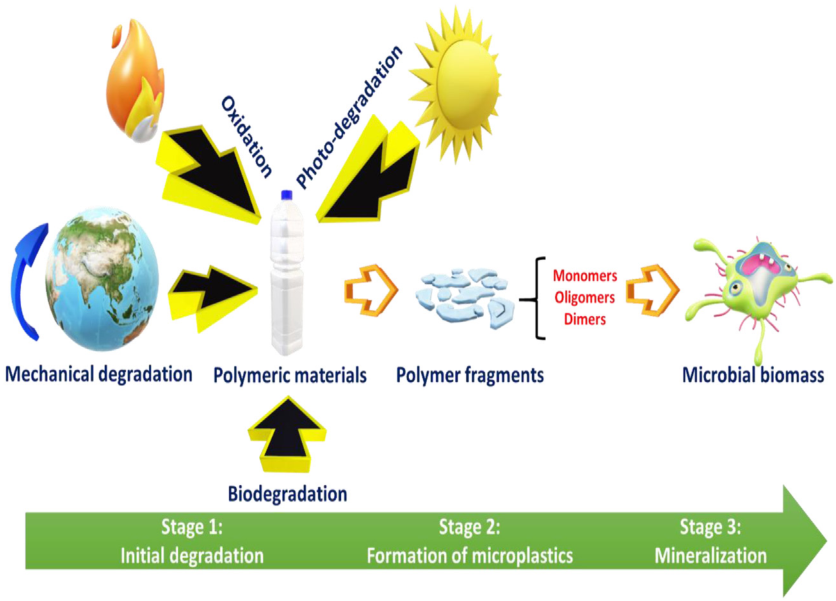

Fig. 2. Degradation pathway of polymer materials in the environment.

products or units (e.g., monomers, oligomers, and chemically modified fragments) and can be feasibly fully mineralized (Eubeler et al., 2009; Klein et al., 2018). The degradation of synthetic polymers in aquatic environments is initiated by UV radiation (photo-degradation) or by hydrolysis, and is eventually followed by an oxidation (chemical) process. The degradation mechanism depends on the category of polymers (e.g., polyesters, polyamides, or polyolefins). Hence, after the initial degradation process/reaction, a decline in the average molecular weight of a polymer can be observed, and reacted fragments/units become available for microbial degradation (Andrady, 2011). The degradation process of polymeric materials that produce MPs is illustrated in Fig. 2.

2.1. Masks and PPE Kits during COVID-19

As of May 20, 2021, the number of confirmed COVID-19 cases worldwide reached 163,738,674, with 3,384,750 deaths (Anon, 2021b). The recurrence of COVID-19 waves has exhausted healthcare systems in many countries (Derraik et al., 2020). Although each country has its own approaches based on the socioeconomic condition (Kang et al., 2020), most authorities recommend that certain workers wear suitable PPE (e.g., masks, respirators, face shields, and gowns) (Nguyen

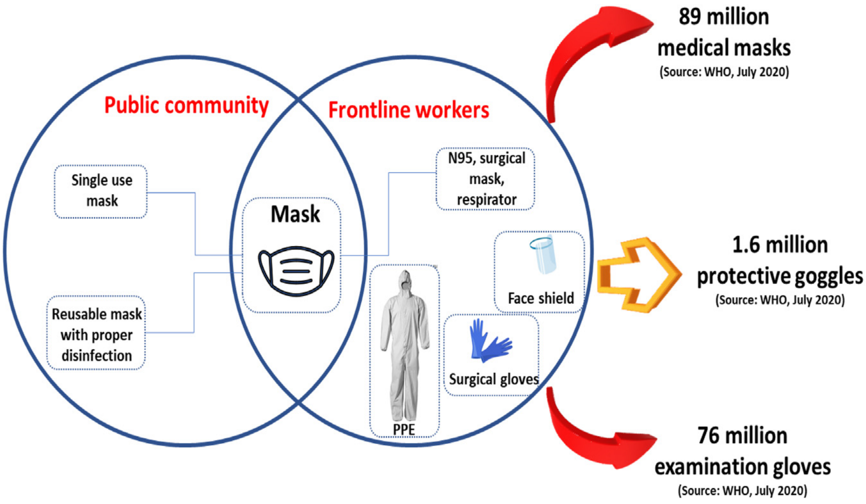

Fig. 3. Hourly requirements for single-use face masks and PPE kits worldwide.

et al., 2020) and that the public wear masks to suppress viral transmission, (Tso and Cowling, 2020) (Fig. 3). Although the effectiveness of face masks against the spread of COVID-19 has been disputed, despite people also discriminating against those not wearing masks, wearing face masks has become largely mandatory and normal practice. The estimated monthly consumption of masks (mostly single-use) in 2020 was 129×10^9 (Xu and Ren, 2021) Moreover, the surge in the demand for PPE is expected to continue until we reach herd immunity following vaccination or acquire a convincing antiviral therapy, (Rowan and Laffey, 2021).

