Journal of Environmental Management 319 (2022) 115741

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Microfiber releasing into urban rivers from face masks during COVID-19

Feifei Wang[a], Haiwen Wu[a], Jiangnan Li[a], Jianli Liu[c], Qiujin Xu[a,b,**], Lihui An[a,*]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[b] Center for Global Health, Nanjing Medical University, Nanjing, 211166, China
[c] College of Textile Science and Engineering, Jiangnan University, Wuxi, 214122, China

ARTICLE INFO

Keywords:
Epidemic
Medical waste management
SEM analysis
Plastic degradation
Public awareness
River management

ABSTRACT

Face masks play a crucial protective role in preventing the spread of coronavirus disease during the COVID-19 pandemic, but the improper disposal of used face masks also causes an emerging environmental problem, such as microplastic contamination. Here, the aim was to evaluate the improper disposal of used face masks and, subsequently, the potential contribution to microplastic contamination in urban rivers. First, we investigated the occurrence of discarded face masks in Qing River through continuously one-month collection on-site, and the disposable masks with a density of $(8.28 \pm 4.21) \times 10^{-5}$ items/m^2 with varying degrees of wear and tear were found. Next, the microfibers shedding from two popular types of new disposable masks were tested. The results showed that 50.33 ± 18.50 items/mask of microfibers, ranging from 301 μm to 467 μm in size, were released from the disposal face mask after immersion in ultrapure water for 24-h. It was significantly higher than the KN95 respirator of 31.33 ± 0.57 items/mask, ranging from 273 μm to 441 μm. Besides C and O elements only found in new face masks, some potentially toxic elements were also detected on the surface of discarded face masks, indicating that various environmental contaminations are easy to adsorb on the surface of discarded face masks. The results implied that these discarded face masks in an aquatic environment are emerging sources of microfibers and could act as transport vectors for contaminants, which would aggravate the present microplastic contamination. In conclusion, these findings were expected to raise public awareness of the proper disposal of used face masks to prevent microplastic contamination and the spread of COVID-19 in the environment.

1. Introduction

Plastic contamination has become an emerging global environmental crisis in recent years. This was caused mainly by the improper disposal of plastic waste after consumption (Sarkar et al., 2022). Consequently, large volumes of plastic waste leak into terrestrial and aquatic environments. The “macro to micro” journey results in the formation of microplastics from the wear and tear and degradation of plastic litter. It raises more attention due to the adverse impacts on wildlife and human health (Campanale et al., 2020; Yong et al., 2020). Furthermore, various types of disasters might also contribute to microplastic contamination unintentionally because of improper management and treatment of plastics after use.

The coronavirus disease (COVID-19) pandemic is a breaking disaster for human beings. As one effective protective measurement, wearing face masks was strongly recommended to prevent droplets that carried the virus from escaping and infecting others. It was especially mandated to wear face masks in concentrated clusters and public areas such as shopping malls or public transportation (Matuschek et al., 2020). This led to a dramatic increase in demand for face masks worldwide. For example, it is estimated that 5,351,520 single-use masks were consumed daily in Victoria, Australia (Boroujeni et al., 2021). The World Health Organization (WHO) also predicted that 89 million medical masks are demanded each month for worldwide health workers, which requires to increase manufacturing of face masks by 40% to effectively fight against infection by COVID-19 (World Health Organization, 2020). The market value of face masks worldwide is forecasted to rapidly increase from 32.76 billion dollars to 50.9 billion dollars by 2025 (https://www.statista.com/). Moreover, face masks were still required even after vaccination because presently available vaccines were ineffective and could not completely prevent infection (Bailey et al., 2020). Of course, it also found that the usage of face masks across countries was considerable

* Corresponding author.
** Corresponding author. State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China.
E-mail addresses: xuqjs@craes.org.cn (Q. Xu), anlhui@163.com (L. An).

