



Impact of waste of COVID-19 protective equipment on the environment, animals and human health: a review

Sheng Yang¹ · Yanping Cheng¹ · Tong Liu¹ · Shaoping Huang² · Lihong Yin¹ · Yuepu Pu¹ · Geyu Liang¹

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Abstract

During the Corona Virus Disease 2019 (COVID-19) pandemic, protective equipment, such as masks, gloves and shields, has become mandatory to prevent person-to-person transmission of coronavirus. However, the excessive use and abandoned protective equipment is aggravating the world's growing plastic problem. Moreover, above protective equipment can eventually break down into microplastics and enter the environment. Here we review the threat of protective equipment associated plastic and microplastic wastes to environments, animals and human health, and reveal the protective equipment associated microplastic cycle. The major points are the following: 1) COVID-19 protective equipment is the emerging source of plastic and microplastic wastes in the environment. 2) protective equipment associated plastic and microplastic wastes are polluting aquatic, terrestrial, and atmospheric environments. 3) Discarded protective equipment can harm animals by entrapment, entanglement and ingestion, and derived microplastics can also cause adverse implications on animals and human health. 4) We also provide several recommendations and future research priority for the sustainable environment. Therefore, much importance should be attached to potential protective equipment associated plastic and microplastic pollution to protect the environment, animals and humans.

Keywords COVID-19 · Protective equipment · Microplastic · Environment · Animal · Human health

Introduction

Since the last century, plastics have revolutionized the world and continue to change and shape the future. As an unlimited innovative potential, plastics have a pivotal status in our lives and define our lifestyle. Because of the flexibility, durability, lightness, versatility and availability, plastics are widely used in industrial sectors and hygienic healthcare (Geyer et al. 2017; Grosso 2022). In 2018, global plastic production reached 368 million metric tons, while due to the Corona virus Diseases 2019 (COVID-19) pandemic, the estimated growth rate sharply dropped in 2020 and will recover in 2021 (Europe 2020). COVID-19 is a highly contagious airborne disease and has caused a serious global public health emergency (Liu et al. 2020a; Valsamatzi-Panagiotou and Penchovsky 2022), which is affecting over 200 countries and territories. As up to 12 April 2022, 500,058,567 confirmed cases and 6,206,108 deaths have been reported. To minimize the chances of COVID-19 spreading, governments worldwide have taken several effective preventive measures, including lockdown of cities, the mandatory wearing masks,

✉ Geyu Liang
lianggeyu@163.com

Sheng Yang
1024227634@qq.com

Yanping Cheng
2250152552@qq.com

Tong Liu
18793100029@163.com

Shaoping Huang
huangsp-8888@163.com

Lihong Yin
lhyyin@seu.edu.cn

Yuepu Pu
yppu@seu.edu.cn

¹ Key Laboratory of Environmental Medicine Engineering, Ministry of Education, School of Public Health, Southeast University, Nanjing, China

² Department of Histology and Embryology, Medical School, Southeast University, Nanjing, China

and the COVID-19 vaccine available (Tobias 2020; CDC 2021b).

Besides, the COVID-19 spread can change the environment and be influenced by their interactions (Huo et al. 2021). Undeniably, the lockdown measures during the COVID-19 pandemic make a temporarily lighter human footprint in nature to help the environment, which can improve air and water quality, drop carbon emissions, reduce land surface temperature, decrease noise levels, and increase wildlife sightings (WEF 2020b; Cecchi 2021; Manchanda et al. 2021; Praveena and Aris 2021; Tian et al. 2021). However, the small environmental benefits of the COVID-19 pandemic coming from the human postponed activities cannot hide the tragic costs of coronavirus to humans. Moreover, the COVID-19 pandemic aggravates plastic pollution, another challenging public health problem (Adyel 2020; Khoo et al. 2021).

Before the COVID-19 pandemic, over 380 million tons of plastics are estimated to be produced annually, of which 10 million tons are dumped into the oceans (Singh and Sharma 2016; plasticoceans 2021). Besides, most plastic wastes are not gotten recycled (Europe 2020; Law et al. 2020), which will lead to roughly 12,000 million metric tons entering landfills or the natural environment by 2050 (Geyer et al. 2017). In view of this, many governments and organizations have actively called for attention to plastic pollution (UNEP 2017; EcoWatch 2018). However, after the outbreak of COVID-19 pandemic, the increased use of plastics is making plastic waste accumulation. Especially, protective equipment has become part of our daily life to prevent person-to-person transmission (Chu et al. 2020), which is adding to the

global plastic problem (Gorrasi et al. 2021). Furthermore, plastic in nature can break down into microplastics (particle size < 5 mm) to be ubiquitous in the water (Bohdan 2022), soil (Kumar et al. 2020b), air (Amato-Lourenco et al. 2020), and even in our bodies (Leslie et al. 2022). Therefore, during the COVID-19 pandemic, protective equipment is an important source for microplastic pollution (Akber Abbasi et al. 2020; Aragaw 2020; Fadare and Okoffo 2020; Akhbarizadeh et al. 2021; De-la-Torre and Aragaw 2021).

To our best knowledge, this is the first review on COVID-19 protective equipment associated plastic and microplastic waste cycle. We summarize the amount of increase production, consumption, and release of protective equipment, and the magnitude of protective equipment associated microplastics during the pandemic. Then we firstly reveal the “protective equipment associated microplastic cycle” to comprehensively discuss the threatens of protective equipment to oceans, freshwater, soils and atmosphere. Importantly, we detailly answer the effects of protective equipment associated plastics and microplastics on animals and human health. Finally, the corresponding recommendations are provided and future research priorities are suggested to solve potential protective equipment pollution to protect the environment and ourselves.

Table 1 Type, usage and composition of protective equipment

Type	Usage	Raw materials	Reference
Medical masks	Medical masks can reduce the transfer of saliva and respiratory droplets to others	Cotton, polypropylene, polyurethane, polyvinyl alcohol, polyacrylonitrile, polystyrene	(Aragaw 2020; Rodriguez et al. 2021)
Cloth masks	Cloth masks can block the exhalation of droplets and particles with carrying microorganisms	natural and synthetic fabrics and fibers	(Bahl et al. 2020; Fischer et al. 2020; Leung et al. 2020)
Gowns	Gowns are indicated for use for direct care of patients	Polyester, polyester-cotton fabrics, polypropylene	(Jain et al. 2020; CDC 2021d)
Medical gloves	Medical gloves protect the hands from contact with potentially hazardous substances	polyvinyl chloride, nitrile rubber, chloroprene rubber and latex rubber	(CDC 2020)
Face shields and Goggles	Face shields provide barrier protection to the facial area and related mucous membranes from exposure to splashes, sprays, splatter, and respiratory secretions	Polycarbonate, Potassium acetate, Polyvinyl chloride, Polyethylene terephthalate, polypropylene	(Jain et al. 2020; CDC 2021c)
Filtering facepiece respirator	Respirators, such as N95 respirators, provide protection against inhalation of very small infectious airborne particulates	Synthetic rubber, Polypropylene, Polyurethane foam	(Rodriguez et al. 2021)

Importance of protective equipment during the COVID-19 pandemic

Because the COVID-19 virus is transmitted between people through close contact and droplets, staying at least one meter physical distancing, washing hands often, and cleaning and disinfecting high touch surfaces frequently are necessary to protect ourselves and others (CDC 2021b). In addition, as an effective measure of administrative controls and environmental and engineering controls, protective equipment is also critical to fight and control the COVID-19 pandemic (CDC 2021a; Akter et al. 2022). The available evidence has been confirmed that rational and appropriate use of protective equipment, including masks, respirators, face shields and goggles, can prevent person-to-person transmission of the coronavirus disease to reduce the risk of infection largely (Jefferson et al. 2011; Chu et al. 2020; Lindsley et al. 2021) (Table 1). Among them, masks can control the release of virus-carrying droplets and reduce the inhalation of these droplets by wearers. In particular, protective equipment provide great benefits in reducing the potential transmission of asymptomatic people, which helps to contain the spread of this virus through droplets (WEF 2020g; Johansson et al. 2021).

