Impact of coronavirus pandemic litters on microfiber pollution—effect of personal protective equipment and disposable face masks

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Abstract
Coronavirus Pandemic is the current biggest challenge against humanity. Apart from the personal health issues and higher mortality by the coronavirus, recent research works have also reported the environmental impacts of the pandemic. The review aims to analyze the current status of face masks and personal protective equipment littering and subsequent environmental impact in terms of microplastic and microfiber pollution. Recent researches in this domain are collected from the leading databases with relevant keywords and critically analyzed. The review results report a multi-fold increment in the usage of personal protective equipment, particularly face masks after the pandemic. Mismanagement of these items leads them to reach the marine environment through a variety of transportation. The results show a significant amount of increment in plastic and pandemic-related littering after the pandemic. The systematic review shows that the use of synthetic fibers in disposable personal protective equipment and masks leads to release of fibers that can add-on to microfiber pollution. The results are also true in the case of reusable masks as the repeated laundry and disinfection methods release a significantly higher amount of microfibers. Only very few studies have addressed the release of microfiber from the mask, and no studies have reported the impact of personal protective equipment. The worldwide mass adaptation and improper disposal of these materials increase the seriousness of the problem multiple folds. These findings suggest the immediate requirement of critical analysis of the pandemic-related littering and microfiber release characteristics. The research also urges the need for the implementation of an environmental management plan as a mitigation strategy around the globe.

Keywords Environmental pollution · Microfiber shedding · Reusable facemask · Single-use tri-layer mask · Waste management strategies

Introduction
Microplastic pollution is a rising concern among environmentalists due to its huge impact on the environment as well as biota. The researchers have witnessed the microplastic contamination in different environmental compartments including hydrosphere, lithosphere, biosphere, and atmosphere (Eriksen et al. 2013; Castañeda et al. 2014; Gasperi et al. 2015; Sanchez-Vidal et al. 2018; Absher et al., 2018; Kaya et al. 2018; Liu et al. 2018; Liu et al. 2019; Ambrosini et al. 2019; Chen et al. 2019). Around 18.75% (1.5 million tons) of total plastics (8 million tons) entering the marine environment were microplastics (Bird 2019). However, unlike macroplastics, the traceability and removal of microplastics are tedious. The higher level of contamination elevates the risks associated with the microplastics. Microplastics were found in different land-based (Selonen et al. 2019; Zhao et al. 2016) as well as water-based living organisms (Cauwenbergh et al. 2015; Jemec et al. 2016; Hossain et al. 2019) and it can affect the ecosystem. Researchers reported microplastics in the edible tissue of seafood organisms like oyster, sardines, prawns, squid, crab (Riberio et al. 2020) whereas the intestinal tracts of terrestrial birds (Zhao et al. 2016) and medicinal animals (Lu et al. 2019) were also found with microplastics. Moreover, these microplastics were also found in various food items including table salt, honey, beer, vegetables, and fruits (Karami et al. 2017; Lee et al. 2019; Diaz-Basantes et al. 2020; Muniasamy et al. 2020; Conti et al. 2020)
due to the production under contaminated surroundings. Researchers reported different routes for microplastics to reach human beings. The contamination of tap water, as well as bottled water along with various food items, can increase the exposure of human beings to microplastics through their daily diet (Cox et al. 2019). Moreover, inhaling contaminated air results in the suck in of microplastics which can cause an adverse impact on the respiratory system (Amato-Lourenço et al. 2020). Few studies have elaborated on the impact of microplastics on human health. Researchers have reported that the existence of microplastics in the human placenta can trigger an immune response (Ragusa et al. 2021). Similarly, the inhalation of microplastics can cause cytotoxic and inflammatory effects in human lung epithelial cells (Dong et al. 2020). Researchers also reported cell proliferation and morphological changes with microplastic exposure (Goodman et al. 2021). These alarming impacts of microplastics seek the attention of environmentalists and researchers.

While backtracking the sources of microplastics, researchers have identified primary as well as secondary sources of microplastics (Boucher and Friot 2017). The production and use of micro-sized plastics in cosmetics, personal care products, cleaning agents act as primary sources whereas the degradation of larger plastics into debris contributes as secondary sources (Quinn and Crawford 2017). Synthetic textiles are found to be the predominant source of microplastics as the fibers that detach or disentangle (microfiber shedding) from the surface of the textile material can be added to microplastics. The significantly higher contribution of synthetic textiles in microplastics has been revealed by the research reports claiming higher fibrous particles over fragments and granules (Zhao et al. 2014, 2016; Lusher et al. 2015; Wang et al. 2019; Tiwari et al. 2019; Ambrosini et al. 2019). Moreover, the link between the type of apparel being used and the polymers found in contaminated regions confirms the role of synthetic textiles in microplastic pollution (Browne et al. 2011; Sanchez-Vidal et al. 2018). In addition to this, the detachment of microfibers from the textile materials has also been reported. The microfiber shedding behavior of textile materials was analyzed in the dry state (wearing) (De Falco et al. 2020; Cai et al. 2021) as well as the wet state (domestic laundry) (Browne et al. 2011; Napper and Thompson 2016; Kelly et al. 2019). Domestic laundering of textiles has been realized as the major cause of microfiber shedding from synthetic textiles. Researchers have pointed out that the increased production and consumption of synthetic textiles due to fast fashion trends are the key accelerators of the contribution of synthetic textiles in microplastic pollution (Ellen MacArthur Foundation 2017). Besides, the rapid disposal of garments due to shorter trend cycles also increases the seriousness as the textile materials can get degraded or fragmented due to aging and exposure to sunlight (Laitala et al. 2018; Henry et al. 2019).