https://doi.org/10.1016/j.jenvman.2022.115741
Received 12 May 2022; Received in revised form 7 July 2022; Accepted 10 July 2022
Available online 12 July 2022
0301-4797/

heterogeneity throughout the COVID-19 pandemic. It was mainly affected by various sociodemographic factors, such as age, gender, and education (Badillo-Goicoechea et al., 2021). At the same time, these used face masks were generally not recycled due to the adsorption of germs and viruses. In most areas, nonrecyclable face masks were disposed of at landfills or incineration. However, the enormous global consumption of face masks every day also caused an emerging environmental issue due to the improper disposal of disposable face masks. For example, it is reported that irresponsibly discarded and disposed of used face masks often occurred in streets, roads, and beaches; subsequently, a proportion of these discarded face masks entered the aquatic environment and finally oceans (Fadare and Okoffo, 2020; Torres and De-la-Torre, 2021). More importantly, this plastic waste not only contains toxic chemicals such as additives like phthalate but also absorbs contaminants from surrounding environments, which might harm wildlife and the human food chain, ultimately human beings.

Protective face masks generally contain three layers of fabric which are composed of an inner layer (lyophobic layer), an outer layer (hydrophilic layer), and a middle layer (meltblown layer). The primary materials are synthetic polymers, including polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, polyethylene, or polyester (Jung et al., 2021). For instance, classical surgical masks are made of pleated cellulose, polypropylene, and polyester. In contrast, molded rayon and polypropylene blend with an acrylic binder are the primary materials used for Aseptex fluid-resistant masks (Leonas and Jones, 2003). The face masks contain microfibers formed during the manufacturing processes of these fine fibers (Hutten, 2007), and also could fragment into microplastics and microfibers due to constant bio-photochemical weathering and degradation in various environments (Fadare and Okoffo, 2020; Shruti et al., 2020). For example, it is reported that a total of 116,600 microfibers were released from a disposable mask by washing ultrapure water three times (Shen et al., 2021). Surprisingly, Ma et al. (2021) also reported that more than one billion nanoplastics and microplastics, ranging from 5 nm to 600 μm, were released from one surgical or N95 mask after rinsing with Milli-Q water one time. Moreover, the number of microplastics released from used face masks was significantly higher than from a new one (Chen et al., 2021). At the same time, UV weathering could also accelerate the release of microfiber from disposable masks (Wang et al., 2021); that is, the number of microfibers released from weathered masks increased to 0.39–4.33 times compared with those from a new mask. All of these indicated that microfibers would be released from face masks. Consequently, discarded face masks release microfibers continuously once improperly disposed of. This would contribute to microplastic contamination in the aquatic environment. These would aggravate the existing microplastic contamination once new or used face masks are discarded into the environment (Chen et al., 2021; Fadare and Okoffo, 2020; Ma et al., 2021; Shruti et al., 2020).

Recently, some studies investigated the presence of discarded personal protection equipment in the environment and found that some used face masks with different types, colors, and textures were observed in the Lake Tana and Bahir Dar city littering (Aragaw, 2020), the coastlines of Bushehr port (Akhbarizadeh et al., 2021), the coast of Lima (De-la-Torre et al., 2021), Kenya's urban beaches (Okuku et al., 2021), and the downtown Toronto (Ammendolia et al., 2021). Most time, littered face masks are easy to be blown into rivers and streams, finally ending up in the aquatic ecosystem as a potential source of microplastic contamination. For example, Peng et al. (2021) estimated that 25.9 ± 3.8 thousand tons of pandemic-associated plastic waste, including face masks, were released into the global ocean. Furthermore, the disposed of face masks might pose more persistent threats to the aquatic ecosystem compared to the terrestrial environment due to the worse degradation circumstances (Hasan et al., 2021), indicating that proper disposal of used face masks is vital to maintain the quality of the environment (Tesfaldet and Ndeh, 2022). The present study aimed to investigate the potential occurrence of discarded face masks in a typical urban river in Downtown Beijing, where the population density was about 10, 330/km^2 in 2020. At the same time, the potential contribution of used face masks to microplastic contamination in rivers was also evaluated based on the changing structural and physicochemical characteristics of face masks and the release of microfibers. Most importantly, it is expected that this information would raise public awareness of eliminating plastic contamination by changing individual behavior and enhancing sound waste management practices.