Sources, occurrence and fate of protective equipment in the environment

To help control the pandemic, the production and consumption of protective equipment are increasing. Health-care workers are the frontline soldiers. The availability of protective equipment is the key to protecting them from COVID-19. Every month, frontline health responders around the world need over 89 million masks, 30 million gowns, 1.59 million goggles, 76 million gloves and other protective equipment (WEF 2020f). A United Nations task force delivers about 500 million medical masks and gloves, as well as other protective equipment for clinical care.

Based on experimental and epidemiological data, community masking can reduce the spread of COVID-19 (Lefler et al. 2020; Mitze et al. 2020, Guy et al. 2021). In addition, On March 2020, The World Health Organization (WHO) called on the industry to increase the manufacturing of protective equipment by 40% to meet rising global demand (WHO 2020b). From June to July 2020, WHO increased deliveries of protective equipment from 5.5 million to 50.4 million pieces, and over 200 million pieces of protective equipment were in store for emergency delivery (Haque et al. 2021). Until October 20, 2020, China has provided 17.9 billion masks, and 1.73 billion protective

Table 2 Production, usage and waste of protective equipment during the pandemic

Region	Production and usage	Waste	Reference
Each continent	Over 3.81 billion, 891 million, 962 million, 490 million, 594 million, and 46 million masks are estimated to be used daily in Asia, Europe, Africa, North America, South America and Oceania, respectively	Over 11,000 tons, 2,600 tons, 2,800 tons, 1,400 tons, 1,700 tons, 141 tons of masks will be discarded daily in each continent, respectively. In Africa alone, over 100 million metric tons of other protective equipment wastes are produced per year	(Nzediegwu and Chang 2020; Benson et al. 2021; Hantoko et al. 2021)
Moroccan	About 12 million mask units are produced per day	Around 41 million masks are discarded weekly, generating over 345 tons of waste	(Mejjad et al. 2021)
Bangladesh	About 3.4 billion pieces of protective equipment are estimated to produced monthly	About 472.30 tons of plastic wastes are estimated to generated every day	(Haque et al. 2021)
Isfahan, Iran		Over 1.49 million masks and 2.98 million gloves are disposed daily	(Zand and Heir 2021)
Turkey	Approximately 50 million masks are used each day	About 200 tons of contaminated waste is created per day	(Akarsu et al. 2021)
England	About 2.3 billion items of protective equipment were distributed to health and social care services between February and July 2020	About 66,000 tons of contaminated plastic wastes are created yearly	(WEF 2020c; Zhang et al. 2021a)
Brazil, Peru, Chile etc	The principal companies produced over 38 million masks monthly in South American countries	More than 85 million masks might be daily disposed in Brazil	(Ardusso et al. 2021; Urban and Nakada 2021)

clothing to 150 countries and 7 international organizations to meet the huge demand for protective equipment (people.cn 2020). Besides, many studies have estimated the number of facemasks and gloves for their countries and the global demand (Prata et al. 2020; Benson et al. 2021; Chowdhury et al. 2021)(Table 2). According to the population information and pandemic spread (worldometer 2021), over 6 billion masks are estimated to be used daily worldwide (Table 2), which exceeds the value reported in previous studies. Unfortunately, hundreds of tons of protective equipment are released and generate massive plastic wastes every day in a city during the pandemic, which is the main source of protective equipment pollution in the environment (Table 2).

Recent surveys demonstrate that COVID-19 protective equipment is invading various environments to be prevalent in the ocean, freshwater, and soil, which can pose great threats to ecosystems, and even human health (details are discussed in the next sections). Protective equipment is commonly manufactured from polymers and polymer fibers, including polypropylene, polyacrylonitrile, polystyrene, polyethylene terephthalate, polycarbonate, and others (Table 1), which is confirmed as a significant source of microplastic pollution in the environment (Schnurr et al. 2018; Fadare and Okoffo 2020; Prata et al. 2020; Zhang et al. 2021a). Therefore, protective equipment without effective disposal is a critical source of microplastics. Protective equipment getting into the environment can be decomposed into smaller pieces of particles by the ultraviolet radiation, weathering, abrasion and biological degradation, which results in microplastic pollution (Aragaw 2020, Ob et al. 2020, Chen et al. 2021, Morgana et al. 2021).

As the most commonly used protective equipment, masks can rapidly increase the accumulation of related microparticles in the environment in a short time (Fadare and Okoffo 2020). With the gradual aging and decomposition, the masks can continuously release particles, and finally completely become billions of microplastics into the environment (Ma et al. 2021; Shen et al. 2021). The adsorption of airborne microplastics in masks also can elevate the overall hazard of the mask as a source of microplastics (Chen et al. 2021). According to the rough calculation, over one hundred billion masks produced in 2020 in China could release more than 1.2×10^{14} microplastics into the environment (Chen et al. 2021). In South Korea, more than 1381 million microplastic fibers are released from the used masks every day (Dissanayake et al. 2021). During the COVID-19 pandemic Saudi Arabia alone may contribute to 32–235 thousand tons of microplastic, accounting for almost half of the total amount of the whole peninsula (Akber Abbasi et al. 2020).

Overall, protective equipment is essential to fight and control the virus spread. Disposed protective equipment becomes the main source of plastic pollution in the

environment during the COVID-19 pandemic. Besides, the fate of the mismanaged protective equipment wastes will end in countless microplastics, which causes the protective equipment associated microplastic waste cycle.

Impacts of protective equipment pollution on aquatic systems

At present, about 150 million metric tons of plastics circulate in the marine environment, and 13 million tons of plastics still flow into the ocean every year (UNEP 2018). Without any action, by 2040, the amount of plastic entering the marine environment will double, and 710 million metric tons of plastic wastes will leak into land and water systems (Lau et al. 2020). Unfortunately, the COVID-19 pandemic makes protective equipment a new scourge to pollute the world's waters. Increasing studies have evidenced the occurrence of different types of protective equipment along the coasts and beaches of coastal cities (De-la-Torre et al. 2021; Okuku et al. 2021), underwater in remote and uninhabited islands (oceansasia 2020), and beneath the waves of the Mediterranean (EcoWatch 2020a), which are polluting the ocean (WEF 2020c) (Fig. 1A and B). As shown in Table 1, protective equipment is constituted by various plastic materials, and characteristics of these materials determine the fates and sinks of protective equipment after reaching the marine environment. Polymers with high density, including polyethylene terephthalate, polyvinyl alcohol and polyvinyl chloride, tend to sink to the seafloor, while low-density polymers, including polypropylene and polystyrene, can float in seawater for a long time (De-la-Torre and Aragaw 2021). The COVID-19 protective equipment can break up into huge amount of microplastics by sun ultraviolet radiation and breaking waves, which cause ubiquitous and almost permanent pollution to the marine environment (Henderson and Green 2020).

