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## Review

## Personal protective equipment (PPE) disposal during COVID-19: An emerging source of microplastic and microfiber pollution in the environment



Muhammad Tariq Khan <sup>a,1</sup>, Izaz Ali Shah <sup>b,1</sup>, Md Faysal Hossain <sup>a,c</sup>, Nasrin Akther <sup>c,d</sup>, Yanbo Zhou <sup>c</sup>, Muhammad Sajawal Khan <sup>e</sup>, Muayad Al-shaeli <sup>f</sup>, Muhammad Suleman Bacha <sup>g</sup>, Ihsanullah Ihsanullah <sup>h,\*</sup>

<sup>a</sup> Department of Science and Environmental Studies, The Education University of Hong Kong, Tai po New Territories, Hong Kong

<sup>b</sup> State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, No. 19, Xijiekouwai Street, Beijing 100875, China

<sup>c</sup> State Environmental Protection Key Laboratory of Environmental Risk Assessment and Control on Chemical Process, East China University of Science and Technology, No. 130, Meilong Road, Shanghai 200237, China

<sup>d</sup> Department of Soil Science, University of Chittagong, Chittagong 4331, Bangladesh

<sup>e</sup> Department of Environmental and conservation science, University of Swat, Pakistan

<sup>f</sup> Institute for Micro Process Engineering (IMVT), Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

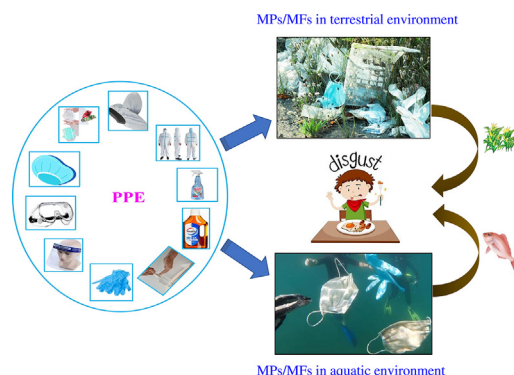
<sup>g</sup> Department of Environmental Science, University of Peshawar, Pakistan

<sup>h</sup> Center for Environment and Water, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

## HIGHLIGHTS

- The impacts of PPE-generated MPs and MFs on human health and the environment are critically reviewed.
- Manufacturing and consumption of PPE have surged since the emergence of COVID-19.
- Weathering of PPE leads to microplastic pollution in the environment.
- The environmental footprint of PPE is assessed and presented.
- Post-COVID-19 demands a paradigm shift in MP prevention and management measures.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Waste generated by healthcare facilities during the COVID-19 pandemic has become a new source of pollution, particularly with the widespread use of single-use personal protective equipment (PPE). Releasing microplastics (MPs) and microfibers (MFs) from discarded PPE becomes an emerging threat to environmental sustainability. MPs/MFs have recently been reported in a variety of aquatic and terrestrial ecosystems, including water, deep-sea sediments, air, and soil. As COVID-19 spreads, the use of plastic-made PPE in healthcare facilities has increased significantly worldwide, resulting in massive amounts of plastic waste entering the terrestrial and marine environments. High loads of MPs/MFs emitted into the environment due to excessive PPE consumption are easily consumed by aquatic organisms, disrupting the food chain, and potentially causing chronic health problems in humans. Thus, proper management of PPE waste is critical for ensuring a post-COVID sustainable environment, which has recently attracted the attention of the scientific community. The current study aims to review the global consumption and sustainable management of discarded PPE

\* Corresponding author.

E-mail addresses: [enr.ihsan.dir@gmail.com](mailto:enr.ihsan.dir@gmail.com) [ihsankhan@kfupm.edu.sa](mailto:ihsankhan@kfupm.edu.sa) (I. Ihsanullah).

<sup>1</sup> M.T.Khan & I.A.Shah equally contributed to this work

in the context of COVID-19. The severe impacts of PPE-emitted MPs/MFs on human health and other environmental segments are briefly addressed. Despite extensive research progress in the area, many questions about MP/MF contamination in the context of COVID-19 remain unanswered. Therefore, in response to the post-COVID environmental remediation concerns, future research directions and recommendations are highlighted considering the current MP/MF research progress from COVID-related PPE waste.

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**1. Introduction**

In December 2019, the COVID-19 pandemic first appeared at the Hunan seafood market in Wuhan, China (Rowan and Laffey, 2021). The infection caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been declared a global public health emergency by the World Health Organization (WHO) (Acter et al., 2020; Sohrabi et al., 2020). After the disease's emergence, it quickly spread to other countries and eventually posed a health risk to the general population worldwide (Rupani et al., 2020; Wu et al., 2020; Zhou et al., 2020). Fig. 1 represents the development of the COVID-19 pandemic over time. It can be observed that the first case was detected in China, and the virus quickly spread and led to a global pandemic, affecting all people and healthcare workers around the world.

The infection was initially assumed to be caused by animal-to-human transmission with no animal-species association (Rahman et al., 2020). Succeeding research confirmed that human-to-human transmission had been the standard mode of viral spread given the high number of patients who did not have a history of market exposure (Guo et al., 2020a). Currently, the most common significant infection routes are direct human-to-human contact, airborne respiratory droplets, contact with contaminated surfaces, and fecal-oral transmission (Dietz et al., 2020; Heller et al., 2020; Ihsanullah et al., 2021; Kitajima et al., 2020). COVID-19 variants

eventually exacerbated the transmission, resulting in a global pandemic. A number of COVID-19 variants have been reported in several countries, including the United Kingdom (variant 20I/501Y-V1, lineage B.1.1.7), South Africa (variant 20H/501Y-V2, lineage B.1.351), Botswana and South Africa (Omicron: B.1.1.529) (Gu et al., 2022), and Brazil (variant 20 J/501Y-V3, lineage P.1) (Jia and Gong, 2021). As the mutations continue to impact viral fitness and transmissibility, it is critical to study the transmission and management of COVID-19 variants comprehensively.

Due to treatment challenges and a lack of vaccines coverage, national and international authorities, including government agencies, health professionals, and scientific communities, have adopted several strategies to prevent infection transmission, such as lockdown, handwashing, wearing PPE (e.g., hand gloves, face masks, face shields, etc.), using antiseptic solutions, and implementing proper social distancing (Cook, 2020; Qian and Jiang, 2022; Sajed and Amgain, 2020; Silva et al., 2020). Significant changes have been adapted to lifestyles that are becoming the new norm in people's lives (Islam et al., 2021; Parashar and Hait, 2021). Handwashing with soap and the use of PPE to prevent and control infectious diseases have the advantages of being low-cost and simple to implement. They were proved to be effective in preventing the spread of the virus (Brauer et al., 2020; Labrague et al., 2018). However, the increased consumption of PPE during the COVID-19 pandemic has now posed a new challenge to both

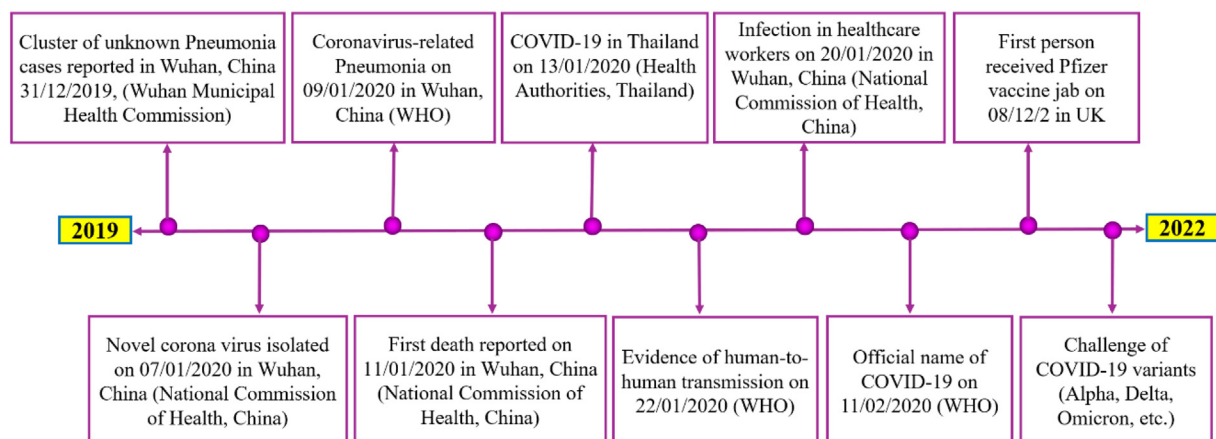


Fig. 1. The development of COVID-19 over time.

aquatic and terrestrial environments in the form of MP and MF contamination (Ardusso et al., 2021; Prata et al., 2020; Silva et al., 2021). It is estimated that >5 trillion plastic particles floating in the world's oceans (Eriksen et al., 2014), while 1.2–2.4 million tons of plastic waste are carried by rivers annually (Lebreton et al., 2017; Prata et al., 2020). Recently, face masks have been found in aquatic environments (Stokes, 2020), which possess severe potential environmental threats. It has been reported that >10 million face masks are released monthly into the environment due to improper disposal practices (Adyel, 2020). With an estimated weight of 3–4 g for each mask, the approximate total is 30,000–40,000 kg of environmental litter (Fadare and Okoffo, 2020; Silva et al., 2021). Huge quantities of plastic discharged into the environment have worsened global MP/MF pollution.