In this context, recently, the use of single-use personal protective equipment (PPE) that includes masks, face shields, gloves, and other protective items has reached its peak due to the rapid spread of Coronavirus (COVID-19). The increased production and consumption of single-use PPEs result in increased as well as unsafe disposal that ends up in the environment. The management of these wastes got complicated with the sudden increment. It has been estimated that switching from single-use masks to reusable masks can reduce plastic wastes by 60,000 tons in a single year (E &T editorial, 2021). Researchers have reported the existence of PPE along coastal sides where masks were found abundantly (87.7%) followed by face shields (6.5%) (De-la-Torre et al. 2021). These should be addressed properly as the surgical masks are generally made of synthetic polymers which can harm the environment (Aragaw 2020). The noticeable impact associated with the increased consumption and disposal of single-use PPE is that it can ultimately increase microfiber pollution in the environment. Researchers have reported the microfiber release behavior of surgical masks during usage and in the disposed state (Aragaw 2020; Chen et al. 2021; Shen et al. 2021). Researchers have also witnessed the release of fibers from the non-woven layer of surgical masks (Chen et al. 2021). With a significant level of microplastic emission issues with the disposable masks, researchers have estimated that a range of 72–31,200 tons of microplastics add up to the ocean in 2020 due to the increased use of surgical masks (2.4–52 billion pieces) (Saliu et al. 2021). The situation should be given even more attention when disposable masks can also act as pollutant carriers (Anastopoulos and Pashalidis 2021). Moreover, disposable masks were found to release heavy metals in addition to micro- and nanoparticles (Swansea University 2021). The microplastic release behavior of masks needs to be analyzed with greater importance as this possesses the risk of inhalation of microfibers (Li et al. 2021). Like single-use disposable masks, reusable masks should also be given equal importance in the case of microplastic issues. Reusable masks do undergo disinfectant processes that can cause the release of fibers which is very similar to the microfiber shedding of textiles during washing (Shruti et al. 2020). The existing complications with microplastic pollution got a greater concern with the increased consumption and disposal of PPEs, more specifically masks. Being a potential pollutant, these PPEs should be handled properly amidst the pandemic to avoid long-term effects. Hence, this paper aims to analyze the environmental impact of PPEs, single-use surgical masks, and reuse face masks. In specific, the review consolidates the potential impact of these articles on the microplastic and microfiber release to the environment. This review process was performed in June 2021 and is
carried out in the Department of Fashion Technology at PSG College of Technology (Coimbatore, India).

Materials and methods

The study involves a critical analysis of the literature that is focused on the area of plastic and microplastic pollution impact of COVID-19 related PPEs. Science direct, the American Chemical Society, and Springer database have been used for collecting research works that are done in this domain. Google Scholar and Researchgate were used to access the works which are inaccessible in the mentioned platforms. For the literature collection, specific keywords such as COVID-19, Personal Protective Equipment, Face masks, COVID-19 littering were used. Further, the research works were narrowed down to environmental pollution, microplastic pollution, and microfiber pollution. After narrowing it down, 32 articles were selected based on their direct relevance to the current research. The collected articles were consolidated based on their direct relevance to the current research. The collected articles were consolidated based on their scope and finding and then analyzed to derive the key findings and the research gap. Moreover, other relevant researches on microfiber pollution due to textile materials and their impacts were also discussed to provide basic support for a better understanding of the issue and its origin.

Results and discussion

PPE and face masks usage in COVID 19

The second wave of COVID-19 created a higher awareness among the general public to use personal protective equipment (PPE). A personal protective kit is typically used by health professionals to avoid infection and disease transmission. Hence, these materials are primarily developed for single-use purposes (Patel et al. 2017). As the high rate of human transmission of COVID-19 is reported through respiratory transmissions, presently general public was insisted to wear face masks in public places by their national governments (Kwak and An 2021). The use of face masks is one of the precautionary measures to protect the person-to-person transmission of COVID-19 and so a sudden increase in the consumption of face masks is noted worldwide. World Health Organization (WHO) reported a worldwide requirement of 89 million surgical masks per month in this pandemic and a 40% increment in the disposal PPE production (WHO 2020a, b). Recent research works also intimated a huge surge in global mask production. Adyel (2020) reported a 12% increment in China’s mask production in February 2020 than the previous year. At this post lockdown, by adhering to the WHO norms, if people use disposable masks daily, the consumption will rise to 129 billion face masks and 65 billion gloves per month (Prata et al. 2020). Due to the large quantity of general public consumption, the masks are disposed of in the environment without proper care. Improper disposal of even 1% of the masks used in the world will develop 10 million masks per month and that can induce 30,000–40,000 kg of plastic into the environment (WWF 2020).

Though the disposable or surgical face masks that are made of synthetic non-woven materials were recommended to avoid the risk of infection (Feng et al. 2020; Potluri and Needham 2005; Aragaw 2020), WHO also approved tri-layered reusable cloth masks with higher filtration efficiency (WHO 2020a). The reusable masks that are commercially sold through retailers increased tremendously as the need for regular use increased after the lockdown. Amazon and Esty reported millions of cloth mask sales in the pandemic alone (Kavilanz 2020). A recent research report mentioned that the global reusable face mask industry will grow at a compound annual growth rate (CAGR) of 23.5% from 2020 to 2027 and reach a value of 7.08 billion USD by 2027 (Reusable Face Mask Market 2020). As far as the fiber contents are concerned, the disposable surgical masks are typically made of three layers. The first layer is the typical inner or skin contact layer that is made of cotton and cellulotic blends to absorb the sweat from the skin. The second layer or middle layer is mainly prepared with synthetic non-woven materials like polypropylene and polyester. It is used to filter or retain the aerosol particle, viruses, and other microorganisms from reaching the wearer. The outermost layer is hydrophobic synthetic material to restrict material and liquid passage, preferably made with nylon, polypropylene, and polyesters materials (WHO 2020b; Shruti et al. 2020). In the case of a reusable face mask, all the types of fibers were used without any regulations. Konda et al. (2020) reported that most of the masks in the commercial retail outlets contain a significant amount of synthetic fiber contents. The few common fibers used were 100% polyester, nylon, polyether-polyurea copolymer, spandex, cotton and polyester blends, and polyester/polyamide mix. These masks are also widely
but after the pandemic lockdown, as the governments used by medical industry people and there was no problem, Malin 2021). Before lockdown, the disposable masks were the public in the proper management of used masks (Zoe. head, World Wildlife Fund, mentioned that the goal is not to risk personal health and medical safety, however, educating the public in the proper management of used masks (Zoe Malin 2021). Before lockdown, the disposable masks were used by medical industry people and there was no problem, but after the pandemic lockdown, as the governments advised to use the mask, the general public adopted the same. It is safe to use against COVID-19 but they are not environmental-friendly as expected.