2.2. Detection of microplastic pollution

Owing much to the diverse nature of microplastics in environment and the increasing concerns regarding this type of pollution, a number of instrumental methods have been developed to specify the presence of microplastics in various environments. A range of those methods mostly belong to two groups, microscopic methods, i.e. stereomicroscopy, SEM (scanning electron microscopy), SEM EDS (SEM-energy disperse X-ray spectroscopy), etc. to qualify and quantify MPs, or spectroscopic methods, i.e. FTIR (Fourier transform infrared spectroscopy), Raman spectroscopy, etc. to identify the chemical ingredients of MPs (Ragusa et al., 2021; Prata et al., 2019a; Kaile et al., 2020). Other techniques named Py GC–MS (Pyrolysis Gas chromatography–Mass spectrometry), LC (liquid chromatography) also have been used to characterize and measure the MPs in samples (Kaile et al., 2020). The former group often relates to the visualization, when the physical properties of MPs were identified and recorded in high magnification mode. Besides, once coupled with EDS, it could clarify the elemental components (Blair et al., 2019). The latter group involves the characterization of MPs, which is considered to provide fingerprints of the MPs. For examples, MPs originated from polybutylene terephthalate (PBT) and polyethylene terephthalate (PET) possess different characteristics spectra (Kappler et al., 2015), hence the specialization of these two polymers is possible. Chromatographic methods, on the other hand, are destructive but also considered to provide fingerprints of the MPs. Under high temperature, characteristic volatile compounds corresponding to the polymers are produced and detected subsequently (Fischer and Scholz-Bottcher, 2019). Each method proves its importance and also cons, hence, in most of the cases, the use of a combination of method is often utilized (Lee et al., 2021), starting with the microscopic techniques to visualize the MPs and later identification with spectroscopic/chromatographic methods (Alvim et al., 2020).

Without a ubiquitously acclaimed laboratory procedure for studies on MPs, it is mostly impossible for verification and comparison results from different studies. Besides, the accuracy of visual inspection may be interfered by various factors, such as subjective property of the techniques, the presence of impurities with similar size with MPs, and so on (Li et al., 2018). To cope with these facts, the use of flow cytometry technique, which takes the advantages of laser beams and detectors to expose the particles (McKinnon, 2018), recently has been proposed to detect MPs (Kaile et al., 2020; Renner et al., 2021). While the method exhibits advantage in MPs identification, limitations remain as further studies on the application of flow cytometry, in particular; and in general, a worldwide analytical standard is of utmost necessity.

2.3. Environmental impact of biomedical microplastic waste

As the use of biomedical products such as masks and PPE has increased rapidly due to COVID-19, the amount of waste discharged has also increased rapidly, and particulate plastic contamination of seawater is increasing (Tanaka and Takada,

Table 1
A framework of impacts, challenges, and future outlook perspectives to tackle the issue of the waste generated from face masks, PPE kits, and medical wastes.

Type of waste	Impact	Challenges	Future outlook/treatment	References
Single-use face masks and PPE kits	Protect against COVID-19, but lead to excessive disposal	• Change in waste composition • Microplastic pollution • Increase in the spread of COVID-19 in the environment	• Recycling of face masks • More emphasis on circular economy • Research and development on treatment processes	Teymourian et al. (2021)
Plastic packaging	Panic buying results in overuse of single-use plastic bags and food packaging	• Huge amount of waste compared to that of pre-pandemic situation • Improper disposal of solid waste	• Follow guidelines based on reduce, reuse, recycle, and recover • Treatment processes such as pyrolysis and incineration • Chemical disinfection	Akinola et al. (2014)
Medical waste	Excessive use of medical care products and vaccine units results in medical waste	• Increased possibility of infection and/or infected waste in the environment • Change in waste composition and amount	• Chemical disinfection • More studies on circular economy • Proper waste management • Follow the guidelines of the World Health Organization (WHO)	Dharmaraj et al. (2021)