COVID-19 has put a lot of pressure on the existing waste management system through overconsumption, enormous production, and improper disposal of PPE (Rhee, 2020; Saadat et al., 2020; Vanapalli et al., 2021). The extensive consumption of PPE shifts these consumables as the primary source of MP/MF contamination in aquatic and terrestrial ecosystems due to the lack of sustainable management. For instance, healthcare waste generated from medical facilities in Wuhan has surged four-fold during the COVID-19 pandemic, and mobile incinerators were installed as an alternate treatment option. Similarly, in the United Kingdom, permission was granted to municipal authorities to use incinerators to treat healthcare waste generated by COVID-19 facilities (Fletcher, 2020; Zhang et al., 2021). Thus, COVID-19 can be considered a holistic risk to the environment and public health, as well as to global economic and societal institutions and plastic waste management (Silva et al., 2020).

Plastic waste has become a serious transboundary issue to the environment and human health, with predictions of a two-fold surge in the plastic litter (including MPs and MFs) by the year 2030. PPE-derived MPs/MFs have the potential to contaminate the food chain, causing starvation and alterations in the reproductive system of aquatic organisms (Anik et al., 2021; Khan et al., 2020). These pollutants can also cause damage by disrupting metabolic and reproductive activities, reducing immunological response, oxidative stress, cellular or subcellular toxicity, inflammation, and cancer (Prata, 2018; Smith et al., 2018). Aquatic organisms swallow and become entangled in MPs/MFs because of their small size, leaving them more vulnerable to suffocation, starvation, physical trauma, or chemical damage, posing growing threats to the food chain (Franzellitti et al., 2019). MPs can also act as vectors for hydrophobic persistent organic pollutants (POPs), which can have a synergistic effect on the environment (Gallo et al., 2018). Recently MPs have been detected in human blood (Leslie et al., 2022), cirrhotic liver tissue (Horvatits et al., 2022), deep lung tissues (Jenner et al., 2022) and placentas (Ragusa et al., 2021). Although preliminary research indicates that MPs enter human bodies via several routes, the specific impact of these contaminants on human health requires further exploration.

The issue of MP/MF pollution caused by PPE is relevant, but it has not been thoroughly investigated in the literature. Consequently, this study aims to provide a comprehensive overview of the impacts of COVID-19 on MP/MF contamination and its potential consequences on human health and the aquatic environment. The significant challenges and potential solutions associated with PPE-generated MP/MF pollution are summarized. The paper also discussed how the COVID-19 pandemic will worsen plastic pollution in the coming years, causing more harm to the aquatic and terrestrial environment and waste management systems. Future research directions are also highlighted in light of the sustainable management of PPE waste and the control of MP/MF contamination in the environment.

## 2. Major types of MPs/MFs in PPE

Most MPs/MFs released from PPE are polymers released from surgical masks including polypropylene (PP) and polystyrene (PS). Similarly, polyvinyl chloride (PVC) is released from commonly used gloves. Other MPs/MFs released from the different kinds of PPE are polycarbonate (PC), high-density polyethylene (HDPE), polyethylene terephthalate (PET), and

low-density polyethylene (LDPE). HDPE and PET are the most often recycled plastics, while LDPE, PVC, PP, PS, and PC are rarely recycled (Klemeš et al., 2020). Table 1 presents the potential common MP/MF polymers released from different PPE products.

Plastic waste generated from COVID-19 healthcare facilities contributes to MP/MF contamination. Single-use PPE have been found in the environment and they are fragmented by physicochemical (wind, UV radiation, and current) and biochemical processes (enzymatic activity) (Fadare and Okoffo, 2020; Prata et al., 2020), resulting in a slew of microscopic particles, such as MPs/MFs and nanoplastics (NPs) with sizes of <5 mm and <1 μm, respectively (Frias and Nash, 2019). Plastic waste carried by rivers, streams, wind, and air currents may spread across the globe (Liubartseva et al., 2016), where wind, sunlight, and other mechanical forces play a significant role in forming MPs/MFs through weathering and fragmentation (Lebreton et al., 2017). As MPs/MFs are non-biodegradable in nature, they will exist in aquatic and terrestrial environments for an extended duration and will affect different biota, compartments, and biological systems (Prata et al., 2020). Without proper management, the unprecedented consumption of PPE and other packaging materials due to COVID-19 is expected to worsen, potentially resulting in a global plastic disaster (Fadare and Okoffo, 2020; Hale and Song, 2020). Improper plastic management poses a risk of virus transmission, and it contaminates aquatic and terrestrial ecosystems (Mol and Caldas, 2020).

## 3. Global demand for PPE by healthcare facilities and households during COVID-19








As shown in Fig. S1, the ongoing COVID-19 pandemic has led to an unprecedented international demand for healthcare safety and prevention products (Park et al., 2019), suggesting a significant increase in the manufacturing and distribution of PPE. Interestingly, numerous bans also constrain the market, including laws on exporting and transporting raw materials required in PPE manufacturing.

A rapid increase has been reported in the production and consumption of PPE and personal care products (PCPs) as shown in Fig. 2a and b. PPE demand is expected to remain high in future. The annual increase in the production of disposable face masks is expected to be 20 % between 2020 and 2025 (Singh et al., 2020). The current trend indicates that the estimated monthly use of gloves and face masks to protect all the healthcare workers and people in the world is about 129 and 67 billion, respectively (Silva et al., 2020). WHO estimates that 1.6 million medical goggles, 76 million hand gloves, and 89 million medical masks are needed monthly to respond to the COVID-19 crisis (Park et al., 2019). Raw material shortages have further increased the pressure and the demand on supply chains, particularly for surgical masks, N95 masks, and medical gowns, which are in high need to protect frontline healthcare professionals (UNICEF, 2020). The PPE market was valued at US\$15.32 billion in 2020, and it is expected to grow to US\$33.07 billion by the year 2026. Gloves accounted for 25 % of the sales revenue, followed by (22 %) for coveralls or suits. Face masks and surgical caps ranked third by region in 2018, with the US having the largest market share (33 %), followed by 28 % for Asia and 14 % for the Pacific and Europe (Park et al., 2019). The market of the disposable face mask was projected to increase from \$800 million in 2019 to \$166 billion in 2020 (UNCTAD, 2020).

In addition, China is the largest manufacturer of PPE products, accounting for about 50 % of the global surgical mask production (i.e., 20 million masks daily, pre-pandemic). Taiwan (as an official part of China) accounts for 20 % of the international supply of face masks, while other countries with PPE manufacturing capacity include Korea, Japan, Mexico, India, Malaysia, Thailand, the U.S., and several other European countries. China has reportedly increased the production of masks more than five-fold in 2020, providing a production capacity of 110 million units per day, and the volume has likely increased production capacity further since then (UNICEF, 2020). However, a notable disparity exists between the volumes forecasted by country demand in the coming months and the products in the pipeline. According to the consolidated UN Inter-Agency Demand

**Table 1**

Common MP/MF polymers released from different PPE products (Alabi et al., 2019; Corrêa and Corrêa, 2020; Haque and Fan, 2022).

| MP/MF polymers                   | Symbol  | Chemical formula  | Properties  | PPE products  |
|----------------------------------|---|---|---|---|
| Polyethylene terephthalate (PET) |  | (C <sub>10</sub> H <sub>8</sub> O <sub>4</sub> ) <sub>n</sub> | Density (between 1.29 and 1.4 g/cm <sup>3</sup> ), colorless, semi-crystalline and hygroscopic, softens at 80 °C, barrier to gas and moisture, solvent resistant, | Hand sanitizer bottles and caps, face masks, and face shields.  |
| High-density polyethylene (HDPE) |  | (C <sub>2</sub> H <sub>4</sub> ) <sub>n</sub>                 | Density (between 0.94 and 0.97 g/cm <sup>3</sup> ), resistant to chemicals and moisture, high strength-to-density ratio, softens at 75 °C.                        | Hand sanitizer bottles, and PPE packaging materials.  |
| Polyvinyl chloride (PVC)         |  | (C <sub>2</sub> H <sub>3</sub> Cl) <sub>n</sub>               | Density (between 1.1 and 1.45 g/cm <sup>3</sup> ), strong, transparent and hard, softens at 80 °C.  | Hand gloves, transparent face shield, transparent indoor shield, protective shields in public transport and shoe cover. |
| Low-density polyethylene (LDPE)  |  | (C <sub>2</sub> H <sub>4</sub> ) <sub>n</sub>                 | Density (between 0.89 and 0.94 g/cm <sup>3</sup> ), softens at 70 °C, scratches easily, produce greenhouse gas when exposed to consistent sunlight.               | Plastic wraps, paper towels and hand sanitizer bottles.   |
| Polypropylene (PP)               |  | (C <sub>3</sub> H <sub>6</sub> ) <sub>n</sub>                 | Density (between 0.895 and 0.92 g/cm <sup>3</sup> ), softens at 140 °C, translucent, high chemical resistance.  | Face mask, surgical mask, surgical cap, gown, hand sanitizer bottles and caps   |
| Polystyrene (PS)                 |  | (C <sub>8</sub> H <sub>8</sub> ) <sub>n</sub>                 | Density (between 0.96 and 1.05 g/cm <sup>3</sup> ), clear, glassy rigid, softens at 95 °C, insoluble in water.  | Surgical mask, packaging materials, surgical gown, apron and shoe cover   |
| Polycarbonate (PC)               |  | C <sub>15</sub> H <sub>16</sub> O <sub>2</sub>                | Density (between 1.20 and 1.22 g/cm <sup>3</sup> ), transparent, low scratch-resistance, softens gradually above about 155 °C.                                    | Face masks and face shields   |