Environmental impact of PPE and masks

Though COVID-19 is a big threat to human life, it indirectly contributes to Sustainable Development Goals (SDG) due to the reduction of air pollution, greenhouse gas reduction, and other controlled activities (Silva et al. 2021). Everyday use of reusable and disposable masks becomes the new normal after the COVID-19 pandemic and the use of PPE also increased significantly as discussed earlier. As the PPE and masks are majorly produced from synthetic fiber material, it is also creating an impact like single-use plastics on the environment. In February 2020, the first concern on face mask pollution was given by the Oceans Asia foundation, which reported a large number of masks on the beaches of Hong Kong. It warned that the disposal of the mask will also end up in a situation like single-use plastics by impacting marine lives (Emily Chan 2020). A report released by Oceans Asia reported that around 1.5 billion disposable masks around the world had reached aquatic (sea) sources at the end of the year 2020. This approximately adds 6,500 tons of additional plastic wastes to the marine environment. The major difficulty comes in mask recycling than other plastics since they were made up of multiple plastics. An environmental simulation study showed that a single face mask can release up to 1,73,000 microfibers per day (Leyla Yvonne Ergil 2021). As the masks are mainly made of polypropylene, the microfibers from the medical-grade disposable face mask will take up to 450 years to decompose (Zoe Malin 2021).

Hence, to avoid contamination and to also regulate the pandemic wastes, WHO released a separate waste management protocol on a regional level based on sustainable approaches (WHO, 2020c). Several studies from all around the world reported the littering of used PPE materials and face mask in open and public places (Prata et al. 2020; Canning Clode et al. 2020; Ouhsine et al. 2020). It was also evident that due to higher consumption than other PPEs, the single-use masks are the most littered item in public places (Ammdendolia et al. 2020; Okuku et al. 2021; Roberts et al. 2021). Detailed analysis on mask and PPE littering was reported recently by Roberts et al. (2021). The recent research analyzed the PPE and mask littering in eleven different countries using Litterati open-source data (Litterati 2020). The research was performed at different periods from March to October 2020, and the results are
presented in Fig. 1. It reported the results at three stages of analysis namely, at emergency (E), at pandemic (P), and after general use recommended (M). From the time of emergency (Jan 2020) to pandemic (March 2020), no significant difference in the litter was noted concerning the PPE items like masks, gloves, and wipes. But after the announcement of the pandemic, the usage of all PPE increased. 0.2% to 2.4% increment in the gloves litters was noted in the pandemic, and similarly, the wipe litters increased from 0.2 to 0.6% in the pandemic and reduced to 0.4% in the post-pandemic. But due to the mass requirements, a gradual increase in the mask littering was noted from March 2020 to October 2020 to the level of 0.84% of total collected litter. Only for the mask littering, 84-fold increment was reported by the study. The research also showed prominent differences among the countries, where the UK showed a significant increment in littering during and post-pandemic, and the Netherlands did not show any differences except for gloves.

An analysis performed in two metropolitan cities namely Toronto, and Ontario found 43 out of 44 surveyed places polluted with PPE debris. Out of several PPE items surveyed, maximum debris of used gloves was found in the city (41%), in the large grocery store, and in residential locations. All the gloves found were made of synthetic materials. The higher prevalence of the gloves is associated with the public mindset about the safety against COVID-19 virus. As the virus remains inert on plastic surfaces (van Doremalen et al. 2020) hand wash was the best method to remove the viruses. Among the various locations verified, an average of 32% place showed the debris of face masks. The maximum amount of litter was found in hospital locations. In the case of mask type, the majority of the littered material noted was single use masks followed by reusable masks. Medical wipes were noted in around 27% of the surveyed areas (Ammendolia et al. 2021). The ecotoxicological effects of micro- and nanofiber debris from disposable face masks were reported by Kwak and An (2021). Researchers used earthworms and springtails to measure the ingestion rate of microfibers from the mask filters. The study results showed a rapid uptake of microfibers in earthworms and springtails. The presence of microfibers on those organisms confirmed the environmental impact of the face masks. It was also reported that the fragmentations of polypropylene fibers can also act as a heavy metal carrier and spoil the soil ecosystem.

The main issue in the face mask comes with the polypropylene content as it was used to protect the wearer from the body fluids and aerosol droplets. Polypropylene never degrades completely instead, it shrinks and converts into debris over years. Studies proposed the reusable mask as a potentially viable option to overcome the pollution related to disposable facemasks (Azyan Zafyrah Mohd Zahid 2020). A comparative study conducted by Environmental Science Center, Qatar University, compared the coastal littering in the west coast region of Qatar between November 2019 and July 2020. The results showed that after a lockdown in July 2020, the researchers reported a higher amount of PPE materials and disposable face masks as littered items than the 2019 study. Through FTIR analysis, they confirmed the presence of polypropylene in identified littered material and suggested that the disposal face mask,
PPE are emerging environmental threats. They also reported that polypropylene will become the source of microplastic pollution in the ocean (Veerasingam et al. 2020). Other researchers reported the COVID-19 related littering in the Kenyan beaches. The study reported 0.43% of litters found are COVID-related PPEs and masks. Out of several beaches evaluated, urban beaches (Mkomani) were noted with 55.1% of COVID-litters than the remote beaches. Concerning the floating material survey in the sea range, the research did not find any COVID-related litter on the surface as the PPE items and disposal masks tend to sink into the bottom of the sea (Okuku et al. 2021). The analysis in Indonesia, also reported a similar trend of PPE debris on the coastal regions of Jakarta Bay. The previous study in April 2016 did not show any such kind of PPE debris; however, the study on June 2020 reported a PPE debris of 16% of the total debris collected. After the pandemic, more medical wastes including gloves, masks, etc., were found in the study. Out of which medical PPEs, masks (disposable) occupied a major percentage of 9.83% of debris (Cordova et al. 2021).