To be sure, as an important part of the global plastic cycle, the ocean is a sink for microplastics (Rochman and Hoellein 2020). Trillions of barely visible microplastics exist in the world's oceans, from the Arctic Ocean to Antarctic Sea ice (Peeken et al. 2018; Fragao et al. 2021), from surface waters to the deep seas (EcoWatch 2020d; WEF 2021a) (Fig. 1). Many studies have reported the microplastics concentrations in the oceans. However, recent researches suggest that microplastics in the ocean far exceed the initial estimation, and over 125 trillion microplastic particles are teeming the oceans (Brandon et al. 2020b; Lindeque et al. 2020). Moreover, researchers estimated that the ocean floor contains at least 14 million tons of microplastics (Barrett et al. 2020). Submarine canyons and deep-ocean trenches, known as microplastic hotspots, are rich in the concentration of microplastics, about 1.9 million pieces in one square

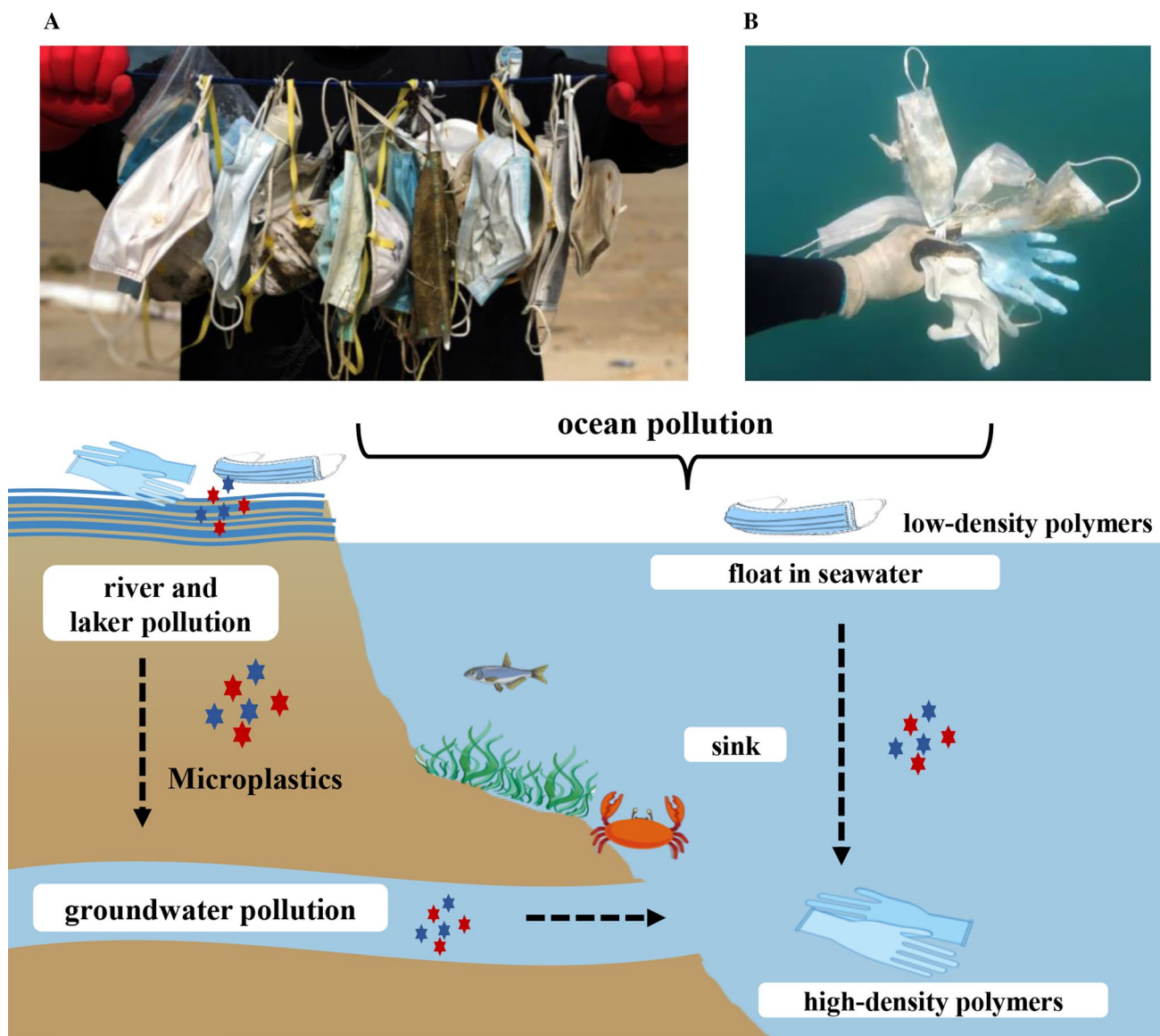


Fig. 1 Pollution by COVID-19 protective equipment in aquatic systems. Protective equipment associated plastic and microplastic wastes can pollute rivers, lakes, groundwater and oceans. A: Many masks were found on the beach (adapted and modified from (oceansasia

2020)). B: Increasing amounts of COVID-19 protective equipment were found in the ocean (adapted and modified from (WEF 2020c)). COVID-19, the Corona Virus Disease 2019

meter (Kane et al. 2020). Therefore, protective equipment associated microplastic pollution in seafloors should be attracted much attention, because less than 1% of plastic stays on the ocean surface and most of protective equipment, such as goggles, gloves, masks, will also sink to the seafloor.

Plastic pollution in the oceans can be mainly attributed to a large amount of mismanaged solid waste from the terrestrial environment, which can be transported through freshwater systems (Jambeck et al. 2015). Freshwater catchment is a crucial pathway for ocean microplastic pollution (Wagner et al. 2014), and more rivers contribute to ocean plastic pollution than previously thought (Meijer et al. 2021).

According to the lastest model of riverine plastic outflows (Mai et al. 2020), about 57,000–265,000 million metric tons plastic debris delivered by rivers leak into the oceans annually.

Nowadays, microplastics can be detected in different freshwater systems worldwide, such as the Yangtze River in China (Xiong et al. 2019), the groundwater in India (Selvam et al. 2021), and the Lake Winnipeg in Canada (Anderson et al. 2017). Just like the oceans, freshwater systems also have the microplastic hotspots, such as the estuaries of densely populated, and heavily industrialized catchments (Wright et al. 2013; Lam et al. 2020), because the

abundance of microplastics is closely associated with human activities (Wang et al. 2021c). However, little emphasis is given to understand the protective equipment pollution in the freshwater systems during the COVID-19 pandemics. Undoubtedly, after the excessive use of protective equipment for protection, the COVID-19 protective equipment in freshwater systems can add the plastic and microplastic load of the environment (Fig. 1). Muhammad et al. (Cordova et al. 2021) monitored the riverine debris in Jakarta Bay from March to April 2020, and observed an unprecedented presence of protective equipment, including medical masks, gloves, and face shields, nearly accounting for one-sixth of the collected riverine debris.