Forecast for PPE (UNICEF, 2020), the remainder of 2020 will need 1.1 billion hand gloves, 13 million goggles, 8.8 million face shields and 2.2 billion surgical masks; overseas manufacturing accounts for 95 % of surgical masks and 70 % of respirators sold in the U.S. (Park et al., 2019). According to COVID-19 data, 72,000 PPE items are consumed daily at four trust hospitals in England, including 1501 gowns, 11,495 gloves, 39,500 face masks, 4201 respirator masks, and eye protectors (Way, 2020). Around 226 trust facilities operate in the U.K., implying the consumption of millions of PPE. Fig. 2a and b provides additional details on the increasing trend of PPE and PCPs consumption following the emergence of the COVID-19 pandemic.

Furthermore, there is not enough being done to treat plastic waste to meet the rising demand for plastic commodities. Not all used PPE, packaging materials and waste produced during mass vaccination are handled or recycled, which makes it difficult for pandemic epicenters to treat the trash. After being released into the environment, some of this poorly managed plastic waste makes it to the ocean (Peng et al., 2021). This global health crisis puts additional strain on traditional waste management practices such as local burnings, direct landfills, and mobile incineration, all of which are ineffective in the sustainable management of PPE (Silva et al., 2020).

#### 4. Sources and impacts of PPE on the environment

Healthcare professionals and sanitary workers need PPE for health safety and infection control in healthcare structures. Consequently, high demands for PPE, particularly masks, gloves, and gowns, have increased more than ten-fold in 2020 (Adyel, 2020). The extensive use of PPE during the pandemic has overwhelmed the existing waste management infrastructures. Available incinerators operate beyond their capacity, further increasing the use of landfills amid the improper management of PPE waste (Fletcher, 2020; Vanapalli et al., 2021). As the disposal service lacks proper infrastructures and waste management systems, the used PPE infiltrates aquatic and terrestrial environments as shown in Fig. 3 (Canning-Clode et al., 2020). MPs/MFs have been found in various environmental components as shown in Fig. 4, including planktons (Lin, 2016), wastewater (Khan et al., 2020), sea sediments (Barrett et al., 2020), soil (Boots et al., 2019), compost (Gui et al., 2021), salt (Yang et al., 2015), fish (Pozo et al., 2019) and human tissues (Jenner et al., 2022). Consequently, MPs/MFs from PPE reach different organisms depending on their nature and characteristics. PPEs are synthetic and non-biodegradable polymers (Fadare and Okoffo, 2020). The breakdown and weathering of PPE produce MPs/MFs before penetrating terrestrial and aquatic environments.

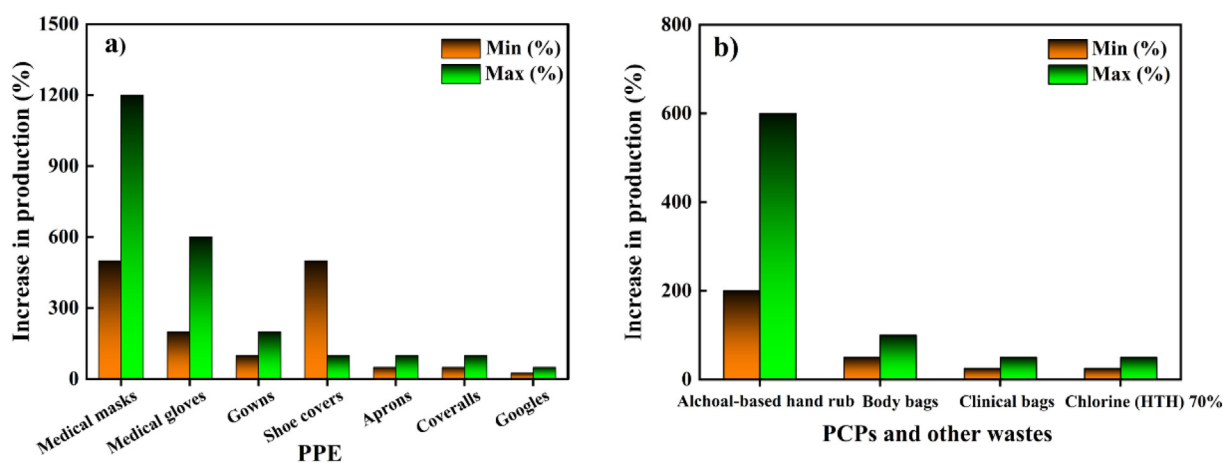


Fig. 2. Estimated peak increases in global production of (a) PPE and (b) PCPs during the COVID-19 crisis, % increase as of December 2020 (FCDO, 2020).

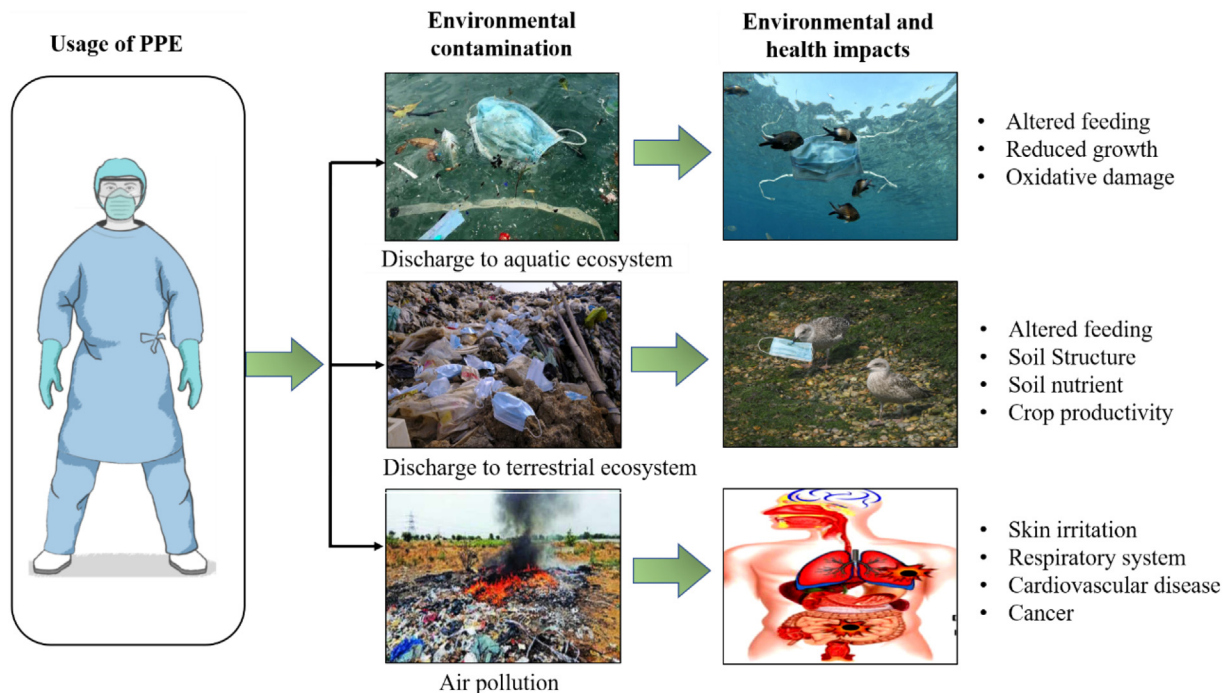


Fig. 3. PPE as a potential source of MP/MF contamination.