Several researchers reported the mismanaged wastes and their impact on pollution (Lebreton and Andrady 2019). They have predicted plastic pollution till 2060 and reported mismanaged wastes as the main source of 91% of the pollution. A recent study by Chowdhury et al. (2021) reported a face mask consumption prediction based on the population in the coastal regions and mask acceptance percentage by the respective country. Out of the countries measured, Asian countries consume 289.63 billion face masks annually than any other country. The study also reported a 65% and above mask acceptance percentage in Asian countries than other countries. When the mismanaged pollution was related due to the higher mask usage, Asian countries contribute much higher. The study reported that approximately 0.15–0.39 million tons of plastic debris enter the ocean yearly. In the case of COVID-related plastics wastes from the mask, the Asian countries contribute 1.51 million tons of waste. The researchers noticed that poor waste management in lower-income countries was the main reason. Other than this, common environmental issues like sewage treatment issues, recycling issues, carbon footprint issues, and other impacts are also associated with the PPE and related plastic items. The detailed information on the long-term effect and carbon footprints can be found elsewhere (Silva et al. 2021).

Due to the increased open-air and landfilling process, to avoid the potential environmental harm caused by PPEs, Aragaw and Mekonnen (2021) reported thermal pyrolysis as a potential method. In a study, researchers reported 75% conversion of PPE as bio-crude oil through the pyrolysis process. It is also reported that the surface littering washed off into the water bodies in several means and adds pollution to the aquatic environment. Initially, it disintegrates to macro-level debris and further to micro-level.
over time. The complete adoption of face mask usage by the global community increased the disposal of PPE and face mask. Studies showed that the COVID situation has brought an environmental disorder in both the terrestrial and aquatic environments (Aragaw 2020). Shruthi et al. (2020) reported the potential issues that arise from the mask that we use during the pandemic. Either it may be disposable or reusable, the researchers understand that they can cause higher microfiber emissions into freshwater systems, land, and the ocean. Since synthetic textiles cause a higher amount of microfiber shedding as reported by earlier researchers (Rathinamoorthy and Raja Balasaraswathi 2021; Napper and Thompson 2016; De Falco et al. 2019), the current recommendation for reusable masks also can contribute similarly to the marine pollution as they are also made of synthetic textiles. A virologist from the University of Cambridge mentioned that for the general public, the use of reusable cloth masks is perfectly safe and adequate. The experts also advise washing the reusable mask at above 60 degrees centigrade to kill any virus particles in non-medical circumstances (Emily Chan 2020; UNE 2020; AFNOR 2020). Other studies report that machine washing of the reusable mask is the better way to control the environmental impacts (in terms of carbon footprint and chemical release to sewage and marine) (Roberts et al. 2020). Figure 2 represents the distribution of various COVID-19 related PPE items (Fig. 2a) and mask types (Fig. 2b) as reported in the literature.

When the environmental impact of these face masks (reusable and disposable) in terms of plastics pollution has been analyzed, it is alarming that the reusable masks are also creating pollution but are comparatively lesser than the disposable mask. As per previous studies, machine washing synthetic textiles can cause higher microfiber shedding from fabric (Lant et al. 2020). Similarly, washing at higher temperatures, above 60 degrees will increase the amount of microfiber released per unit square of fabric with statistical significance (Yang et al. 2019; Zambrano et al. 2019). Hence, the use of a reusable face mask is also not completely safer in terms of plastic pollution is concerned. Further, the lifetime of the reusable masks is not standardized and it is essential to wear masks in day-to-day routine; hence, a higher number of repeated washes can contribute to a significant level of microfiber and microplastic pollution. A survey conducted in the UK reported that reusable masks reduce the environmental impact by about 95% (compared to single-use surgical masks), followed by a reusable mask with one-time use filters (60% reduction). The least impact was noted with

![Fig. 3 Distribution percentage of COVID litters as reported by the literature](image)
the reusable mask with no filters whereas the face shield had a higher environmental impact. The study reported that disposable masks can cause 10 times higher pollution than reusable masks (Allison 2020). Though several researchers reported the recycling of disposable masks is difficult due to their multiple fiber types, few existing technologies were also suggested to disinfect, sterilize and reuse the disposable face masks. A review report by Rubio-Romero et al. (2020) evaluated the different cleaning methods like decontamination with ozone, Vaporized Hydrogen Peroxide, Low-Temperature Moist Heat, ultraviolet C radiation, and ultraviolet germicidal irradiation for their effectiveness on Filtering facepiece (FFP) respirators. However, no specific method for the decontamination and sterilization of disposable PPEs was detailed in this study. Figure 3 denotes the use of various COVID-19 related PPE items distributed at different locations as reported in the literature.

The literature indicated a higher amount of face mask littering all around the world compared to other PPEs. The mass adaptation of facemask usage after the pandemic was reported as the major reason for higher consumption. In the case of disposal, inadequate knowledge of individuals and poor waste management practices of the nations were reported as potential sources of environmental littering. Due to the synthetic fibers content and non-woven structures, the disposed surgical masks quickly interact with sewage paths or river streams, or seawater and releases microfiber. Studies often reported that the use of reusable face masks reduces the environmental impact to a significant level. However, without proper regulation, similar to a disposable mask, the repeated use, and laundering of the reusable mask is also capable of releasing microfibers.