2016). Marine biota are exposed to MPs through a variety of sources (Rochman et al., 2015b), and MPs related to masks and PPE have been found in more than 20% of marine crustaceans, and even in the stomachs of fish. Environmental exposure to MPs can cause a variety of problems. Because MP particles cannot be digested, biomolecules and aggregates containing MPs can cause gastrointestinal disorders or obstruction (Jeong et al., 2016). In addition, the hydrodynamic diameter of particulate plastic particles increases with increasing NaCl concentration (Cai et al., 2018). This is because PS NPs aggregate at high NaCl concentrations; hence, PS NPs are expected to aggregate easily in seawater. Interactions with various impurities, which also become aggregated, can harm aquatic organisms and absorb MPs. Microplastics with a diameter of <1.5 μm can directly damage cells. In addition, owing to the hydrophobicity of these particulate plastics, the adsorption of organic substances occurs, causing bacterial colonization and microalgae growth. These biofoulings can subsequently lead to the sinking out of larger plastic objects, furthering increasing marine pollution (Artham et al., 2009). Table 1 summarizes some major recommendations from various research works that could be helpful in tackling the issue of different wastes produced from single-use face masks, PPE kits, and medical waste during the COVID-19 pandemic.

Hand sanitizer bottles, gloves, water logged masks and other coronavirus wastes are being traced on seabed which increases the day-to-day detritus in the ecosystem. The coronavirus wastes pose a serious threat for an increase in MPs in water bodies. Typically, disposal PPEs are made up of polymers, such as nitrile, latex, or polyethylene, that require the use of additives like stabilizers, softeners to enhance the physical characteristics. When PPE kits are widely spread into the ecosystem, these additives can be toxic to flora and fauna as well as human health that undergo leaching processes in water bodies. Above all, some polymeric substances are also toxic and having endocrine disrupter features. MPs has the ability of absorbing water pollutants including dyes and toxic substances due to their dimension, that could be ingested by water organisms, affecting the food chain or food web in the ecosystem (Binda et al., 2021). Typically, MPs enter the human system via ingestion, inhalation, and dermal contact. Nano- and micro-sized plastics may cause various inflammatory diseases, along with obstructions and accumulation in organs. Humans can have prolonged exposure to MPs, which may result in chronic irritation, oxidative stress, cytotoxicity, altered metabolism, immunity disruption, neurotoxicity, reproductive toxicity, and carcinogenicity (Rahman et al., 2020).

2.4. Consequences of microplastic pollution

In aquatic environments, plastic produced from Single-use face masks and PPE waste can absorb various organic and toxic pollutants, thus forming a toxic film. This process can lead to the poisoning of aquatic organisms that ingest plastic-based particles (Williams-Wynn and Naidoo, 2020). After MPs undergo fragmentation, bioaccumulation occurs in the food chain, which can result in detrimental environmental impacts, as shown in Table 2.

Polymer degradation is a change in the chemical and physical structure of polymer chains and ultimately leads to molecular weight reduction (Gewert et al., 2015). Usually, there are various environmental factors causing polymer degradation in nature. In general, hydrocarbon-based polymers are sensitive to thermal decomposition, and epoxy or polymers containing aromatic functional groups are sensitive to UV. Representative environmental factors of polymer degradation include thermal, photochemical, and oxidative degradation. In the case of thermal degradation, as the temperature increases, the intramolecular vibration is amplified to accelerate the conformational change, and finally, polymer is oxidized and decomposed. Photochemical degradation depends on the photon energy and the degradation occurs in various way (Guillet, 1980). For example, light or UV makes some groups of the polymer into reactive, UV or RTG

Table 2
Environmental impact of aquatic plastic pollution.