Plastic polymers can be negatively, positively, or neutrally buoyant in water systems. Polyvinyl alcohol (PVA), polyester (PEST), and PVC are high-density polymers that sink and ends up in seabed sediments. In contrast to high-density polymers, low-density polymers such as expanded polystyrene (EPS), PE, and PP with densities of 1.03 g/cc float in seawater (De-la-Torre and Aragaw, 2021). However, the materials used to manufacture PPE differ depending on the company and brand. The majority of three-ply surgical masks are composed of PP (0.90–0.91 g/cc), while others

may comprise PE (0.92–0.97 g/cc), PC (1.20–1.22 g/cc), PEST (1.24–2.3 g/cc), and PS (1.04–1.1 g/cc) (Chua et al., 2020; Hidalgo-Ruz et al., 2012; Shim et al., 2018). Commercially, nitrile gloves, latex, and PVC (1.16–1.58 g/cc) are the most widely available PPE. Face shields can also be manufactured from various materials, such as PET glycol, acetate, PVC and PC (Roberge, 2016). The different manufacturing materials and the non-degradability and environmental persistence of PPE imply that these wastes are varied based on their features. Some PPE can persist in the

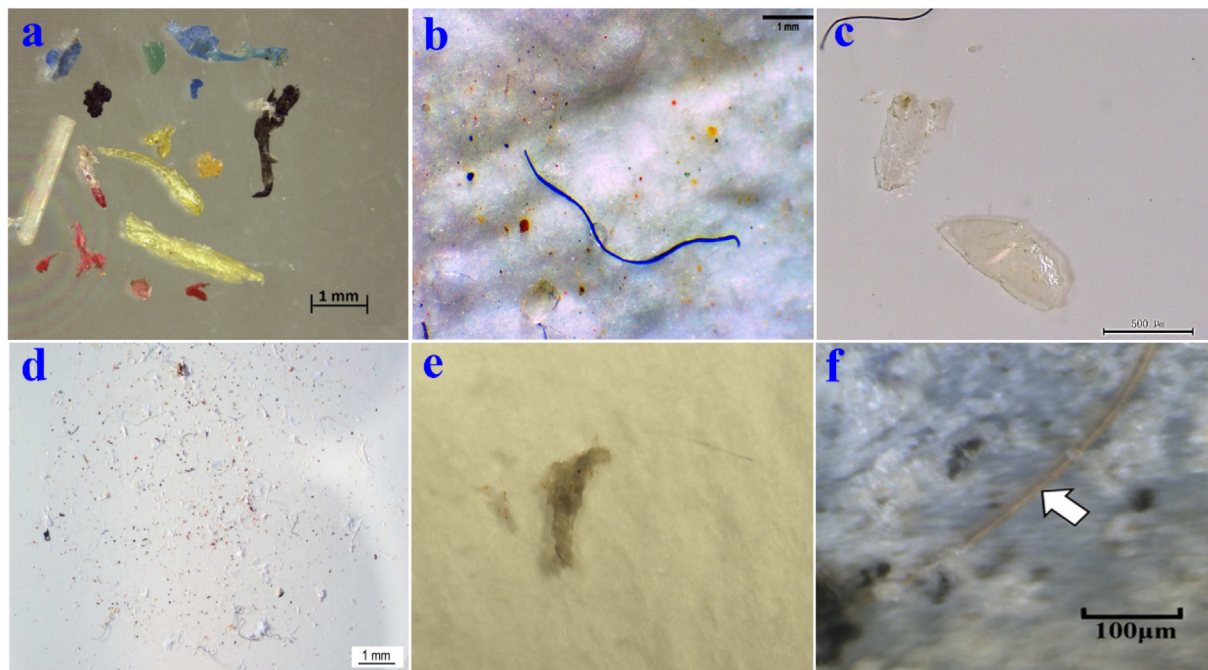


Fig. 4. MFs/MPs detected in different environmental matrices (a) wastewater treatment plant, (b) sea salt sample, (c) marine biota (d) drinking water (e) sludge, and (f) human tissues. Reprinted with permission from Ref. (Harley-Nyang et al., 2022; Jenner et al., 2022; Mintenig et al., 2019; Parvin et al., 2022; Talvitie et al., 2017; Wang et al., 2021a). Copyright (a) (2017) Elsevier Ltd., (b) (2022) The Author(s). Published by Elsevier Ltd., (c) (2021) Elsevier B.V., (d) (2018) Elsevier B.V., (e) (2022), Elsevier, and (f) (2022), Elsevier.

environment for long durations, possibly due to surface oceanic currents. In contrast, other PPE may be buried in sediments, and eventually become part of geological records similar to other plastic materials (De-la-Torre and Aragaw, 2021).

In addition, a recent study has reported that MP particles produced by PPE can enter aquatic and terrestrial ecosystems (Abbasi et al., 2020). In early 2020, a large number of face masks were discovered in Hong Kong oceans (Fadare and Okoffo, 2020) and Indonesia (i.e., 250 masks per day) (Cordova et al., 2021; Silva et al., 2021). Kenyan beaches were ten-fold the number of disposable masks on the streets (Okuku et al., 2021). Hospitals and parking lots appear to have five-fold the number of disposable face masks in household areas (Ammendolia et al., 2021; Fadare and Okoffo, 2020). In addition, the outer and inner layers of masks comprised of PP and PE, which could discharge to the aquatic and terrestrial environment respectively. To improve their hygienic and fashion properties, disposable face masks may also include additives, such as fragrances, dye compounds, anti-bacterial and anti-viral barriers. Disposable face masks are expected to be gradually responsible for the release of potentially harmful chemicals besides MPs (Prata et al., 2020).

Furthermore, recent studies have established that MPs/MFs are certainly released from PPE (Saliu et al., 2021; Wang et al., 2021b). MFs are released from face masks as a result of the ultraviolet (UV) light effect, contributing to aquatic environmental pollution (Saliu et al., 2021). Wang et al. (2021b) investigated the effects of UV light on disposable mask weathering (Wang et al., 2021b). UV light was used to treat virgin masks for 18 and 36 h. The outer and inner layers had visible deformation or even surface damage after 18 h of weathering. Simultaneously, several fragments of fibers formed near the damaged site. However, most of the fibers in all three layers fractured after 36 h of weathering, resulting in MF

fragments of varying lengths (Wang et al., 2021b). Meanwhile, the small particles attached to the mask fibers began to appear, as the weathering duration increased (Fig. 5). In another study, Saliu et al. (2021) reported that a mask exposed to 180 h of vigorous shaking and UV light in an artificial salt-water produces up to 173,000 fibers per day (Saliu et al., 2021).

Moreover, similar signs of structural and chemical degradation were found in surgical masks collected from Italian beaches according to Scanning electron microscope (SEM) and micro-Fourier-transform infrared spectroscopy (FTIR) characterizations, suggesting that similar processes may be occurring in natural coastal environments (Wang et al., 2021b). According to the studies mentioned above, millions of PPE end up in the environment, resulting in thousands of MF contaminations daily. The concentration of MFs dominates that of MPs (Rebelein et al., 2021). Amid the COVID-19 pandemic's leaking or intentional littering of disposable masks, MP/MF contamination has increased globally. Up to 102.4 fibers/kg were found in the shoreline sediments of Magdalena River Huila, Colombia, among which 75 % are PP and PE besides synthetic nonwoven materials (Martínez Silva and Nanny, 2020). Synthetic MFs were found in Saigon River, Vietnam, reaching 519,000 items/m<sup>3</sup> (Lahens et al., 2018; Silva et al., 2021). These scenarios suggest that plastic particles accumulating in the environment with a faster rate. Similar findings have been previously reported for four sea surface stations and eight sandy beaches along Qatar's coastline (Abayomi et al., 2017). Forecasts suggest that the widespread use of face masks to combat the COVID-19 pandemic will continue to increase MP contamination in the coming years.

In many regions worldwide, no regulations are currently implemented to address and manage the rising problem of MP/MF pollution. This scenario can contribute to the lengthy persistence and transmission of pathogens, including COVID-19, resulting in future disease outbreak