Like other single-use plastic wastes, COVID-19 protective equipment will provide a growing, extensive and innovative habitat for harmful microbes and microorganisms, and then create conditions causing ocean acidification (Harvey et al. 2020). As a result, the combination of plastic pollution and ocean acidification poses great threats to biodiversity. In addition, protective equipment associated microplastics can also serve as vectors for other toxic pollutants, such as heavy metal and various chemicals, to enhance the bioavailability (Li et al. 2020; Eder et al. 2021; Lee et al. 2021). In freshwater ecosystems, microplastics provide novel substrates to form as microplastic biofilm, which can participate in the nutrient cycles and serve as vectors for antibiotic resistance genes and pathogens (Wu et al. 2019; Chen et al. 2020b).

Overall, protective equipment associated plastic and microplastic wastes are polluting ocean and freshwater systems. Research is need to analyze the sources and fate of the COVID-19 protective equipment in freshwater systems and understand the dynamics the aquatic environment.

Effects on the atmosphere

The lockdown measures during the COVID-19 pandemic seem to reduce greenhouse gas emissions and improve outdoor air quality at first glance. However, the large production and use of protective equipment bring about a hidden crisis of global greenhouse gas emissions in a long-term scenario. The production and incineration of plastic products more than 850 million metric tons of greenhouse gases yearly, while the cumulative greenhouse gas emissions from plastics will exceed 56 billion tons in 2050, accounting for 10–13% of the total remaining carbon budget (CIEL 2019), which are not conducive to maintain the global temperature rise below 1.5 °C. Protective equipment made of plastic begin as fossil fuels and greenhouse gases are emitted at each stage of the lifecycle, including extraction and transportation of fossil fuel, production and use of protective equipment, and management and disposal of protective equipment wastes

(Kumar et al. 2020a; Rodriguez et al. 2021). The greenhouse gas footprint of N95, surgical and cloth masks is, respectively, 0.05 kg CO₂eq/single-use (exclude transportation), 0.059 kg CO₂eq/single-use (include transportation) and 0.036 kg CO₂eq/usage (including washing), suggesting that disposable mask usage could exacerbate climate change by 10 times than reusable masks (Klemes et al. 2020; Patricio Silva et al. 2021). Many countries have estimated the footprint of protective equipment during the pandemic and confirmed that protective equipment contributed large amounts of greenhouse gases (Usubharatana and Phungrassami 2018; Mejjad et al. 2021; Patricio Silva et al. 2021; Rizan et al. 2021). Besides, landfills and incineration of protective equipment waste can release harmful compounds, such as dioxins and furans, to pollute the air (Vanapalli et al. 2021).

Recently, the studies of microplastics mainly focus on the impact on rivers and oceans, but COVID-19 protective equipment also can fragment and persist as microplastics in the air (Zhang et al. 2021a). Airborne microplastics identified so far across the world include polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride and others (Enyoh et al. 2019), which are the main materials of protective equipment. Airborne microplastics travel in the atmosphere, deposit all over the world, and accumulate in the air, ocean and land (Peeken et al. 2018; Chen et al. 2020a). However, the ocean is not the final fate of microplastics and gives microplastics back to humans as the form of the sea breeze (Allen et al. 2020). Researchers estimate that 136,000 tons of microplastics can be released from the ocean into the atmosphere every year. In addition, wastewater sludge, compost spreading, surface sediment of soil, and ash from solid waste incinerators are also identified as potential sources for airborne microplastics (Sridharan et al. 2021; Yang et al. 2021c). Therefore, the atmosphere is an important part of the protective equipment associated microplastic cycle, and participates in the progress of microplastics permeating into different environments (Fig. 5).

Interestingly, microplastics from the sea can seed clouds to form white clouds, reflect the heat of the sun and influence the climate (Huang et al. 2010). Apart from serving as sinks of harmful chemicals, microplastics can also serve as vectors for the transport of bacteria and virus in the aquatic and soil environment. So far, no studies have demonstrated that airborne microplastics could be the carrier of the viruses. However, scholars believe that that contaminated airborne microplastic surfaces might be the potential transmission route for COVID-19, especially airborne microplastics emitting from improper disposal of protective equipment could become a potential vector for COVID-19 transmission (Ebere et al. 2020; Liu and Schauer 2021). Therefore, protective equipment associated microplastics are harmful to human health, which will be further discussed below.

In brief, the large production and use of protective equipment significantly increase the energy consumption, environmental footprint and air pollution. Besides, the atmosphere participates in microplastic cycle to make protective equipment associated plastic and microplastic wastes deteriorate air quality, influence the climate and absorb harmful chemicals.

Effects on soils

Recent studies on plastic pollution, including protective equipment pollution, have heavily focused on the marine environment, while few of them have paid attention to the soil. As we know, approximately 32% of the plastic wastes are present in the soil environment (de Souza Machado et al. 2018). Importantly, the soil is also the first environment for plastic transportation. Therefore, extensive used COVID-19 protective equipment may increase the possible plastic threats to the soil, which should be received enormous