Sources	Problems	Consequences	References
Plastic wastes from daily life	Entanglement due to plastic threads	Death of marine fauna and other aquatic animals (e.g., seabirds and turtles)	Haque et al. (2020)
Macro-plastics from face masks	Mismanagement of single-use face masks and face shields	Act as a medium for COVID-19 outbreaks because microparticles can accumulate in the food web	Klemeš et al. (2020)
Macro-plastics from PPE kits	• Improper disposal of PPE kits and surgical gloves • Mismanagement of solid waste	• Medium of COVID-19 outbreaks • Bioaccumulation of toxic substances, eventually entering the food web	Haque et al. (2020) and Klemeš et al. (2020)
Plastic bin bags from medical waste	• Mismanagement and improper disposal of bin bags from medical waste • Improper solid waste management from medical field	• Bioaccumulation of toxins • Bioaccumulation of organic pollutants • Bioaccumulation of persistent organic pollutants (POPs) and heavy toxic metals	Yang et al. (2020)
Other plastic wastes	• Consist of various toxic substances and chemicals • Adsorption of various toxic chemicals and POPs	• Toxic substances or chemicals can be released to aquatic environments during the degradation process • Affect marine organisms and contribute to environmental deterioration	Selvaranjan et al. (2021)

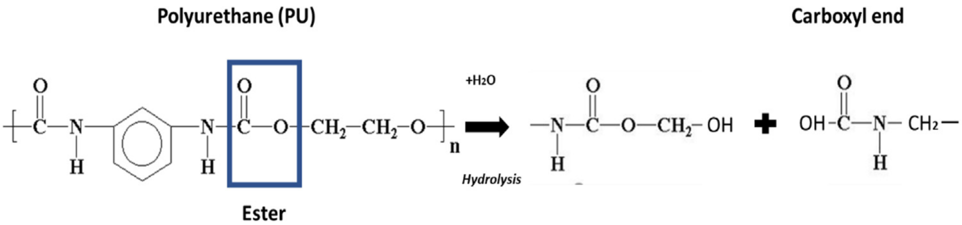

Fig. 4. Chemical reaction involved in hydrolytic degradation of ester bond in polyurethane (PU).

dissociate some bonds to radicals, and RTG or γ-rays release electrons from the molecule to create radical ions. Because of these, various reactions occur depending on the structure of the polymer and the conditions, resulting in cleavage or transformation of molecules. Oxidative degradation is a radical chain reaction that always occurs in the corrosion of polymers exposed to air (Bondarev et al., 2010). Typical oxidation is a long-term decomposition in which hydroperoxyl functional groups are gradually generated and accumulated in the polymer chain. As the OOH groups in the polymer chain are sufficiently increased, decomposition occurs more rapidly, resulting in the loss of its original properties. That is why polymers typically show no change for years or longer and then show a sharp decline in quality within weeks or months. For instance, polyurethane (PU) polymeric substances consist of large and complex moieties of carbon (C), oxygen (O), and nitrogen (N) in the polymeric chain. Typically, ester bond in the backbone is more vulnerable to degradation. Thus, hydrolysis, biodegradation and photo oxidation are responsible for degradation of PU substances (Szycher, 1999). Fig. 4 represents the chemical reaction involved in degradation of PU substances.

As far as human health is concerned, the ingestion process has become the major entry point into the human system (Waring et al., 2018). A recent study found 0.44 MPs/g, 0.11 MPs/g, and 0.03 MPs/g in sugar, salt, and alcohol respectively (Cox et al., 2019). Typically, it can be assumed that humans ingest approximately 80 g/day of MPs via various sources, such as fruits, vegetables, fish, and water, (Ebere et al., 2019; Campanale et al., 2020).

The existence of MPs and microbeads in fish, bivalves, and crustaceans in aquatic systems is well known. For instance, the number of MPs was found to be approximately 3–5 fibers/beads per 10 g of mussels from five different countries in Europe (Nelms et al., 2016). Hence, humans are exposed via diet, as particles smaller than 150 μm can enter the gastrointestinal epithelium, which leads to systemic exposure. However, the human digestive system is capable of removing 90% of MPs ingested via the excretion process (Smith et al., 2018). Table 3 lists the various categories of diseases caused by nanoplastics and MPs in aquatic systems.

Table 3
Summary of human health hazards due to MP pollution.

Category of diseases	Threat type	Impact	Reference
Acute diseases	Chemical and toxicological threat: Inhibition of an organism's detoxification mechanism (e.g., ABC transporters) causing acute toxicity and lethality	Digestive issues, interstitial lung diseases, airway diseases, and inflammatory diseases	Prata (2018) and Suman et al. (2020)
Chronic diseases	Toxicological threat: Release of mutagenic and genotoxic compounds Endocrine disrupting agents	Carcinogenesis Reduced male fertility and breast cancer in females	Fackelmann and Sommer (2019)

3. Remediation of microplastic pollution

In addition, to management and proper disposal procedures, advanced remedies must be explored to remove MPs from PPE and disposable masks in aquatic systems. In recent studies, WWTPs have performed efficiently to eradicate the issue of MPs. However, some authors have suggested novel methodologies to enhance the removal efficiency of MPs, such as primary treatment of the inlet effluent, which includes settling and skimming processes, whereas 95% of MPs are removed by the tertiary method (Hu et al., 2019; Malankowska et al., 2021).