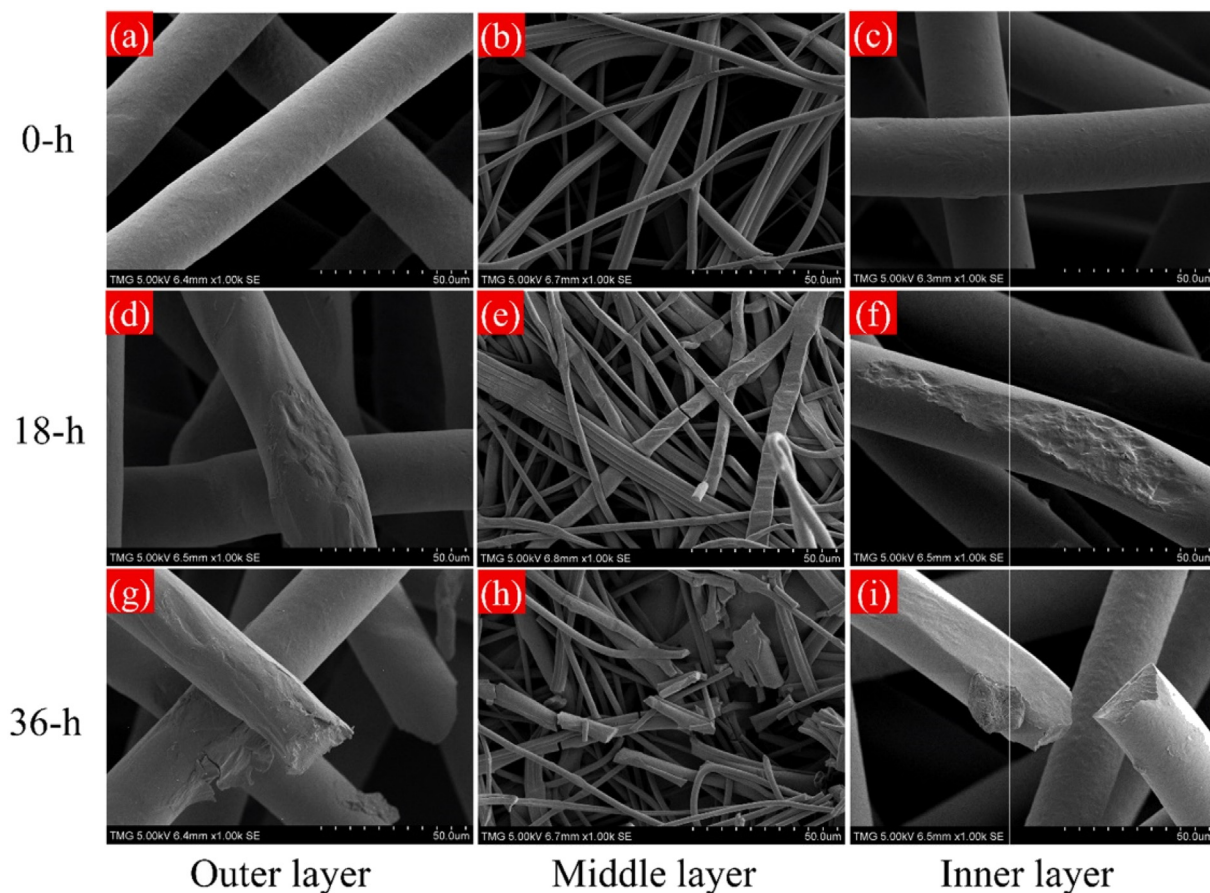


Fig. 5. SEM images for the three layers of masks with different UV weathering durations: (a, d, g) Images at 1000 magnification of the outer layer of mask with UV irradiation for 0, 18 and 36 h. (b, e, h) Images at 1000 magnification of the middle layer of mask with UV irradiation for 0, 18 and 36 h. (c, f, i) Images at 1000 magnification of the inner layer of mask with UV irradiation for 0, 18 and 36 h. Reprinted with permission from Ref. (Wang et al., 2021b). Copyright (2021), Elsevier B.V.

(Abbasi et al., 2020). Plastic pollution has severe impacts including damage to aquatic and terrestrial organisms (due to ingestion) and ecosystem contamination (due to the release of additives or pollutants and viruses). Research data have established the potential toxicity of MPs/MFs to aquatic organisms. Besides, these MPs/MFs entering the food chains, thus posing a health risk to human.

## 5. Impact of MPs/MFs on aquatic ecosystems

Mismanagement of waste has led to large amounts of PPE ending up in urban areas (public parks, gardens, and streets), beaches, natural reserves and even high mountains (Kalina and Tilley, 2020; Silva et al., 2021). By the action of sunlight, mechanical waves, and other external physical and mechanical forces, MPs/MFs from PPEs find their way to the environment (Fadare and Okoffo, 2020; Kalina and Tilley, 2020). The increased consumption of plastic PPE poses severe threats to human health and environmental sustainability (Martínez Silva and Nanny, 2020; Sharma et al., 2020). Stokes (2020) reported an estimated 300 million tons of plastic being manufactured annually, with over 8 million entering the oceans, thus posing a threat to aquatic life (Stokes, 2020). Improper PPE disposal during the current pandemic further exacerbates the problem by causing MP/MF pollution, affecting aquatic species and wildlife, even the fishing and tourism industries, costing at least \$8 billion in marine ecosystem damage (de Sousa, 2020). In addition, Kühn et al. (2015) reported that over 200 species, including seabirds, sea turtles, and marine mammals, were entangled in plastic waste or have consumed it (Kühn et al., 2015). By limiting mobility and eating ability, both entanglement and ingestion can harm the reproduction and the survival of various animals (Table 2). Several cases have been recently reported about animal talons, beaks, necks, legs, and other body parts being entangled in disposable face masks (Hiemstra et al., 2021).

Furthermore, long-term consequences, such as malnutrition, low enabling predation, and tiring resulting from strangulation, infections, severe wounds, and amputations of animals, have been associated with undeliberate consumption of PPE. The ingestion of MPs/MFs, even in small amounts, can considerably affect the morphometrics and blood calcium levels of seabirds (e.g., *Ardenna carneipes*) and increase their cholesterol, amylase levels and uric acid (Lavers et al., 2019). The majority of marine litter is plastic, as evidenced by these materials both on the surface and in the deep-sea (de Sousa, 2020). By 2060, around 155–265 million tons of plastic are estimated to accumulate in the natural environment. Moreover, aquatic MPs can function as substrates, favoring certain species

over others and generating distinct communities in permanent and floating substrates (Silva et al., 2021; Zettler et al., 2013). Previous research study has found that plastic litter is suitable as a habitat and a vector for microbial pathogens and invasive species (Mantelatto et al., 2020; Rech et al., 2018; Wu et al., 2019). Plastic particles can act as a potential carriers of pathogenic microorganisms, such as fungi, bacteria, and viruses (Jiang, 2018; Neto et al., 2019). These microorganisms can find niches or form biofilms on MP/MF surfaces (Jiang, 2018; Zettler et al., 2013). Pathogenic species, including *Aeromonas salmonicida* and *Vibrio parahaemolyticus* that cause diseases in fish and humans respectively, were identified by (Viršek et al., 2017) research studies.

MPs/MFs from PPE affect aquatic organisms as presented in Table 2. Bouwmeester et al. (2015) and Jiang et al. (2020) have recently confirmed that the larger plastic particles (>4 µm) remain in the bodies of blue mussels, while smaller particles (less than 10 µm) can accumulate in the stomach and be absorbed into the circulatory system (Bouwmeester et al., 2015; Jiang et al., 2020). The consumption of MPs/MFs kills numerous seabirds and mammals. The movement and colours of these remnants in waterways entice these animals, mistakenly taking the MPs/MFs as prey, and the vast majority of them perish as a result of malnutrition. The environmental effects of MPs/MFs were previously investigated by (Browne et al., 2011; Cole et al., 2011; Derraik, 2002; Kiessling et al., 2015). Anderson et al. (2016) found that MPs/MFs enter through three pathways: (i) ingestion stress (physical obstruction or egestion energy expenditure), (ii) leakage of plastic additives (plasticizers), and (iii) exposure to contaminants associated with MPs/MFs (persistent organic pollutants) (Anderson et al., 2016). According to Ramesh et al. (2019), MPs/MFs adversely affect certain behaviors of vertebrates, including breathing and feeding, eventually limiting survival and inhibiting development and reproduction (Ramesh et al., 2019). MPs/MFs caused by the disintegration and fragmentation of PPE can obstruct the digestive system (Nelms et al., 2016). Li et al. (2016), reported the death of sea mammals (e.g., manatee) due to blockage of the digestive tract following MP/MF ingestion (Li et al., 2016).

Plastics are composed of toxic chemicals, including polymers, dyes, and plasticizers (Rochman et al., 2019). Oxidative stress is a common reaction to the exposure of MPs/MFs (Qiao et al., 2019; Yu et al., 2018). Besides chemicals, plastics represent a vector for the transportation of organisms, potentially introducing diseases and non-native species (Kirstein et al., 2016; Reisser et al., 2014). Most laboratory investigations have not found MPs/MFs to be intrinsically harmful upon acute exposure, with a few exceptions (Gray and Weinstein, 2017; Jemec et al., 2016). However, lower trophic organisms exposed over more extended, more realistic