**Microfiber/microplastic release from face masks**

Microfiber emission from these PPEs and face masks is one of the significant environmental impacts of these products. Single-use disposable masks are being used widely in this pandemic and results in huge disposal. The microfibers/microplastics releases from the PPEs were witnessed by few researchers and specifically the microplastic release behavior of the masks as the masks are dominant among others in the PPEs used. The morphology of the layers can be responsible for the microfiber release. In the case of a disposable surgical mask, the inner and outer layer of the mask is made of randomly arranged fibers that are intertwined without proper fixation. This accelerates the slippage of fibers under external force (Shen et al. 2021).

Saliu et al. (2021) have evaluated the potential of disposable surgical masks to emit microplastics after being disposed of. To replicate the weathered masks, artificial aging has been done with ultraviolet (UV) irradiation. Moreover, the artificial seawater surroundings with mechanical agitation were also made to simulate real-time conditions. Researchers compared different types of commercially available surgical masks sourced from different vendors. The microfiber release from the mask under the simulated conditions reported a maximum of 173,000 microfibers/day whereas the average release is around 135,000 microfibers/day. The combined mechanical and chemical degradation leads to the formation of microplastics. However, in the sea, mechanical degradation dominates over chemical degradation because of the abrasion induced by the sediments. To validate the reliability of laboratory-scale aging simulation in real time, the masks that are collected from the beaches were compared with the experimentally aged masks and found with the same morphological and chemical degradation (Saliu et al. 2021). Similarly, the other researcher mimicked the real deterioration conditions of surgical masks in the aquatic environment by applying simulated shear stress. This revealed that the masks could release thousands of microplastic particles even when subjected to low-level shear energy densities (Morgana et al. 2021).

The change in the physio-chemical properties of the disposable masks under UV weathering leads to the breaking down of masks into microplastic particles that can have a severe impact on the environment. Researchers have reported changes in the chemical composition, chain structure, and reduction in the mechanical strength of the masks after being exposed to UV radiations. UV radiations can provide energy which leads to the breakage of C–C and C–H bonds and forms alkoxy and peroxy radicals. This causes chain scission. This decrease in molecular weight over UV weathering leads to a decrease in the mechanical strength of the mask layers. The surface analysis has reported that exposure to UV radiation causes fiber fracture which results in the formation of fiber fragments. Among all layers, the middle layer which is the melt-blown cloth is made of polypropylene and is the most vulnerable to the UV radiation which releases polypropylene microfibers. Since the melt-blown layer is made of fibers of a smaller diameter than the outer and inner layer fibers, the increased fiber breakage was noted after the UV exposure and it results in rapid microfiber release. They have also reported 1.5 million microplastic particles to be released from the single mask.
due to UV weathering which can increase up to 16 million particles while considering the abrasion in the presence of sand. However, the exceeding UV weathering over 36 h have not shown any significant impact of abrasion of sand (Wang et al. 2021). Similarly, the other researcher reported the microfiber release from the mask under two months of natural exposure. The aging under natural conditions showed a significant increment (25,000 times) in the microfiber release. The increased release in aged masks was attributed to the fact that aging makes the material more fragile. The SEM analysis of the aged masks shows obvious fracture marks and destruction of nodes. The failure of binding the fibers in the structure results in aging and leads to the release of fibers. Moreover, while considering the length of the fibers, aged masks release shorter fibers than normal masks (Shen et al. 2021).

In line with this, a study reported the new as well as used masks for microfiber release and noted a significant increase in the microfiber release from the used mask than the new mask (new mask—183.00 ± 78.42 particles/piece; used mask—1246.62 ± 403.50 particles/piece). The presence of loosely bound fibers is the reason for the microfiber release in the case of new masks whereas abrasion during usage and aging was the major reason for the increased release of microfibers in the case of used masks. The actions like adjusting, folding, pulling during the wear phase can cause mechanical deformation of the structure which results in fiber breakage (Chen et al. 2021). This can be related to the finding of the previous researcher who reported abrasion of sediments in the sea that accelerates fragmentation and release of microfibers from the surgical masks (Saliu et al. 2021). It has to be noted that the microfiber release ability of the surgical masks could not be related to the material quality and function which is evident from the results showing a correlation was not found between microfiber release and price of the mask (Chen et al. 2021).

In addition to the microplastic release in the disposal stage due to degradation and abrasion, the researchers have reported microfiber emission while wearing masks. This possesses the risk of direct inhalation of microplastic particles by the wearer. Masks are potential enough to prevent the inhalation of microplastics suspended in the atmosphere. However, the prolonged use of these masks can result in the inhalation of microplastics originated from the mask itself. The release characteristics of microfiber/plastic particles from different masks including N95 respirators, surgical masks, cotton masks, fashion masks, non-woven masks, activated carbon masks were reported by Li et al. (2021). With breathing simulation, the researchers have witnessed the risk of inhalation of microplastics. Initially, wearing masks for a lesser duration helps in preventing inhalation of atmospheric microplastics which is evident from the results showing higher microplastic particles in the specimen without masks compared to the specimen wearing a mask for 2 h. However, the prolonged wearing of a mask increases the microplastics inhalation than not wearing a mask. When compared to the case of not wearing a mask, wearing masks such as activated carbon mask, surgical mask, cotton mask, fashion mask, and non-woven mask increases microfibers inhalation by 1.17, 0.16, 0.40, 0.54, 0.04 times, respectively, over 720 h of wearing. The higher fiber release with the activated carbon mask is linked to the inferior quality materials (Li et al. 2021).