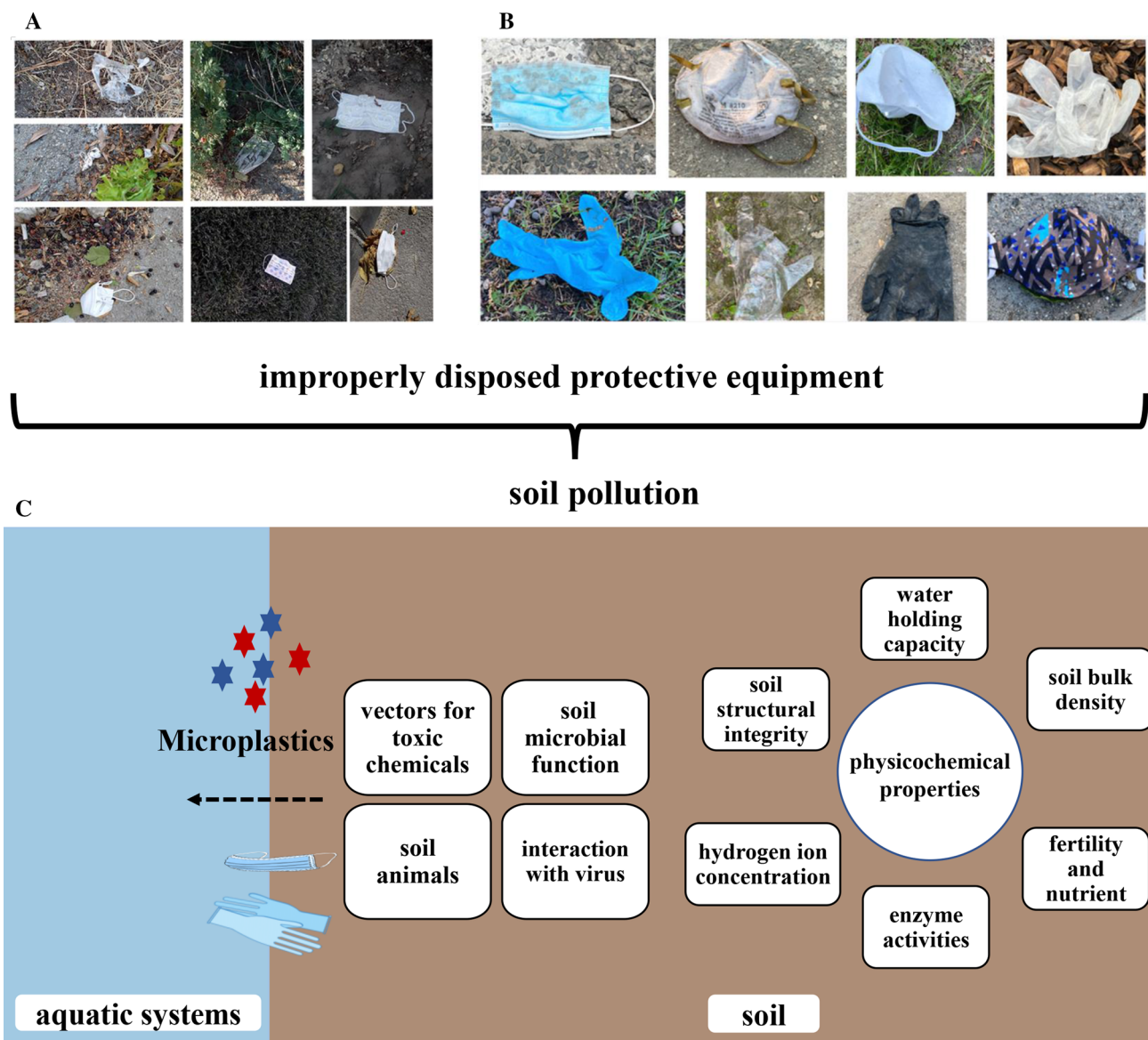


Fig. 2 Adverse effects of protective equipment pollution on soil environment. A: Different colors and types of masks were found in the streets (modified from Akarsu et al. (2021)). B: Many protective equipment, such as masks and gloves, were found in trails (modified

from Ammendolia et al. '2021). C: Microplastics derived from protective equipment can influence soil properties and enter into aquatic systems

attention. Though protective equipment is required to be treated as medical wastes, many masks, gloves and other protective equipment are mixed with household solid wastes and thrown out in streets, parks and roads (Akarsu et al. 2021). According to an exploratory survey in the Moroccan community, 70% of the respondents admitted that they discarded masks and gloves in household dustbins or in open dumps after their first use (Mejjad et al. 2021). Another study on the spatial distribution of protective equipment debris in Toronto, Canada estimated that 14,298 protective equipment debris items would be leaked in the surveyed areas yearly, showing that large grocery store parking lots had the highest average density of protective equipment, followed by entrances and green spaces proximity to medical facilities, long and short residential areas, and recreational trails (Ammendolia et al. 2021) (Fig. 2A-B).

Microplastics are ubiquitous in the soil of various terrestrial ecosystems, including agricultural systems (Kumar et al. 2020b), industrialized areas (Fuller and Gautam 2016), floodplain (Scheurer and Bigalke 2018), sands (Ding et al. 2021) and forests (Ng et al. 2021), which may come from various sources, such as landfills, sewage sludge, composts and wastewater-irrigation (Wang et al. 2020; Ya et al. 2021). The COVID-19 protective equipment wastes mixed in domestic wastes make landfills and water bring abundant microplastics to the soil. On the other hand, soil erosion is also an important pathway of microplastics entering aquatic systems (Rehm et al. 2021). Therefore, the soil also participates in the protective equipment associated microplastic cycle. Accurate treatment of COVID-19 protective equipment wastes is an important measure to protect the soil and the aquatic environment.

Microplastics can interact with a variety of soil properties, which may be a key factor in understanding the risks posed by microplastics to terrestrial ecosystems (Fig. 2C) (Rillig 2012; Liu et al. 2017). The microplastics exposure in soils may reduce the soil bulk density, alter the permeability and water holding capacity (de Souza Machado et al. 2018) and destruct soil structural integrity (Wan et al. 2019). There also are many chemical properties, such as the hydrogen ion concentration values and enzyme activities, that microplastics influence over and above the altered physical properties (Boots et al. 2019; Fei et al. 2020). Besides, polypropylene, polystyrene microplastics and other main materials for COVID-19 protective equipment participate in soil carbon, nitrogen and phosphorus cycle, playing an important role in soil fertility and nutrient (Liu et al. 2017; Huang et al. 2019). As sinks of harmful chemicals (antibiotics, pesticides, heavy metals), microplastics can change the sorption capacity of soils to affect the mobility of chemical contaminants, bio-availability and biodiversity (Huffer et al. 2019; Xu et al. 2021).

Similar to microplastic biofilm in the aquatic environment, microplastics in soils also can provide adsorption sites for soil microorganisms and form unique microbial communities (Zhang et al. 2019), inducing alteration in soil microorganism function. However, several pathogenic microorganisms are also included, which may increase the potential risks to animals and humans (Imran et al. 2019). However, the current studies on protective equipment associated microplastics in the soil environment are deficient, especially the coexistence of microplastics and the COVID-19 virus.

Overall, the main reason of soil pollution is that contaminated protective equipment are thrown as daily rubbish on the road, in household dustbins and garbage dumps, helping plastic and microplastic pollution enter the water and atmosphere. Protective equipment wastes add the microplastic load to the soil, which can alter soil physicochemical properties, decrease soil fertility and nutrient, and soil fertility and nutrient soil microorganism function. The interaction between protective equipment associated microplastics and COVID-19 virus in soils, and the potential impacts and ecological risks on the terrestrial ecosystems remain to be further explored.

Effects on animals

As shown in one of the best pictures on the environment in 2020 shown, a seagull carrying a protective face mask at the port of Dover, Britain, has aroused the profound reflection on the risks of COVID-19 protective equipment pollution to wildlife (WEF 2020a) (Fig. 3A). Lack of human activity during the COVID-19 lockdown led to wildlife sightings increasing, which seemed to herald the spring of flourishing wildlife. However, incorrect disposal of protective equipment is intensifying plastic pollution and posing a blooming threat to the animals by entrapment, entanglement and ingestion.

The entrapment of organisms in the plastic wastes is often reported, such as hermit crabs are entrapped in plastic containers (Lavers et al. 2020). The first victim of COVID-19 wastes is a fish entrapped in a latex glove in the Netherlands (Hiemstra et al. 2021) (Fig. 3B). Therefore, COVID-19 protective equipment, including gloves and gowns, thrown around in the environment could make such entrapments more frequent in future.

The entanglement, another negative interaction between protective equipment pollution and animals, can result in immediate death by suffocation. However, interactions with protective equipment litters are not always directly negative. Protective equipment also causes chronic effects, which can weaken animals' mobility and feeding ability, exhaust the animals, and cause strangulations, infections



Fig. 3 Harm of protective equipment pollution to animals. A: A seagull carrying a protective face mask at the port of Dover, Britain. B-D: Protective equipment wastes can kill animals by entrapment, entanglement and ingestion. B. A fish entrapped in a latex glove (adapted and modified from (Hiemstra et al. 2021)). C. Nests made

by protective equipment wastes (adapted and modified from (Tavares et al. 2016)). D. A penguin was found dead because of mask ingestion (adapted and modified from (Gallo Neto et al. 2021)). E: Microplastics are proved to be ingested in various aquatic and terrestrial organisms

and severe wounds. As the data available on <https://www.covidlitter.com> (Auke-Florian Hiemstra 2021), different wildlife species are facing the risk of entanglement in COVID-19 protective equipment, including American robins, swans, mallards, gulls, bats, hedgehogs, pufferfishes, shore crabs, octopuses. Besides, using plastic to construct nests is more common (Jagiello et al. 2019). Now, COVID-19 protective equipment also becomes nesting materials by common coots and sparrows (Fig. 3C) (Hiemstra et al. 2021). However, plastics incorporated into nests can alter the thermal and drainage properties and increase the risk of entanglement or ingestion, which

may compromise nutritional requirements and reproductive success (Tavares et al. 2016; Thompson et al. 2020).