**Table 2**  
Impact of MPs/MFs on aquatic ecosystems/organisms.

| Compounds/particles                              | Organisms/species                                   | Health effect/toxicity type  | Reference   |
|--|---|--|---|
| High-density polyethylene PE                     | <i>Mytilus edulis L.</i>                            | ✓ Tumor  | (Chae and An, 2017; Ha and Yeo, 2018)                                       |
|  | <i>Hyalella azteca</i> , <i>Idotea emarginata</i> , | ✓ Growth inhibition  | (Au et al., 2015; Ha and Yeo, 2018; Hämer et al., 2014; Rehse et al., 2016) |
|  | <i>Daphnia magna</i>                                | ✓ Increased mortality  |   |
| Polylactide, Polyvinylpyrrolidone PS             | <i>Arenicola marina</i>                             | ✓ Behavioral disorder  | (Au et al., 2015; Green et al., 2016; Ha and Yeo, 2018)                     |
|  | <i>Echinoderm</i>                                   | ✓ Eating disorder  | (Au et al., 2015; Ha and Yeo, 2018; Hart, 1991)                             |
| Unplasticised PVC PS                             | <i>Arenicola marina</i>                             | ✓ Eating disorder Inflammation   | (Au et al., 2015; Ha and Yeo, 2018; Wright et al., 2013)                    |
|  | Nematode ( <i>Caenorhabditis elegans</i> )          | ✓ Intestinal injury, oxidative stress                                  | (Issac and Kandasubramanian, 2021; Yu et al., 2020)                         |
| PA   | Zebra fish ( <i>Dania rerio</i> )                   | ✓ Intestinal damage  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PE   | Zebra fish ( <i>Dania rerio</i> )                   | ✓ Intestinal damage  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PP   | Zebra fish ( <i>Dania rerio</i> )                   | ✓ Intestinal damage  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PVC  | Zebra fish ( <i>Dania rerio</i> )                   | ✓ Intestinal damage  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PS   | Ascidian <i>ciona intestinalis</i>                  | ✓ Growth, food uptake  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PET  | Sardinella gibbose (Fish)                           | ✓ Body weight  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
|  |   | ✓ Feed habit   |   |
|  |   | ✓ Body weight  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PA   | Sardinella gibbose (Fish)                           | ✓ Feed habit   |   |
|  |   | ✓ Body weight  | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PE   | <i>Emys orbicularis</i> (pond turtle)               | ✓ Liver and kidney   | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| PS   | <i>Crepidula onyx</i> (Mollusca)                    | ✓ Growth   | (Issac and Kandasubramanian, 2021; Lei et al., 2018)                        |
| Triclazan (anti- microbial additive to plastics) | <i>Phaeodactylum tricornutum</i>                    | ✓ Reduction of immunological response and survival                     | (Browne et al., 2013; Chaukura et al., 2021)                                |
|  |   | ✓ Reduces capacity to feed and digest sediments                        |   |
| PE, PVC  | <i>Phaeodactylum tricornutum</i>                    | ✓ Chronic toxic exposure caused lipid accumulation in the algal fluid. | (Du et al., 2021; Guo et al., 2020b)  |



environmental timescales may experience chronic sublethal harm and knock-on effects in their ecosystems, leading potentially to trophic cascades (Botterell et al., 2019; Galloway et al., 2017). Notably, these analyses usually rely on ecosystems and species believed to be globally broad or adaptive, such as organisms found along temperate coasts (Coppock et al., 2017).

PPE can be both a vector and a source of chemical pollutants. Heavy metals and organic molecules that interact with plastic surfaces are absorbed through one or more sorption pathways, including hydrophobic and electrostatic interactions (Fred-Ahmadu et al., 2020). Furthermore, the extreme climatic condition causes harmful compounds to leak from plastic products, including flame retardants and polychlorinated biphenyls (Bejgarn et al., 2015; De-la-Torre and Aragaw, 2021). The effectiveness of chemical sorption or release is affected by environmental factors and physicochemical properties of plastic polymers.

## 6. Impacts of MPs/MFs on human health

The contamination of MPs/MFs from COVID-19 PPE may increase the pollution load of the global environment. The long-term impacts of this pollution needs more detail investigation (Aragaw and Mekonnen, 2021;

Fadare and Okoffo, 2020). MPs/MFs pose risks to human health via food transfer as they are ingested by freshwater and marine organisms and thus accumulate in the food web (Fig. 6). MP ingestion by aquatic species has been reported among worms, turtles, fish, seabirds and crustaceans throughout the marine food web (Wright et al., 2013). Water pollution caused by the contamination of MPs/MFs generated from PPE is a socio-environmental concern that threatens human health, aquatic flora and fauna. Humans are also exposed to MPs/MFs by ingesting or air inhalation (Munyaneza et al., 2022). The presence of MPs/MFs has been confirmed in food chain including seafood, sea salt, sugar, and honey (de Sousa, 2020).

In terms of seafood consumption, MPs/MFs, due to their small size, are mistakenly ingested by aquatic organisms, such as plankton and filter feeders, at the lower trophic level (Cole et al., 2011). Consequently, MPs/MFs accumulate up the food chain, with the highest MP/MF amounts found in the higher trophic level organisms, such as crabs and molluscs. The bioaccumulation of MPs/MFs entails hazardous chemicals and thus results in highly toxic seafood products, reaching human consumers (Revel et al., 2018). Meanwhile, dermal exposure to MPs/MFs occurs when products containing microbeads are applied to the skin (Revel et al., 2018). However, as the stratum corneum (outer skin layer) is limited to particle sizes of 100 nm (i.e., the size of microbeads ranges between 0.1

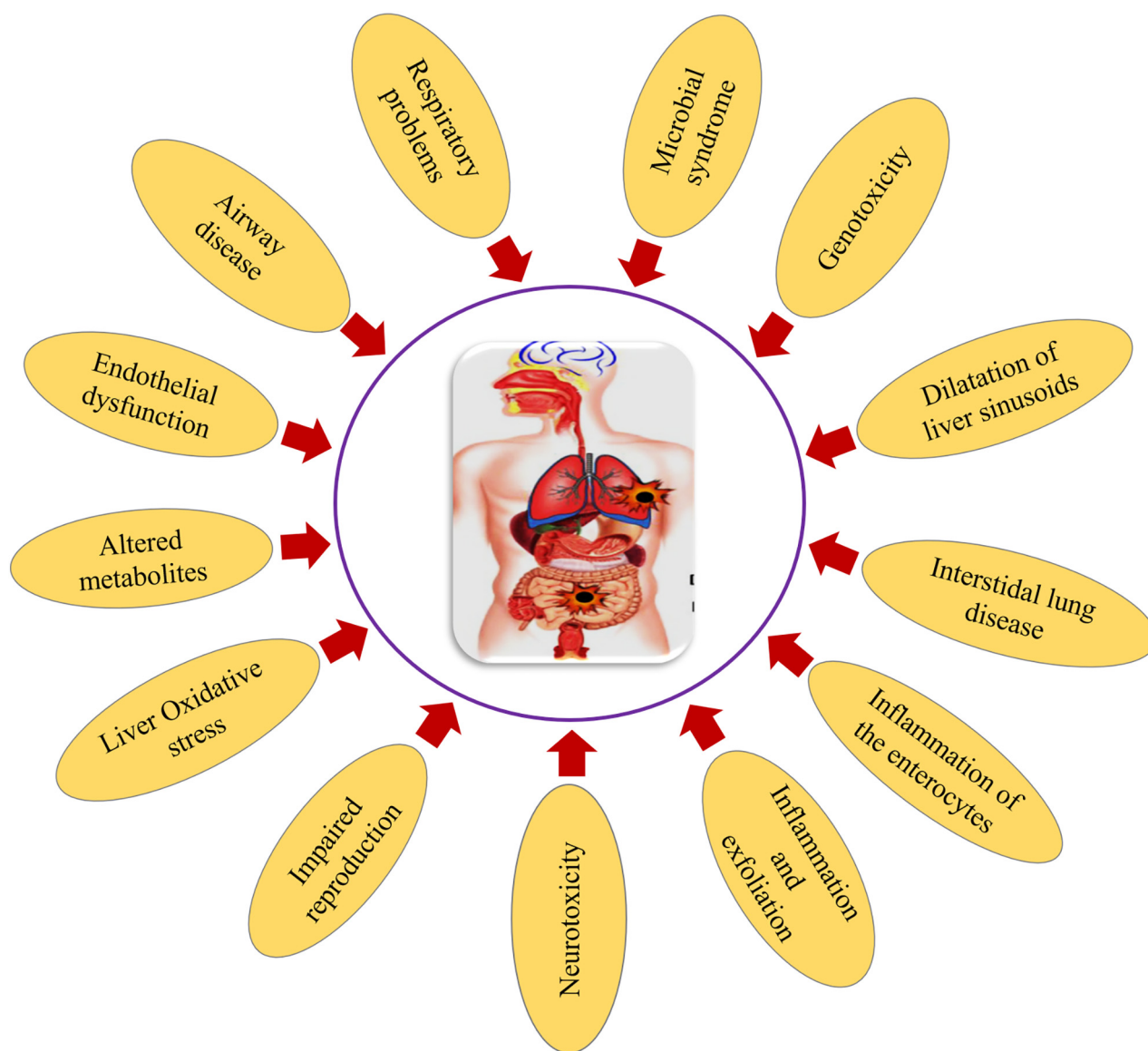


Fig. 6. Human exposure to MP/MF pollution.

and 5 mm), the dermal absorption of MPs/MFs is unlikely (Revel et al., 2018). Although the human skin is an effective barrier, MPs contain much smaller components, such as NPs, that potentially penetrate the skin through absorption (Revel et al., 2018).

The other route of MP accumulation in the human body is inhalation. Plastic-based items emit and contribute to airborne MPs, which can enter the environment and are spread by wind currents (Prata, 2018). Cellular uptake and tissue accumulation of MPs/MFs, including NPs, have been demonstrated in past studies. For instance, various MPs were found in human feces, implying that MPs can enter the body via the digestive system and be excreted in feces (Schwabl et al., 2019). Eight stool samples tested positive for MPs/MFs and contained 20 types of MPs/MFs (ranging from 50 to 500  $\mu\text{m}$  in size)/10 g of human stool. PP and PET were the most common contaminants among the nine detected plastic types. In summary, MP/MF contamination via human inhalation has been studied, but the gastrointestinal burden has not yet been investigated despite MPs/MFs in marine animals' food and gastrointestinal tracts (Prata, 2018; Schwabl et al., 2019).