These studies clearly show that masks are emerging as one of the greatest contributors to microplastic pollution. The different layers of the masks are prone to release microplastics and fibers. Generally, the outer and the inner layer of the masks were made of spun-bond non-woven whereas the middle layer will be of melt-spun non-woven which acts as a filter (Dharmaraj et al. 2021). The spun-bonded structure will have a random arrangement of fibers that are held together by nodes which can provide strength. This intertwine of fibers without proper fixation (like
yarns in fabrics) leads to fiber release from the inner and outer layers of the mask. Moreover, the nodes can get fractured over a period of time when exposed to external actions that lead to easy detachment of fibers (Shen et al. 2021). Whereas, the middle melt-blown layer is highly sensitive to UV radiation, which can release polypropylene microfibers while exposed to UV lights (Wang et al. 2021). The non-woven structure is mainly used in these PPEs to reduce product costs. As yarn production and fabric manufacturing steps are eliminated, the product cost reduces significantly. Further, as they tend to be disposed of after single use, the fibers are bonded in such a way that they cannot withstand much strength. In both melt-blown and spun-bonded fabric, the fibers were randomly bonded throughout the structure. The physical, as well as chemical changes in the structure of these non-woven layers when exposed to different environments, causes the release of microfibers from the structure. Figure 4 illustrates the structure and composition along with the microfiber release potential of different layers of disposable masks.

Risks with reusable masks

With the increased demand for face masks due to the rapid spread of the infection, the habit of reusing the masks has been increased. Though different methods of disinfection process are being adapted, simple washing, washing with detergents, disinfection with UV exposure, disinfection with air blower, disinfection with alcohol, disinfection with sunlight are the common methods (Li et al. 2021; Shen et al. 2021). These methods of disinfection can have a significant impact on microfiber emissions. Researchers have quantified the microfiber release from the masks treated with alcohol and detergent solutions. The results reported that the used mask releases significantly more microfibers irrespective of the method of disinfection. While considering the method of disinfection, simple washing with ultrapure water was noted to release lesser fibers which is then followed by disinfection with alcohol and the use of detergents. The use of detergent can cause more fiber fracture as well as dissolution of nodes in the non-woven structure which results in loss of fiber bondage and enhances more fiber release (Shen et al. 2021). Similarly, the other researcher analyzed the microfiber inhalation risks of different types of masks after the disinfection process. They have been exposed to UV irradiation, alcohol disinfection, air blower disinfection, washing in running water, sunlight disinfection processes. The results reported that these disinfection processes increase the risk of inhalation of microfibers while wearing. Alcohol disinfection technique showed a higher level of microfibers for all the types of masks (N95 respirator, surgical mask, cotton masks, fashion masks, non-woven masks, activated carbon masks). They have also reported that alcohol damages the structure of the mask which facilitates the fiber release. Since simple washing in running water showed lesser fiber release, researchers suggested following the practice of simple washing and gentle indoor drying to reduce the risk of inhalation of microfibers (Li et al. 2021). Moreover, while considering cloth masks, the most common habit will be simple washing. In such cases, the release of microfibers is obvious as like the microfiber shedding from synthetic textiles during washing. Besides the release of microfibers during washing, it also weakens the fabrics that lead to rapid disposal and also increased microfiber release in the disposal stage. This shows that the reusable masks need to be evaluated for microfiber release during
| S.No | References       | Scope of the study                                                                 | Method adopted                                                                 | Key findings on environmental impact                                                                 | Research gap identified                                                                 |
|------|------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
|      |                  |                                                                                     |                                                                                 |                                                                                                       |                                                                                        |
|      |                  | **Mismanagement of Wastes**                                                        |                                                                                 |                                                                                                       |                                                                                        |
| 1    | Ouhsine et al. (2020) | To analyze the influence of COVID-19 on household waste and its management          | The survey has been conducted by interviewing the residents of the study area (Khenifra – urban; Tighassaline – Rural) | 87%—mix COVID related PPEs in the household waste 9%—dispose of used masks randomly in public spaces 4%—respondents put COVID related wastes in special bags to dispose separately |                                                                                       |
|      |                  |                                                                                     |                                                                                 |                                                                                                       |                                                                                        |
|      |                  | **Microfiber release**                                                              |                                                                                 |                                                                                                       |                                                                                        |
| 2    | Briain et al. (2021) | To track the source of microfibers along with the marine sediments near WWTP       | Marine sediments and sewage-related wastes were sampled                         | The analysis of microfibers found in the sample sites revealed that they are similar to the fibers that are used in the sanitary towels and wipes which are often flushed in toilets | Particles < 500 µm were not included  The microfiber release behavior of the products was not analyzed |
| 3    | Chen et al. (2021)  | To quantify the release of microfiber emission from new and used masks             | Replication of used masks was made by wearing the mask for one day             | 183.00 ± 78.42 particles/new mask 1246.62 ± 403.5 particles/used mask                                |                                                                                       |
|      |                  |                                                                                     | Masks were immersed in deionized water for 24 h under 120 rpm agitation       | PET and polypropylene are the dominant fibers Most of the fibers are transparent and blue in color      |                                                                                       |
| 4    | Lee et al. (2021)  | To investigate the release of microfibers from wipes under different conditions    | The dry state and wet state of wet wipes were considered                       | Wet wipes immersed in water – 210 ± 57 particles/25 sq. cm Dried wipes immersed in water – 74 ± 20 particles/25 sq. cm Wet wipes while cleaning – 22 ± 1 particles/25 sq. cm Dried wipes while cleaning – 54 ± 15 particles/25 sq. cm | In wet state, the simple immersion can’t replicate the real-time as there will be mechanical actions when the wipes end up in an aquatic environment |
| 5    | Morgana et al. (2021) | To examine the release of micro and sub-micro fibers from the masks that end up in the aquatic environment | Masks were subjected to shear forces by varying energy densities and time The experiments were done with MilliQ water | 2.1 ± 1.4 × 10^{10} microparticles/mask (Sizes are mostly in the range of 0.1–0.5 µm and < 0.1 µm) | Though the shear forces replicated the real-time physical actions MilliQ water could not replicate the actual composition of the sea and freshwater |
| S.No | References | Scope of the study | Method adopted | Key findings on environmental impact | Research gap identified |
|------|------------|--------------------|----------------|--------------------------------------|-------------------------|
| 6    | Shen et al. (2021) | To examine the release of microfibers from the new mask and naturally weathered mask | Microfiber release of an individual layer of the mask was examined in water, alcohol, and detergent mediums | 3600 particles/mask in the water | As the disposable masks are washed rarely, the relevance of the results with real-time scenarios is less |
|      |            |                    | The masks were agitated under the medium for 24 h at 120 rpm | 5400 particles/mask in detergent solution | The chances for microfiber release into the environment while exposing to natural weathering were not considered and the quantification has not been made on that |
|      |            |                    | Masks were exposed to natural weathering for 2 months in the terrace of the laboratory | 4400 particles/mask in alcohol solution | |
|      |            |                    | 25,000 times increment in the particles when the masks are exposed to natural weathering | 5400 particles/mask in detergent solution | |
| 7    | Wang et al. (2021) | To examine the release of microfibers from different layers of the disposable masks | Masks were exposed to UV irradiation for different periods of time | 1.5 million fibers/mask in the aquatic environment | Researchers used deionized water over normal or seawater |
|      |            |                    | Masks were agitated at 300 rpm in deionized water for 24 h in the presence and absence of sand | 16 million fibers/mask in the aquatic environment along with physical abrasion due to the presence of sand | The particle size distribution (PSD) was analyzed using a laser in-situ scattering and transmissometry analyzer with a detection range of 1 - 500 µm |
|      |            |                    | The middle layer shed higher number of fibers than the other two layers | | The data repeatability and accuracy not reported |
| 8    | Sailu et al. (2021) | To examine the microfiber release potential of disposable masks under UV irradiation and Seawater | Masks are exposed to UV radiation and agitated under artificial seawater | The experimental aging was similar to the masks end up on beaches | The masks were examined as a whole; however, the microfiber release of individual layers was not examined |
|      |            |                    | The experimentally aged masks were compared with actually disposed masks end up on the beach sides | A single mask can produce up to 173,000 fibers/day | Artificial seawater was used for analysis |
|      |            | Impacts of PPE items | Sorption of dyes was examined under different dye concentrations, temperature, and contact time | Masks can act as good carriers of Malachite Green, Crystal violet, and a lesser extent of Methylene Blue in the aquatic environment | The sorption of dyes was only analyzed; however, the sorption of other types of pollutants in different matrices should be explored |
|      | Anastopoulos and Pashalidis (2021) | | Carbonization of masks was done at 500ºC for 1 h under nitrogen atmosphere | Carbonized masks also showed a higher affinity toward these dyes | |
| S.No | References               | Scope of the study                                                                 | Method adopted                                                                                                           | Key findings on environmental impact                                      | Research gap identified                  |
|------|--------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------|
| 10   | Kwak et al. (2021)       | To examine the release of nanofibers from a melt-blown layer of face masks and their effect on soil species | Microfiber fragments were prepared by cutting masks and sieving. Contaminated soil was prepared by mixing 100 mg of microfibers in a kilogram of dry soil. | Inhibited reproduction and stunted growth in springtails. Decreased intracellular esterase activity in earthworm. | –                                        |
| 11   | Li et al., (2021)         | To examine the potential risk of inhalation of microfiber particles due to the wearing of a mask | Microfiber release was examined by artificial breathing simulation. A vacuum pump of 15L/min flow rate was attached to a suction cup. The microfibers ejected onto the suction cup were taken for analysis. | Wearing N95 masks reduces the exposure to micro-particles compared to not wearing a mask. The use of surgical, cotton, fashion, and activated carbon masks pose a higher fiber-like microplastic inhalation risk. The disinfection process increases the microfiber release. | –                                        |