2. Materials and methods

2.1. Collection of discarded face masks along Qing River

Qing River is a typical urban river with a water depth of 0.5–1.0 m. It locates northwest of downtown Beijing and continuously flows through the Haidian and Chaoyang districts. It receives effluents discharged from four municipal sewage treatment plants throughout the year and runoff in the rainy season as primary replenishment water sources. Many residential areas, and retail and leisure parks are distributed along both sides of the river. There are also heavy pedestrians and traffic every day across the river. So, the river is affected notably by human activities. To maintain the river's cleanliness, local authorities employ cleaning workers to remove floating debris from the water surface and harvest excessive aquatic plants daily.

To prevent coronavirus transmission, Chinese health authorities issued a series of guidelines upping the requirement of mask-wearing for the public, including in outdoor areas. It was mandatory to wear face masks and keep physical distance in transport and all public situations as strict measurements. At the same time, various effective measures and rules have been implemented in Beijing to eliminate plastic contamination. For instance, conducting waste sorting and recovery is mandatory. During COVID-19 in 2020, a 1-km river channel before Yangfang Dam cruised every day to collect discarded face masks in the surface water from Jun 13 to July 12 (Fig. 1). The 1-km area was selected because some communities, stores, and enterprises are distributed. Moreover, some residents like to play such as fishing around in this region. With the help of cleaning workers, the discarded face masks were picked up individually by hand from the day's accumulated floating debris. At the same time, we also cruised along the river bank every day to collect the discarded face masks. After removing dirt from the surface of the objectives, the discarded face masks were counted and then stored individually in a freezer for further analysis. Of course, masks discarded in the river that did not collect in time that day would accumulate and be collected at next day. So, the sampling could represent the number of masks discarded during two-time points duration.

2.2. Characteristics of structural and physicochemical properties

To learn the structural and physicochemical properties of face masks, the discarded face masks from the Qing River were firstly dried at 50 °C in an incubator. Then, the surface morphology of face masks' outer and inner layers was analyzed using a scanning electron microscope (SEM, SU8020, HITACHI, Japan) attached to an energy dispersive X-ray spectroscopy (EDS). The samples were cut into small pieces (about 1.0 cm × 1.0 cm), then a sub-sample randomly selected from these pieces was fixed on the surface of the sample holder using conductive adhesives. After that, the sample was coated with a layer of gold for SEM imaging and viewed at a magnification from 100 to 5000 with 5 kV electron accelerating voltage. Three parallel pieces were observed for each sample. At the same time, the new disposable masks and KN95 respirators purchased from a store were also observed to compare the changing physicochemical properties.