In addition, prolonged and continuous use of the same face masks have become common due to various factors, including poverty and the limited availability of face masks. The rise in face mask usage has increased human exposure to MPs/MFs via inhalation. Li et al. (2021) found that the prolonged use of face masks causes humans to inhale fiber-like particles (Li et al., 2021). Their reuse, especially after disinfection treatment, can further increase the risk. Face masks can also pose risks to aquatic life, which comprise a large part of the food system and is essential to human survival.

MPs are recently detected in human blood (Leslie et al., 2022), cirrhotic liver tissue (Horvatits et al., 2022), deep lung tissues (Jenner et al., 2022) and Human placentas (Ragusa et al., 2021). Although, initial research indicates that MPs have been detected in human bodies as a result of human exposure. However, the research is limited regarding the direct impacts of MPs on human health. Most plastic materials that humans encounter daily are PPs (found in yogurt containers) and polyethylene (found in plastic bags), but they are usually inert and safe (Revel et al., 2018; Rist et al., 2018). However, the decomposition of these complex substances has become a widespread concern, as their constituent chemical additives may leach and cause toxic effects on humans. Table 3 depicts the various additives used in the production of different plastics, as well as their effects on human health. Extensive research on plasticizer additives, such as bisphenol A and phthalates, revealed the potential of these endocrine-disrupting chemicals to harm human reproduction and growth, and they can even cause carcinogenesis (Cole et al., 2011; Rist et al., 2018).

## 7. Environmental footprints of PPE

The current high demand for PPE implies its importance in protecting humans against COVID-19 and preventing the spread of the virus. However, the materials used in PPE manufacturing are associated with a high percentage of carbon emissions. For instance, synthetic fibers account for two-thirds of 10 % of international carbon emissions associated with textile materials (Fadare and Okoffo, 2020). Every year, 500 million tonnes of MFs are released into the environment. The impact is both direct and indirect as

depicted by the environmental footprints of PPE between 2019 and 2020 (Uddin et al., 2021). The volume of imported disposable gowns (HS Code 621010) has increased in the U.S. (606 %), France (6209 %), and the U.K. (606 %). Similarly, the importation of surgical masks (HS Code 630790) has surged intensely in the U.S. (415 %), France (1207 %), and Germany (83 %) (Uddin et al., 2022). In addition, along with the rise in imported quantities, the environmental impacts of PPE in terms of water, energy, solid waste, and greenhouse gas emissions have also increased between 25 February and 23 August 2021, and the carbon footprints of all PPEs provided to England's social care and healthcare services (Rizan et al., 2021). The total harm to human health during this period was calculated to be 314 disability-adjusted life years (DALYs), with a 0.67 species per year effect on the ecosystem (loss of local species per year). The average contribution of material production to the total carbon footprint was 33 % (22 %–36 %) as opposed to 31 % from transportation (26 %–41 %), 28 % from clinical waste (21 %–31 %), 4 % from packaging material production (0.4 %–9 %), and 3 % from electricity used in manufacturing (1.5 %–19 %) (Rizan et al., 2021). Overcash (2012) applied life cycle assessment (LCA) on six reusable and disposable surgical textiles and found that reusable surgical gowns and drapes consumed more natural resource energy (i.e. 200 %–300 %) and water (i.e. 250 %–330 %) but have lower carbon footprints (i.e. 200 %–300 %) and produced few volatiles organics and solid waste (750 %) than disposable gowns and drapes (Overcash, 2012). In addition, a reusable commercial surgical gown requires  $\approx 36.1$  g of packaging, whereas disposable gowns require  $\approx 57.8$  g of packaging. This results in 8 % of total energy consumption for reusable surgical gowns as opposed to 13 % for disposable gowns (Vozzola et al., 2020). However disposable gowns or other single-use PPE may not be replaced unless manufacturers find a recyclable alternative that can meet the severe regulatory standards for preventing COVID-19 and other highly contagious diseases (Uddin et al., 2021).

Reusable masks can reduce waste by 95 %, followed by reusable face covers with single-use filters by 60 % (Allison et al., 2020). Machine-washable, reusable face masks with no filters presented the lowest overall impact on climate change ( $<2.00\text{E}+008$  Kg CO<sub>2</sub>-eq) (Silva et al., 2021). In contrast, reusable face shields with single-use filters and single-use face shields had the highest impact on climate change ( $1.50\text{E}+009$  Kg CO<sub>2</sub>-eq and  $\sim 1.47\text{E}+009$ , respectively) (Aragaw and Mekonnen, 2021). The use of disposable masks worsens climate change by ten times more than the use of reusable masks. In Malaysia, synthetic rubber glove manufacturing requires 10.0413 MJ of energy per kg of production, implying high dependence on energy production (Silva et al., 2021). In Thailand, the overall carbon footprint was approximately 42 kg CO<sub>2</sub>-eq per 200 pieces of rubber gloves (Usubharatana and Phunggrassami, 2018). Taking into account the estimated internationally monthly use of hand gloves is 65 billion (Prata et al., 2020) and the previously projected carbon footprint release is  $1.4410\text{E}+010$  Kg CO<sub>2</sub>-eq kg (14 Mt. CO<sub>2</sub>-eq) (Usubharatana and Phunggrassami, 2018). Furthermore, the incineration and landfilling of COVID-19 pandemic plastic waste can degrade air quality in moderate to long-term periods (Prata et al., 2020). Substantial amounts of CH<sub>4</sub> and CO<sub>2</sub> are produced by plastic decomposition during landfilling and combustion (Prata et al., 2020). In the U.K., incineration produces 0.179 t of CO<sub>2</sub>-eq

**Table 3**

The various types of additives used in plastic production, their effects, and the types of plastic (Source: (Alabi et al., 2019; Halden, 2010)).

| Toxic additives                         | Uses   | Public health effect (s)  | Plastic types |
|---|--|---|---------------|
| Bisphenol A                             | Plasticizers, container lining.                        | <ul style="list-style-type: none"> <li>✓ Mimic estrogen</li> <li>✓ Ovarian dysfunction</li> </ul>                             | PVC, PC       |
| Phthalates                              | Plasticizers, man-made perfumes.                       | <ul style="list-style-type: none"> <li>✓ Testosterone and spermatozoa motility interference</li> </ul>                        | PS, PVS       |
| Persistent Organic Pollutants (POPs)    | Pesticides, flame repellents, etc.                     | <ul style="list-style-type: none"> <li>✓ Potential harm to the neuro-reproductive system</li> </ul>                           | All plastics  |
| Dioxins                                 | Resulted from the lower temperature combustion of PVC. | <ul style="list-style-type: none"> <li>✓ Carcinogenic</li> <li>✓ Inhibits the synthesis of testosterone</li> </ul>            | All plastics  |
| Styrene monomer                         | Break down the product                                 | <ul style="list-style-type: none"> <li>✓ Carcinogenic</li> <li>✓ Creates DNA adducts</li> <li>✓ imitating estrogen</li> </ul> | PS            |
| Polychlorinated biphenyls (PCBs)        | Dielectrics are used in electrical equipment.          | <ul style="list-style-type: none"> <li>✓ Interferes with the generation of thyroid hormones.</li> </ul>                       | All plastics  |
| Polycyclic aromatic hydrocarbons (PAHs) | Used in the manufacture of pesticides                  | <ul style="list-style-type: none"> <li>✓ Affect growth and reproduction</li> </ul>  | All plastics  |

carbon footprint/t of municipal solid wastes (MSW), whereas landfilling produces 0.395 t of CO<sub>2</sub>-eq per tonne of MSW (Jeswani et al., 2013). Kumar et al. (2021) assessed the environmental impacts of PPE kits and found that PPE bodysuit disposal has the maximum impact in terms of (Global warming potential (GWP), followed by gloves and goggle disposal (Kumar et al., 2021). The use of metal strips in face masks entailed the most significant Human toxicity potential (HTP) impact. Compared with landfill disposal, incineration (centralized: 3816 kg CO<sub>2</sub>-eq; decentralized 3813 kg CO<sub>2</sub>-eq) had a high GWP but a notably low impact on Acidification potential (AP), Eutrophication potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), photochemical Ozone Creation potential (POCP), and HTP, suggesting a high overall impact of landfall disposal compared with incineration. Among all impact categories, decentralized incineration is a more environmentally sound management option compared with centralized incineration. Furthermore, transportation has a significant environmental impact (2.76 kg CO<sub>2</sub>-eq); thus, long-distance transportation must not be overlooked. These findings presented can assist regulatory authorities in delineating actions pertaining to the safe disposal of PPE kits (Kumar et al., 2021).