Researchers found that marine plastics smell like food to sea turtles, and in one study, all turtles surveyed had plastics in their stomachs (EcoWatch 2020c). Maybe, COVID-19 protective equipment also smells and looks like food to other animals. A penguin was found dead on Jukehy Beach. The case is the first recorded report of marine animal death caused by COVID-19 protective equipment ingestion (Gallo Neto et al. 2021) (Fig. 3D). Disturbing observations show that long-tailed macaques chew on a face mask, gulls scramble for face masks and

domestic animals devour COVID-19 litter (Hiemstra et al. 2021). Similar, several animals that feed on landfills will ingest food along with protective equipment wastes, causing acute and chronic effects (Seif et al. 2018). Exposed to protective equipment wastes by ingestion, animals may experience negative consequences on fitness, such as the restriction of feeding activity and alteration of blood chemistry parameters (Lavers et al. 2019), resulting in biodiversity declining.

Apart from the potential risk of entrapment, entanglement and ingestion of protective equipment wastes, the interactions of animals with microplastics from protective equipment wastes also need much attention. Microplastics are proved to be ingested in various aquatic and terrestrial organisms (Fig. 3E), including the invertebrate, the protochordate and the vertebrate (Al-Sid-Cheikh et al. 2018; Vered et al. 2019; Parton et al. 2020), and are recorded in every corner of the world, from small organisms in Antarctica and bird eggs in the Arctic to deep-sea species (Choy et al. 2019; Bergami et al. 2020). The interaction between microplastics and microbe can alter intestinal flora to reduce mucus secretion and induce gut dysbiosis (Wang et al. 2021a). Because, the most important route for microplastics into animals is their food source, microplastics can accumulate in organisms and transfer to higher consumers through food chain amplification, finally threatening human health (Wang et al. 2021a).

In addition to accumulating in the gastrointestinal tract, microplastics can also be distributed to other organs, causing many other physiological hazards and even sublethal effects (Gandara et al. 2016; Xu et al. 2020). In one study, 67% of sharks sampled contained at least one microplastic (Parton et al. 2020). Though only the stomachs and digestive tracts in sharks were examined, microplastics might also present in other organs and tissues, which were proved in various species. After crabs ingest microplastics, the hepatopancreas has the highest accumulation, followed by guts, gills and muscles (Wang et al. 2021b). Billions of microplastics can be rapidly taken up by scallops, then spread through the intestines and distributed across kidneys, gills and muscles (Al-Sid-Cheikh et al. 2018). Exposure to microplastics derived from COVID-19 face masks, the reproduction and growth of juveniles are inhibited, the intracellular esterase activity and spermatogenesis in earthworms are suppressed, suggesting that microplastic can harm animals at the tissue and cellular levels (Kwak and An 2021). Besides, microplastics contain chemical pollutants attached to them can lead to more serious consequences by additive and synergistic effects, impacting various systems (Roda et al. 2020; Yan et al. 2020).

Overall, the COVID-19 protective equipment is harming animals around us by entrapment, entanglement and ingestion. Besides, associated microplastics can accumulate in organisms by food chain and cause adverse effects. Future

researches should address the ecotoxicological effects of protective equipment wastes to protect ecosystems and biodiversity.

Effects on humans

Limited studies in adsorption characteristics and toxicological assessment of contaminated protective equipment presents great challenges of understanding the human health risk of COVID-19 protective equipment associated plastics and microplastics. Evidence confirms that respiratory droplets or airborne virus from patients can be deposited directly onto the protective equipment and remain active for over 72 h (Liu et al. 2020b; Ryan et al. 2020; van Doremalen et al. 2020). However, the knowledge gap in the interaction between microplastics and virus adsorption should be further bridged.

Certainly, the impacts of protective equipment associated microplastics on human health is of great concern. Microplastics are increasing in human lives, making the human body plasticized. In 2018, through analyzing 47 human tissue samples from lung, liver, spleen and kidney samples, researchers detected microplastics in human organs for the first time (EcoWatch 2020b). Subsequently, microplastics were found in the human placenta (Ragusa et al. 2021) and colon (Ibrahim et al. 2021). An important route of microplastic exposure is ingestion (Fig. 4), by which, the global average of 0.1–5 g microplastics may enter human bodies weekly (Senathirajah et al. 2021). Various microplastics have been detected in adult stools, where polypropylene and polyethylene terephthalate are the most abundant (Schwabl et al. 2019). A lasted study reveals that there is little difference in microplastic composition between adult and infant stool samples, but surprisingly, the microplastics on infants are much higher than adults, up to 20 times, indicating that microplastics are spreading to infants (Zhang et al. 2021b).

Besides, microparticles can pollute the food chain and transfer from producers to consumers. Microplastics are widely present in commercial marine species (Vital et al. 2021), freshwater fish (Martinez-Tavera et al. 2021), edible vegetables and fruits (Oliveri Conti et al. 2020). Because of the high demand for food energy and the possibility of microplastic transfer, consumers, especially human beings as the top consumer, are more vulnerable to risks than the lower trophic levels (Carbery et al. 2018). Ingestion of microplastics can interact with the gut microbiota to change the intestinal microenvironment, cause oxidative stress and inflammation to destruct the intestinal barrier (Huang et al. 2021). Therefore, as a potential source of microplastics in the environment, protective equipment wastes can increase the potential threat of microplastics to human health.