**Mitigation Strategies**

| 12   | Aragaw and Mekkonnen, (2021) | To analyze the potential of face mask to be converted into fuel | FTIR and Thermogravimetric analysis were done for the characterization of masks and gloves. Pyrolysis was taken place at 350—500 °C for two hours | Polypropylene and PVC thermoplastic was noted to get converted into fuel energy through pyrolysis. Because of high oil content, these wastes can be converted into oil. | High energy consuming process. Limitations in commercialisation. Compared to the mass of masks disposed of per day around the world, a better method of recycling is necessary to handle the problem. |
machine laundering as well as hand laundering. Moreover, their microfiber release after disposal (after multiple washes) should also be measured (Shruti et al. 2020).

Researchers have reported microfiber release from the mask during different stages. Microfiber release was noted with new masks, re-used masks, disposed masks (Chen et al. 2021; Li et al. 2021; Shen et al. 2021; Wang et al. 2021; Saliu et al. 2021). The release of microfibers from the new and re-used masks has increased the possibility of microfibers directly reach human beings through inhalation (Li et al. 2021). The effect of these microfibers on human beings was not analyzed systematically. However, another team of researchers analyzed the release of microfibers from the melt-blown layer of the masks and reported their effect on soil species. They have noticed inhibition of reproduction and stunted growth in springtails whereas earthworms were noted with decreased intracellular esterase activity (Kwak and An 2021). Figure 5 illustrates the various pathways a PPE or mask can take to pollute the different environments.

Besides microplastic particles, researchers have reported the leaching of other chemical pollutants. Sullivan et al. (2021) studied the organic and inorganic materials from disposable surgical masks. Seven different brands of masks were reported to leach micro- and nano-level polymeric particles including fibers along with leachable inorganic and organic chemicals. Researchers reported lead, cadmium, antimony, and copper in the leachates of masks (Sullivan et al., 2021). When the sorption characteristics of disposable surgical masks were studied against the dye molecules, it was noted that the surgical masks are capable of carrying dye molecules including Methylene Blue, Crystal Violet, and Malachite Green in the aquatic environment (Anastopoulos and Pashalidis 2021). This pollutant carrying characteristic will be more harmful in micro-size where the surface to volume ratio is higher. Table 1 consolidates the existing literature’s method of analysis, with identified shortcomings at COVID-waste, microfiber release, environmental impacts and mitigation stages.