Schmutz et al. (2020), reported a higher environmental footprint for two of the impact categories, namely water footprint (3.5 m<sup>3</sup> Water-eq versus 0.07 m<sup>3</sup> Water-eq for surgical masks) and ecological scarcity (924 Eco points versus 255 Eco points for surgical masks) (Schmutz et al., 2020). Except for the category carbon footprint of surgical masks, the impact of incineration for different types of masks is lower. Incineration is responsible for 36 % of the total impact. The higher relevance of incinerating surgical masks is that burning PP emits fossil CO<sub>2</sub>, whereas incinerating cotton emits biogenic CO<sub>2</sub>. Biogenic CO<sub>2</sub> emissions are excluded in the calculation of incineration in the GWP because the same amount of emitted CO<sub>2</sub> previously reported for the growth phase of a manufacturing plant is represented (Schmutz et al., 2020). The use, production, and disposal of PPE have considerably augmented because of the COVID-19 pandemic. In view of combating the entry of PPE into the marine environment, researchers should first identify the primary sources and drivers (e.g., poor waste management, beachgoers, fishing activity, oceanic currents and river flow etc.). Eventually, once PPE enters the marine environment, researchers must track them to determine their potential fate.

## 8. Challenges and future recommendations

Alternative recycling and reusing options must be developed as part of long-term management to eliminate the direct threat of plastic waste to the environment, especially the disposable waste that comes from medical services (De-la-Torre and Aragaw, 2021). Fig. 7 shows eco-friendly techniques for hospital solid waste management (Ekanayake et al., 2023). Applications of artificial intelligence techniques can also revolutionize and

improve the solid waste management process (Ihsanullah et al., 2022). Previous research study has revealed the presence of COVID-19 PPE in municipal areas (Fadare and Okoffo, 2020; Prata et al., 2020), and some photos of PPE in marine environments have been circulated on social media. Despite this phenomenon, the extent of PPE contamination is unknown. This type of marine litter should be included in monitoring plans to determine whether PPEs are increasing or decreasing over time and understand how recent legislation can prevent the transmission of COVID-19 through proper waste management. The pandemic has caused a substantial increase in the production, use, and disposal of PPE. Although preliminary estimates provide insights into the growing global problem of PPE, few empirical data have been collected as the COVID-19 has limited the capacity of organizations and individuals to conduct field studies, particularly those in coastal areas. Aside from the scarcity of debris data collected during the pandemic, the key debris items within the emerging PPE category also need urgent attention (Canning-Clode et al., 2020). The identification of MPs with sizes of >5 mm should be prioritized to enhance our understanding of how fragmentation eventually leads to the generation of MPs/MFs with lengths of 5 mm (Fadare and Okoffo, 2020; Rochman et al., 2019).

PPE has been used extensively in recent years due to the COVID-19 pandemic. Masks and gloves have been observed on beaches and land areas. Recent reports and studies have highlighted the presence of PPEs in marine environments (Stokes, 2020). A 3 % overall loss rate can be applied to the mask consumption figures to calculate the total number of face masks entering the environment. The weight of these masks can be approximated by multiplying this number by 3 to 4 g. However, to accurately estimate MPs/MFs, the load released from PPE should be thoroughly investigated. The physical impacts of PPE and the related waste accumulation have been reported in print and electronic media. However, scientific research about the effects is rare and thus should be considered. MP/MF detection and identification during COVID-19 is essential in calculating the exact load of MP/MF pollution carried to aquatic environments. Aragaw (2020) has attempted to explore the potential composition of MPs/MFs in surgical masks (Aragaw, 2020). However, a more detailed investigation of other PPE is indeed required.

In addition, MPs/MFs have accumulated in terrestrial and aquatic environments. Nonetheless, the release of MPs/MFs in the air by incineration and PPE burning by healthcare facilities is superficially explored. Limited studies reported the impact of MPs/MFs on various aquatic species and terrestrial ecosystems. More importantly, risk assessment studies can help to describe the overall impact on various environmental components fully. Similarly, wastewater treatment plants have been frequently investigated in terms of MP/MF load. However, these areas need further research to identify the rise of MPs/MFs load during COVID-19. There is a need for efficient MP/MF remediation techniques for environmental sustainability and safety. Protons, hydrothermal conditions, and other recently developed

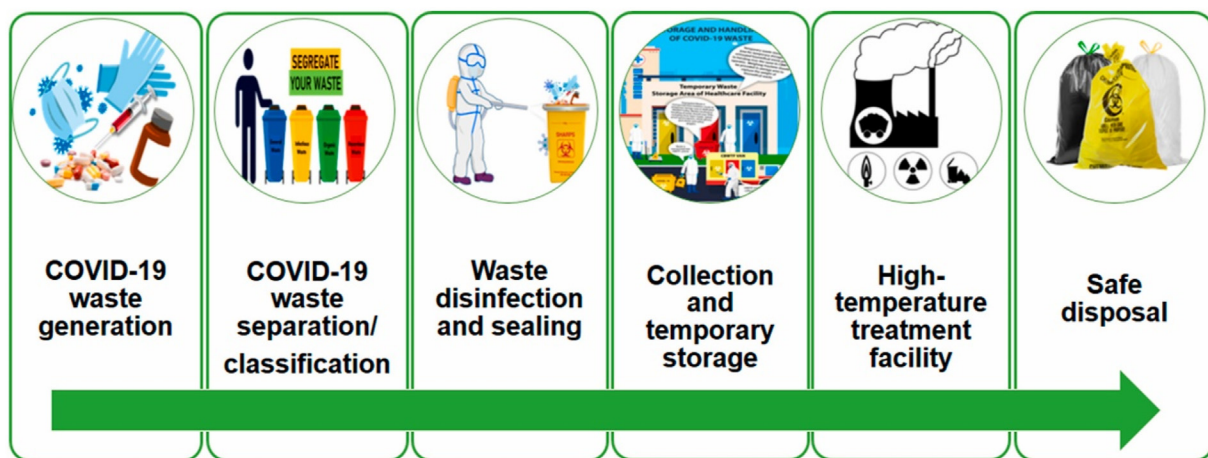


Fig. 7. Schematic of hospital eco-friendly solid waste management techniques. Reprinted with permission from Ref. (Ekanayake et al., 2023), Copyright (2023), Elsevier B.V.

techniques have improved MP/MF degradation with a range of sizes and shapes. In tertiary wastewater treatment facilities, the MPs elimination step of the hydrothermal Fenton process could also be an option (Hu et al., 2021). One of the effective remediation strategies for eliminating MP/MF from the environment, and a viable alternative to traditional methods is MPs degradation through photocatalysis. Designing a coupling strategy that incorporates density separation and physical or chemical techniques for MP/MF remediation in aqueous systems (such as membrane filtration, photocatalytic degradation, and AOPs to achieve the separation and/or degradation of MPs from the environment) will be promising in the future (Chen et al., 2022). Recently, several studies have reported the presence of MP particles in human blood, deep lung tissues and the placenta (Jenner et al., 2022; Leslie et al., 2022; Ragusa et al., 2021). This finding is the initial proof of MPs/MFs penetrating the human body. Thus, the load and impacts of MPs/MFs on human bodies should be thoroughly investigated. Although the sustainable management of plastic-made PPE is challenging, more research studies on using green materials is essential. The researchers and planners must seek multidisciplinary inputs from environmental and biomedical perspectives to focus on the recycling and reusing of plastic-made PPE within our working environment where pollution is not a potential risk. More importantly, we need to encourage people to wear reusable and washable face masks and to use sustainable alternatives whenever possible (Dean, 2020).

## 9. Conclusion

The consumption of PPE in healthcare facilities and households pollutes the environment in the form of plastic waste and MP/MF contamination. In 2020 alone, approximately 1.5 billion masks were washed out into the seas, and the amount is equal to 200 tons of additional plastic waste, thus threatening the aquatic and terrestrial biota. The current data about MP/MF loads concerning PPE disposal is not reliable and necessitates further research. To the best of our knowledge, face masks and their plastic polymer components have not been seriously investigated. MPs and/or MFs have continuously contaminated water systems. The COVID-19 pandemic has put an additional strain on traditional solid waste management practices. Huge amounts of plastic waste from PPE have been produced worldwide due to improper disposal, landfilling, and incineration techniques, and they pollute aquatic ecosystems. Consequently, the amount of PPE waste reaching the marine environment increases and will even progress. Several issues about COVID-19 PPE, including how they pollute the marine environment (e.g., source and fate in the environment and the potential threats to ecosystems) have been elaborated in this study. Given the current lack of scientific knowledge regarding the effect of PPE, we propose some research insights that must be addressed immediately to clarify the pandemic's plastic-associated environmental problem. Many studies on the presence of MPs and MFs in the aquatic and terrestrial environments have been conducted in the past, but it is critical to assess the MPs/MFs load before and during the COVID-19 pandemic.

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## CRediT authorship contribution statement

**Muhammad Tariq Khan:** Writing – original draft, Writing – review & editing, Conceptualization. **Izaz Ali Shah:** Writing – original draft, Writing – review & editing, Conceptualization. **Md Faysal Hossain:** Writing – review & editing. **Nasrin Akther:** Writing – review & editing. **Yanbo Zhou:** Writing – review & editing. **Muhammad Sajawal Khan:** Writing – review & editing. **Muayad Al-shaali:** Writing – review & editing. **Muhammad Suleman Bacha:** Writing – review & editing. **Ihsanullah Ihsanullah:** Writing – review & editing, Conceptualization, Supervision.

## Data availability

Data will be made available on request.

## 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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