2.3. Microfiber release evaluation

New disposable masks and KN95 respirators, two popular face masks

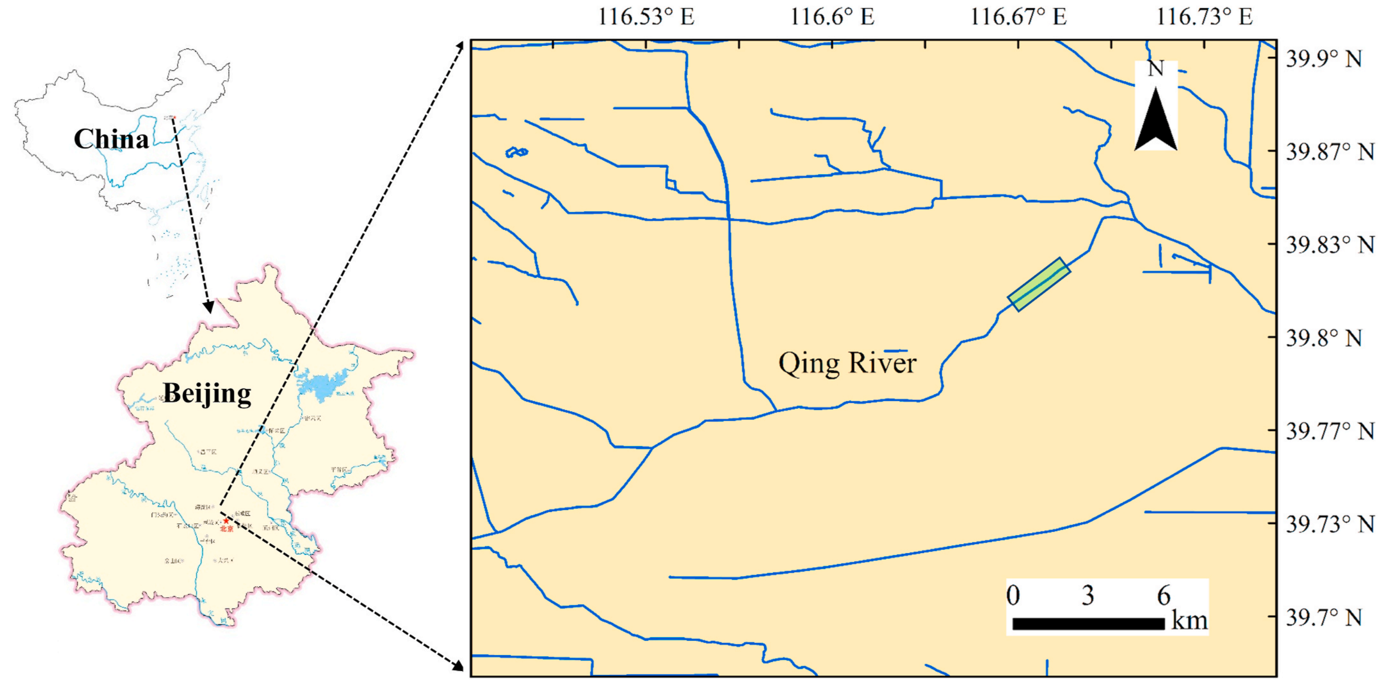

Fig. 1. Sampling site for investigating discarded face masks along Qing River (Green area). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

used during COVID-19 for most people, were purchased from a chain pharmaceuticals store in Beijing. The disposable masks have three layers, two filter layers made of non-woven fiber and one middle layer made of melt-blown fabric (Aragaw, 2020). KN95 respirators have four structural components: outer layer, filter layer, "cotton" layer, and inner layers (Yim et al., 2020). The materials of the inner and outer layers of the commercial KN95 respirators and disposable masks were confirmed to be polypropylene (PP) (Fig. 2). Before the test, all elastic earloops and nose bridges were removed to avoid any possible contamination from other materials. First, new disposable masks and KN95 respirators were fully immersed individually in glass beakers (1 mask/beaker, $n = 6$) with 2-L ultrapure water for 24-h at room temperature, and rinsed thoroughly three times with ultrapure water without rubbing. After that, all water was filtered through a stain-steel membrane (10 μm) to count the number of particles shedding from face masks. At the same time, six blank groups without face masks were also performed with only ultrapure water. Moreover, to avoid contamination, some strict measures

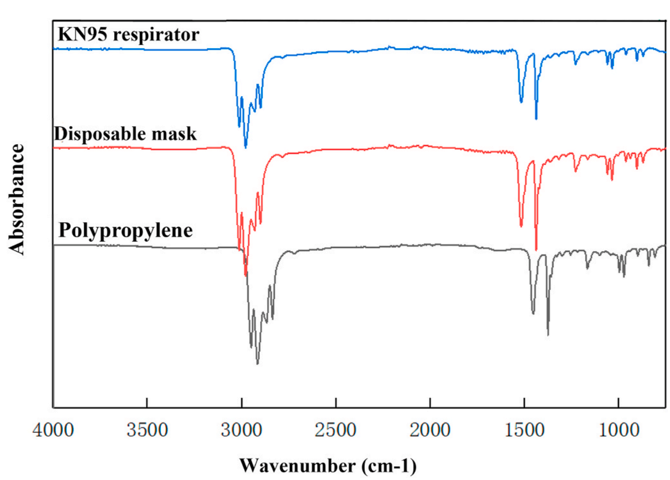

Fig. 2. FTIR spectrum of new face masks and discarded disposable masks collected from Qing River.

were performed throughout the experiments to obtain reliable outcomes. All beakers and filter membranes were rinsed 3 times carefully with ultrapure water and covered with aluminum foil. No plastic tools were used to minimize the background contamination, and the ultrapure water was filtered on a clean bench. Cotton laboratory coats and nitrile gloves were worn to avoid cross-contamination during operations. The floor and tables in the lab were cleaned daily using a sticky roller to remove the particles. Notably, three blank control experiments were performed each time, and the results were used to calibrate the experimental results if necessary.