**Proposed mitigation strategies**

Being an environmental threatening issue, the microfiber pollution associated with disposable masks should be addressed properly and tackled. From the analysis of the literature, the review result suggests the scope of mitigation strategies in the following aspects:

- As the researchers have reported different quantities of microfiber release from different types of masks (Li et al. 2021) as well as the different layers of masks (Shen et al. 2021; Wang et al. 2021), it is clear that the characteristics of masks influence the microfiber release. Hence, the effect of inherent textile properties of the non-woven (fiber type, weight per unit area, thickness, etc.) and production properties (manufacturing method) on the microfiber release should be analyzed. The optimization of the manufacturing parameters of the masks can reduce the microfiber release.
• Studies have reported that the microfiber release from the masks get increased when they are exposed to natural weathering (Shen et al. 2021), seawater (Sailu et al. 2021), water currents (Morgana et al. 2021), and other environmental conditions. Hence, the proper waste management system should be developed which can potentially restrict the masks to end up in such an environment. Consumers should be educated about the safe disposal of these single-use surgical masks.

• Though the proper disposal method can effectively reduce the microfiber release into the environment, the cycle can be completed only if the wastes are reprocessed effectively (Circular economy). In this aspect, either higher quality raw materials should be used or options for recycling of non-woven fabrics that are being used in the masks should be explored. Recently, Aragaw and Mekonnen (2021) have reported the potential of these masks to be converted into oil. Their thermoplastic behavior supports the conversion through the pyrolysis process. However, a more effective and simplest way of recycling these non-woven wastes should be developed as the quantity of waste is very high and they should be processed economically.

• In addition to this, to properly manage this risk of higher usage of PPEs as a whole, the implementation of an Environmental Management Plan (EMP) will be thoughtful. While bringing down the usage of masks and PPEs is a solution to control the spread of the disease, there should be proper EMP that can reduce or mitigate the adverse impact on the environment. However, implementing such strategies on a large scale (either nationwide or state-wide) has its disadvantages including implementation difficulties and associated costs. Knowledge of all the stakeholders (manufacturer, general public, and governments) associated with the usage and production of PPEs is the key factor for such initiatives. The general public should be sensitized about the PPEs and microfiber pollution associated with it as equally as the importance of PPEs usage in the pandemic. A proper and separate waste management system for the safer disposal of these PPEs is the need of the hour requirement.

• Implementation of laws related to the environmental impacts of such disposable items is another important way to regulate the manufacturers, retailers, and users. Similar initiatives were already implemented in various countries in controlling the microfiber shedding from the apparel fabrics with synthetic textiles (New York Assembly Bill A01549, 2018). Whereas, a law implemented in the California state is mandated the use of microfiber filtering systems in all synthetic textile manufacturing industries, associated laundry, and effluent treatment facilities (AB 129 2019). Though no common laws were made in Europe, several nations in Europe implemented their own regulations to restrict microfiber pollution from textiles (Report to the Legislature on the Findings of the Synthetic Microfiber Working Group 2019). However, no such regulation was found on disposable PPEs. These types of initiatives should be taken either worldwide or nationwide by considering COVID-19 related disposable PPEs.

Research gap in microfiber release from PPEs

From the literature, it is evident that the PPEs and masks that are being widely used for the protection against virus transmission also have negative impacts on the environment. Researchers have reported PPE littering in beaches and oceans. Moreover, these materials are the potential source of microplastics in the environment. While the researchers are focusing on macro plastic pollution associated with the PPEs, only a few research works addressed microplastic pollution.

Researchers have reported microfiber release in the aquatic environment by exposing them to distilled water, detergent solution, seawater, and UV exposure (Sailu et al. 2021; Wang et al. 2021; Shen et al. 2021) and quantified the microfiber release. However, the microfiber release in the dry state, that is, during wearing or from the masks that are ended up in landfills were not explored. Though researchers reported mechanical deformation during the wearing phase of the masks (Chen et al. 2021), the microfiber release during the usage phase was not detailed. With the threatening of microfiber inhalation by the wearer (Li et al. 2021), the microfiber release of different layers of the masks in a dry state during wearing has to be investigated. Most of the studies addressed the microfiber release of single-use disposable masks whereas in the case of reusable masks, the effect of disinfectant processes on microfiber release was analyzed (Li et al. 2021; Shen et al. 2021). However, the reusable masks in the market are made from different materials with 6 to 7 layers. Hence, the microfiber release of different layers of reusable masks due to the disinfectant process should be detailed. The microfiber release of cloth masks during laundry has to be given more importance because domestic laundry of textile materials was noted as
the important source of microfiber pollution (Browne et al. 2011; Napper and Thompson 2016). Researchers reported that the disinfectant process can affect the microfiber release behavior of masks; however, the microfiber release during the process of disinfection is not taken into account. As far as disposal is concerned, disposable and reusable masks need to be tested for their microfiber release in soil, normal water (river currents), and also in the seawater condition, as most of the mismanaged PPE ends up in the aquatic system. The analysis of microfiber release from the masks has to be made in these aspects also to get an insight on the microfiber emission behavior of masks. Though masks were identified as the most commonly used PPEs, others like gloves, head covers, and gowns, are also being used widely. Hence, the exploration of microfiber release from these products should not be exempted.

**Conclusion**

The increased awareness on COVID-19 related safety measures significantly increased the usage and disposal of PPEs which includes face masks, gloves, and others. This study shows a significant increase in the littering of these PPEs on seashores and landfill in post-pandemic. It is also very clear that the awareness on safe disposal of these products and proper waste management system is lacking among the public. The initial research on the microplastic issue associated with these disposable PPEs has already begun; however, very few studies alone reported the magnitude of the issue. This review elucidates the research gap in the area of microfiber pollution associated with the PPEs. Considering the number of PPE and masks (reusable or disposable) used per day during this pandemic, the impact of the usage will result in a huge deposit of microfibers and microplastics in the land and aquatic system. This study points to the necessity of future research in this domain. Focused research on the impact of disposable, reusable masks, microfiber release behavior of masks in different lifecycle stages, and more attention should also be paid to PPEs other than masks. The implementation of nationwide or state-wide environmental management plans will be a potential option to create awareness among the public and to have effective waste management.

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**Declarations**

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