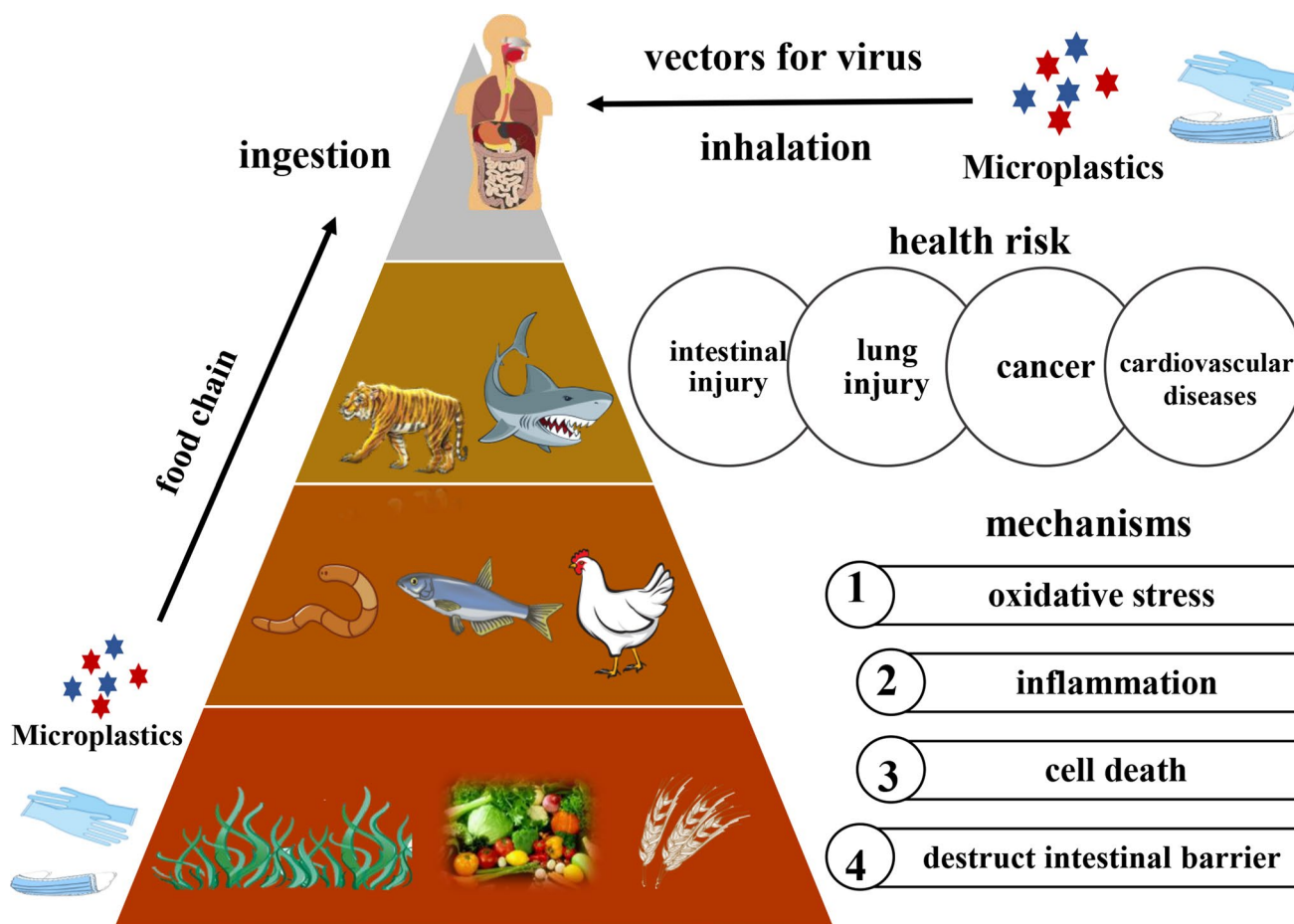


Fig. 4 Potential risks of protective equipment pollution to human health. Human can be exposure to the protective equipment associated microplastics by ingestion and inhalation, resulting in diseases through many mechanisms

Airborne microplastics are widely distributed in the atmosphere, resulting in the potential risk of inhalation exposure (Fig. 4). Nowadays, protective equipment wastes become an emerging source for airborne microplastics (Chen et al. 2021). Increasing evidence is provided the pulmonary toxicity of airborne microplastics by in vivo and in vitro models, suggesting that microplastics can trigger oxidative stress and inflammation, followed by cell death and epithelial barrier destruction (Dong et al. 2020; Lim et al. 2021; Yang et al. 2021b), to potentially induce respiratory and cardiovascular system diseases, and even cancers (Prata 2018). Protective equipment can protect us from airborne particles and the COVID-19 virus, but microplastics generated from the masks can be inhaled by mask wearers during usage (Ma et al. 2021), especially poor-quality masks and reusing masks with disinfection can increase the risk of microplastic inhalation (Li et al. 2021). Besides, all masks can be detected organophosphate ester. Although the calculation indicates the safety of masks with organophosphate ester

contamination (Fernandez-Arribas et al. 2021), the interaction between organophosphate ester and microplastics is not considered. Therefore, selecting the correct masks to wear can avoid microplastic inhalation during the COVID-19 pandemic.

To conclude, ingestion and inhalation are important routes for human microplastic exposure, which helps to understand the potential risk of protective equipment wastes to human health. Humans are affected by toxic effects of microplastics via mechanisms including interaction with the gut microbiota, oxidative stress and intestinal barrier destruction. Incorrect use of mask can increase the risk of microplastic generation and inhalation. Further studies are needed to confirm the ability of protective equipment associated microplastics to adsorb viruses.

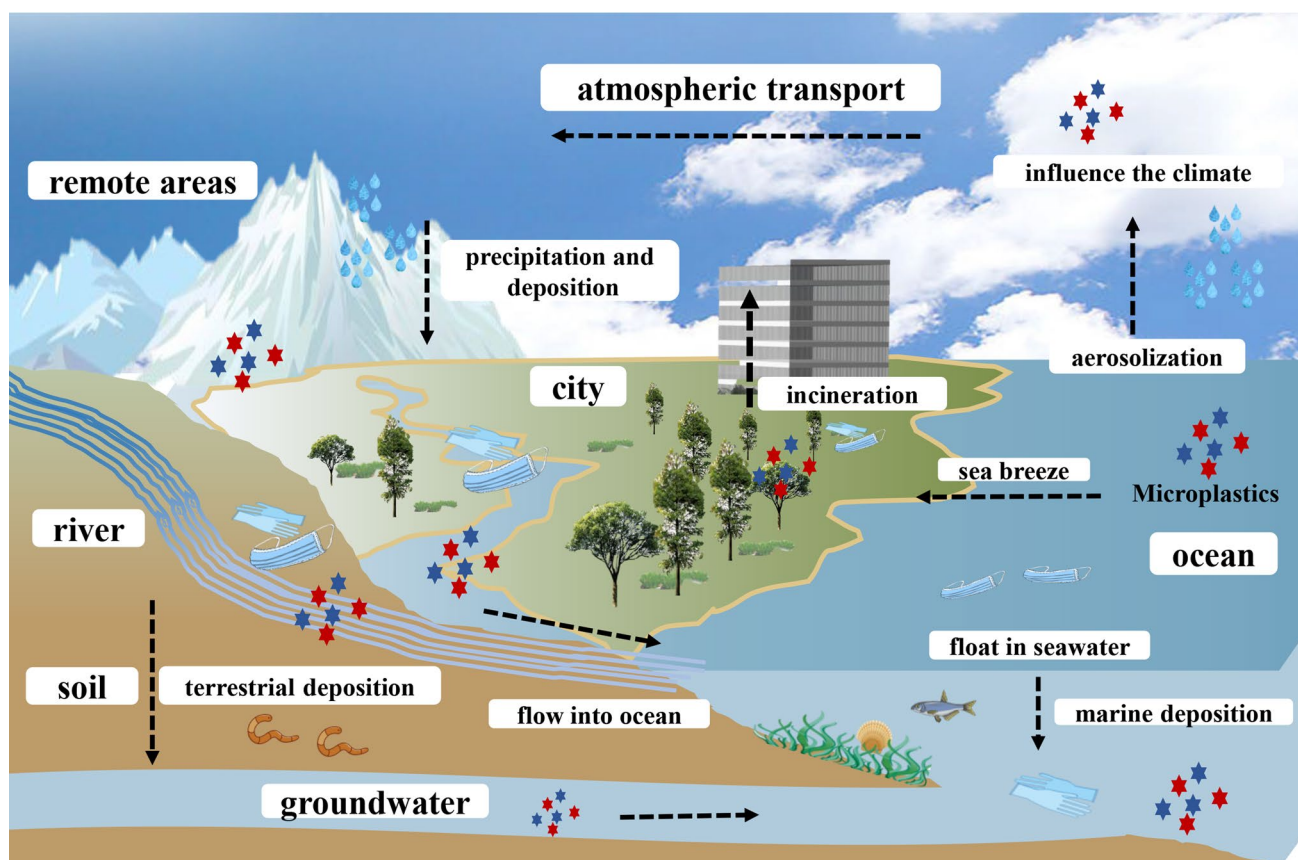


Fig. 5 The protective equipment-associated plastic and microplastic cycle. Disposed protective equipment is massively accumulating plastics and microplastics in different environments, making microplastic cycle and polluting the aquatic, terrestrial, and atmospheric environments