Over the last few decades, plastic degradation has been thoroughly studied. However, there are other major strategies for the removal of MPs in aquatic systems: (a) microbial degradation, (b) advanced oxidation processes (AOPs), (c) thermal degradation, (d) adsorption, and (e) membrane treatment. Typically, thermal degradation and AOPs accomplish rapid decomposition and highlight the potential to produce carbon and hydrogen as fuel (Hu et al., 2021b).

Membrane technology has emerged as a versatile technique to eradicate the issue of MPs in aquatic systems, which can be attributed to the lower energy consumption, excellent stability, good productivity, facile control, and scaling-up process. This technology has the capability of handling a large feed stream that consists of brackish water and seawater (Ray et al., 2021). Membrane technology is based on the treatment mechanism and size of treated particles as well as the pore size of the membrane, and includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), forward osmosis (FO), membrane distillation (MD), membrane bioreactor (MBR), and dialysis (Ray et al., 2018; Sinha Ray et al., 2020a,b). A brief illustration of MP treatment techniques in a typical WWTP is shown in Fig. 5.

3.1. Management of disposable and reusable face masks

Reusable masks are more porous and breathable but generally less protective than surgical masks or respirators in serious circumstances (Konda et al., 2020). From an environmental perspective, reusable masks create a lower carbon footprint than surgical masks or respirators (Klemes et al., 2020). The life cycles of multi-use and single-use masks have been assessed, with findings suggesting that the life cycle impacts of multi-use masks account for only 5% of single-use masks (Eckelman et al., 2012). Fig. 6 indicates the assessment of the reprocessing of single-use face masks during the COVID-19 pandemic.

Thorough considerations are necessary to contain the spread of COVID-19 while minimizing the environmental impacts of PPEs (J.C.S. Prata et al., 2021). The main strategies are to optimize reusable masks and improve the environmental performance of PPE.

- The first step to standardize the quality of non-medical face coverings, including reusable masks, was specified in ASTM F3502 (Freeman et al., 2021). Although the standard does not regulate all expected criteria, such as leakage quantification, this first establishment could address the most basic prerequisites for the effective use of disposable masks and rule out unnecessary confusion for customers.
- To minimize the carbon footprint of PPE products, each step in the corresponding life cycle must be considered. At the manufacturing stage, cotton from organic sources or recycled polymers could be used for washable and disposable masks, respectively. Preference should be given to local products to reduce the footprint from logistics (Rizan et al., 2021). Finally, every mask, regardless of the type, needs to be disposed of properly, from segregation to incineration, dumping in sanitation landfills, and recycling, if possible. The possibility of recycling this type of waste is limited, especially for medical PPE due to the chance of virus transmission. Pilot recycling programs worldwide (e.g., TerraCycle in the United States, Plaxtil in France, and Vitacore in Canada) are underway to create road materials, plastic pallets, storage containers, and so on.
- To raise public awareness of environmental protection, authorities and related parties could (i) be involved in campaigns that promote the advantages of qualified cloth masks, (ii) model waste handling, and (iii) provide detailed instructions on required masks in each specific condition. Table 4 presents the influencing factors of various face mask selections and design specifications during the COVID-19 pandemic.

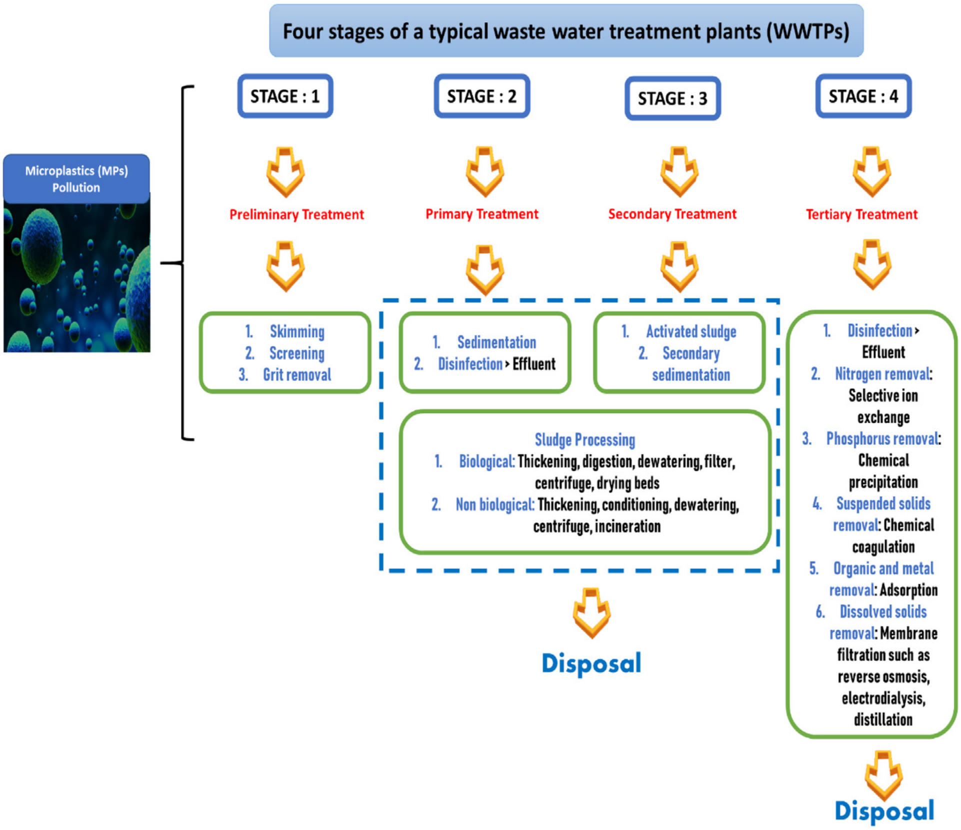

Fig. 5. Four stages of a typical wastewater treatment plant.

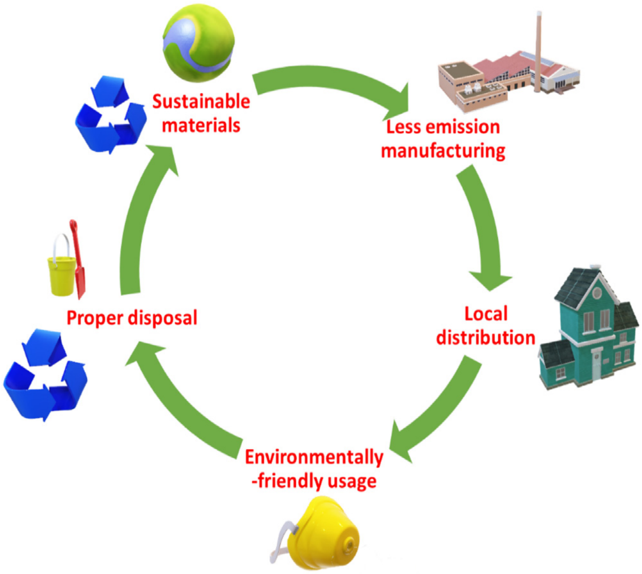

Fig. 6. A brief assessment of processing single-use face masks during the COVID-19 pandemic.

Table 4
Factors influencing face masks selection during the COVID-19 pandemic.

Factors	Disposable masks	Reusable mask
Category	Frontline workers	General public
Carbon footprint Klemes et al. (2020)	0.059 kg of CO_2 equivalent per single use	0.036 kg of CO_2 equivalent per usage (included washing)
Public concern	Plastic waste	Protective efficiency
Usage	Single use	Multiple use
Solution	Proper disposal	Quality control; sufficient cleaning (with soap and hot water) between uses and drying

Fig. 7. Zero-waste pathway to address the issue of plastic waste during the COVID-19 pandemic in water systems.

3.2. Strategies to tackle microplastic pollution

Similar to the approaches for handling MP pollution from PPE, strategies for MP pollution of other items call for comprehensive and integrated approaches that prioritize reducing plastic production and banning intentionally produced plastic microbeads. In this section, the leading role of authorities in the fight against MP pollution is emphasized.