Recommendations

Certainly, the ocean is the sink for plastics and microplastics (Rochman and Hoellein 2020). However, the ocean is not the ultimate fate. Instead, microplastics can also cycle through freshwater, terrestrial systems and the atmosphere. In addition, disposed protective equipment is massively accumulating microplastics in different environments, resulting in protective equipment associated microplastic cycle (Fig. 5). Raising public awareness, improving plastics production, identifying and removing protective equipment associated plastic and microplastic pollution are critical recommendations to provide for a sustainable environment and future research priority.

Raising public awareness

Raising the public awareness is necessary to decrease protective equipment pollution. Relevant publicity should be strengthened, especially on the rational use of protective equipment, and the potential environmental and health dangers. The public can follow the guidelines for selecting and wearing appropriate protective equipment from the centers

for disease control and prevention (WHO 2020a; CDC 2021a). After use, protective equipment should be considered infectious and collected separately in special medical waste bags or bins for further centralized disposal.

Improving plastic production

We do need to raise awareness of protective equipment pollution dangers on the environment and health. Importantly, the only way that really makes a difference is to stop protective equipment related plastic pollution from the source, suggesting that the production should be decoupled from fossil fuel-based resources. Biobased plastics as potential alternative sustainable materials are emerging, which can shift the dependency from fossil fuels to bioproducts (Nanda et al. 2022). Biobased plastics are made from polymers derived from biological sources, including higher plants, microalgae, and cyanobacteria (Karan et al. 2019). The diversity of bio-based raw materials provides opportunities for the production of renewable plastics with an expanding range. Now, biobased plastics are being made into COVID-19 protective equipment, such as the facemasks made by banana trees (WEF 2020e) and biodegradable gloves made

of natural rubber (WEF 2020d). Therefore, the government should fast-track and optimize the plastic industry transition to develop and produce biobased plastics with easier biodegradation, better renewability and lower global warming impact, which can promote bioplastic-based protective equipment innovation and circular economic development.

Identifying plastic pollution

More research should be performed to assess the life cycle of COVID-19 protective equipment, especially microplastics derived from protective equipment. As mentioned above, protective equipment associated microplastics are widely distributed in aquatic, terrestrial, and atmospheric environments, which cycle around the world. More comprehensively and deeply researches should be performed to observe and understand the sinks, sources and spatial and temporal distribution of COVID-19 protective equipment wastes and their interaction with the environment and ecosystems. Therefore, we can build a global protective equipment wastes cycle model to evaluate and deal with plastic and microplastic pollution.

Because of the diversity and complexity of microplastics (materials, size, shapes and modification), there are difficulties in obtaining reproducible and uniform results, including the recent studies on the microplastics from masks (Li et al. 2021; Ma et al. 2021). Besides, limited observation methods underestimate the number of protective equipment associated microplastics in the environment and the potential influence on humans (Chen et al. 2020a). Therefore, precision analytical tools and standardized methods are urgent for separating, sampling, classification, quantification, quality control and characterization of microplastics, especially smaller-sized microplastics.

Remediation

Incineration as a safe, simple and effective method is widely employed for plastic management. Recent incineration methods have a few limits, such as particle and hazardous gas emission (Parashar and Hait 2021), which should be improved. Therefore, future novel technology should have the enough incineration capacity and high purification capacity to completely kill the COVID-19 virus and other microorganisms, and reduce dust and toxic pollutant production. Decontamination of protective equipment can enhance the recyclability to meet the scarcity challenges and promote the circular economy. Neil (Rowan and Laffey 2021) has reviewed different technologies and approaches of protective equipment disinfection and decontamination for safe reuse. Besides, decontaminated protective equipment can be mixed in concrete to improve the mechanical properties (Kilmartin-Lynch et al. 2021; Saberian et al. 2021),

braided into lightweight, cheap and hygienic mattresses (WEF 2021b), and turned into new materials by chemical recycling (Ragaert et al. 2017). New findings suggest that mealworms can eat plastic without any adverse side-effects and bioaccumulation (Brandon et al. 2020a), which provides solutions to protective equipment pollution.

Microplastic separating procedure is also the important stage for next microplastic removal (Razeghi et al. 2022). Nowadays, scientists have confirmed sorption and filtration methodologies can treat microplastic-containing wastewater with good efficiencies. In addition, biological degradation and chemical treatments are also potential removal strategies (Padervand et al. 2020). However, the majority of these methods focused on water. Therefore, continuous research is needed to develop specific methods and strategies for separating and removing protective equipment associated microplastics from different environmental samples.

Limitations and perspectives

Although there are some studies on protective equipment associated plastics and microplastics, these are far from enough. More perfect ecotoxicological studies should be built to access the potential hazards of microplastics on the various ecosystems. Several species can serve as biological indicators to conduct biological monitoring by evaluating the toxicity in organisms, such as sea squirts that are evolutionarily related to humans (Vered et al. 2019). Nevertheless, the measurement of internal exposure of microplastics in the human body is still in the infancy (Vethaak and Legler 2021), suggesting that the ability of microplastics to cross the blood-air, intestinal and skin barriers is needed deep insights. Importantly, the research conditions that reflect real environments should be considered to assess the exact hazards on humans. Moreover, the possibility of microplastics as a vector of COVID-19 viruses needs clearer understandings. Fortunately, emerging *in vitro* models, including organ-on-a-chip and organoids, provide opportunities to accurately simulate and reproduce the exposure and fate of microplastics in the human body with feasibility, adjustability and reliability (Yang et al. 2021a).

Conclusion

During the COVID-19 pandemic, protective equipment can reduce the risk of virus infection, but extensive use and improper disposal are exacerbating the plastic problems. We must recognize that COVID-19 protective equipment associated plastic and microplastic wastes, as the byproducts of pandemic control, have been a global environmental challenge of our time. The review is the first to reveal the protective equipment associated plastic and microplastic cycle, as the review provides a thorough assessment of the impacts in aquatic, terrestrial and atmospheric environments.

Besides, we cannot ignore the irreparable harm to animals and should spark scientific interest in protecting biodiversity. Importantly, the risks of protective equipment associated microplastics to human health are inadequately understood, which should be fueled people's concern. Moving forward, raising public awareness, improving plastics production, identifying and removing protective equipment associated plastic and microplastic pollution are important strategies to solve related pollution in the environment. On the research priority side, we should focus on the biological monitoring and *in vitro* models for the toxicology assessment of protective equipment associated plastics and microplastics, and the possibility of serving as the COVID-19 virus vectors.

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Declarations

Conflict of interests The authors declare no conflict of interest.

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