Authorities could implement various integrated approaches, including legislative, economic, and educational strategies. The European Commission has set an example at the global level with a range of directives on plastic management, targeting the transformation into a "zero-plastic" or "circular plastic economy" (Anon, 2021a). Primary MPs and microbeads are largely banned for use in personal care products (Rochman et al., 2015a). Before the pandemic, single-use plastics were scheduled to be banned in several countries (Chen et al., 2021). As soon as the pandemic is over, there will be many actions that worldwide leaders need to take to reverse the plastic crisis (Vaughan, 2020). In addition, stricter punishment in terms of both economic and administrative perspectives for violation of plastic waste management legislation will soon be in effect, together with other market tools that play a "stick and carrot" role for other stakeholders. Clean-up activities and educational programs serve as tools to raise community awareness (Prata et al., 2019b), and also provide support to scientific research, for instance, collecting plastic waste from the marine environment and finding alternative environmentally friendly materials. To address the problem of MP pollution in aquatic systems during the COVID-19 pandemic, a more sustainable approach must be encouraged for the zero-waste pathway, as illustrated in Fig. 7.

In recent times, the major raw materials for the production of face masks are typically non-biodegradable in nature. These synthetic polymers are derived from various petrochemicals. Consequently, the disposal of these non-biodegradable face masks causes serious environmental impact. It is well known fact that these non-biodegradable face masks are not environmentally friendly. Hence, many researchers and scientific communities feel that there is a need of biodegradable and eco-friendly face masks which can execute similar performance as the existing non-biodegradable masks. The biodegradable face mask can be manufactured by using natural fibers such as hemp and cotton etc. Even these natural textiles can be made anti-microbial in nature by using various herbal extracts such as basil, aloe vera and turmeric etc. Furthermore, few biomaterials such as chitin, chitosan, cellulose acetate, gluten and alginate and their respective blends for the synthesis of facemasks seems to be sustainable. For the production of biodegradable masks, new protocols, methods and setup might be required. Many face masks producers have tried to manufacture bio-masks which are sustainable and worthy (Pandit et al., 2021).

4. Conclusions

During the COVID-19 pandemic, MPs have gained considerable attention as an emerging pollutant. The demand for single-use face masks, face shields, and PPE kits is unlikely to reduce significantly in the post-pandemic period up to 2025. As per "Our World in Data", since 1950's, over the 65 years, the annual plastic production has increased nearly 200-fold to 381 million tons in 2015. These plastic materials cause negative environmental impacts and can adversely affect human health via the food chain. The existence of a high amount of MPs sourced from various daily personal products have been widely reported; however, few studies have investigated the MPs and micro/nanofiber pollutants produced from single-use face masks and PPE kits that might end up in aquatic systems. This article emphasizes how the improper disposal of single-use face masks and PPE kits poses a potential threat to the aquatic environment and human health. Once discarded, these items degrade to different extents depending on numerous factors, such as mechanical stress, hydrolysis, oxidation, heat, chemical composition, UV radiation, biodegradation, and bio-disintegration. Therefore, sophisticated techniques such as Fourier-transform infrared spectroscopy, Raman spectroscopy, and gas chromatography–mass spectrometry must be used to identify MPs and microbeads in samples. Recently, much research has been conducted on bio-based polymeric masks; however, the availability of these bio-based masks is significantly lower than that of conventional and commercial masks. The recycling of various face masks is a time-consuming and costly pre-treatment process, which includes the separation of plastic materials and disinfection. Therefore, it is necessary to put more effort into implementing a circular economy considering the huge quantity of face masks and PPE kits produced during the COVID-19 pandemic. There is a need for more research and development to scale-up analyzes to determine the suitability of performing such operations. It is recommended to apply circular economy principles to address it with materials and technologies. Such approaches are prominent for managing PPE kits and single use face masks in the midst of COVID-19 pandemic. Thus, plastic circular economy is urgently needed to close the plastic loop. Long-term preventive measures and remedial strategies regarding the consequences of MP pollution due to improper disposal of face masks and PPE kits should focus on environmental awareness and education with respect to waste management. In the coming years, MPs must be given top priority worldwide to eradicate the issue of plastic leakage and pollution. More effort should be made to ensure sustainable growth with feasible solid waste management to avoid a plastic pollution pandemic.

CRediT authorship contribution statement

Saikat Sinha Ray: Conceptualization, Roles/Writing – original draft, Project administration. **Hyung Kae Lee:** Data curation, Roles/Writing – original draft. **Dao Thi Thanh Huyen:** Data curation, Roles/Writing – original draft. **Shiao-Shing Chen:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Young-Nam Kwon:** Funding acquisition, Investigation, Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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