The microfibers and particles shedding from face masks were counted under an optical microscope (Shanghai Fulai Optical Technology Co., LTD, China) described by Yang et al. (2019). Detailly, the filter membrane was divided into four equal parts, and then the number of microfibers was counted in 50 grids (1 × 1 mm^2) in each filter membrane. A microfiber was counted only if more than half of its volume was located in the grid. The total number of microfibers was calculated based on these grids and the membrane area. The whole area for calculating microfibers was more than 10% of the membrane area. The microfiber number was counted using Formula (1).

$$C_i\left(\frac{\text{items}}{\text{mask}}\right) = \frac{\sum_{a_i=1}^{50} n_i + \sum_{b_i=1}^{50} n_i + \sum_{c_i=1}^{50} n_i + \sum_{d_i=1}^{50} n_i}{200} \times S_{filter} \quad (1)$$

In Formula (1), n_i is the number of microfibers in each grid; 200 is the total grids counted on each filter membrane; a_i, b_i, c_i, and d_i are the numbers of microfibers in each quadrant; S_{filter} is the membrane area used for filtering (1384.74 mm^2); C_i is the number of microfibers shedding from mask calculated from filter membrane (items/mask).

At the same time, the microfibers were imaged using a Leica DM4M digital microscope (Germany), and the length was measured using its attached embedded scale bar. After that, 100 microfibers were selected randomly from each sample, and their polymers were further identified and confirmed with Spotlight 200 FT-IR Microscopy Systems (m-FT-IR) (PerkinElmer, USA). The spectrum was searched automatically to match the reference in the Bio-Rad KnowItAll® Informatics System 2018 (64-bit)-IR Spectral Library (Bio-Rad Laboratories, USA).

2.4. Data analysis

The number of microfibers (items/mask) was expressed with mean ± standard deviation. A Student t-test was used to determine the statistical difference between types of face masks using SPSS version 22.0 (SPSS Inc, Chicago, IL, USA). Statistical significance was accepted at $p < 0.05$.

3. Results and discussion

3.1. Presence of discarded face masks in Qing River

During a one-month investigation on-site along with the same sector of Qing River, a total of 84 discarded face masks, that is, 0–6 disposable masks daily, were collected from the surface water and the bottom of the river (Fig. 3(a)). Only one day, no objective was found during the investigation period, implying that the leakage of used face masks occurred nearly every day. Additionally, some face masks were newly discarded that day (Fig. 3(b)). However, a few were severely damaged due to long-time floatation and suspension in the environment where it is hard to be found, or deposition into the bottom of the river where they are not easy to be removed (Fig. 3(c)). These face masks might be directly discarded into the river despite some garbage bins along river banks, or blown into the river from other sites although we did not find them on site. Moreover, only disposable masks were found, and no different types were collected, such as KN95 respirators, reusable face masks, gloves, or face shields. This indicates that disposable face masks are easier to be discarded after use than others and finally leak into the environment. It is related to the vast amount of daily use because each person is strictly required to wear it in public. During the investigation, we also found more than 95% of pedestrians wear a disposable mask on the road, whether walking or riding a bike. Still, we didn't find a person who discarded his face mask intentionally.

According to the investigated area along the Qing River (length: 1.0 km; average width: 30 m), the average density of discarded face masks was $(8.28 \pm 4.21) \times 10^{-5}$ items/m^2, ranging from 0 to 1.71×10^{-4} items/m^2. This was similar to the coastal zones in Lima where $(6.42 \pm 1.11) \times 10^{-5}$ items/m^2 of personal protective equipment (PPE) was found, also mainly the face masks (De-la-Torre et al., 2021). However, it was significantly lower than the $(1.01 \pm 1.55) \times 10^{-3}$ items/m^2 of PPE reported in metropolitan Toronto (Ammendolia et al., 2021), $(7.71 \pm 0.01) \times 10^{-3}$ items/m^2 to $(2.70 \pm 0.02) \times 10^{-2}$ items/m^2 along the coastline of Bushehr port (Akhbarizadeh et al., 2021), and 0–3.8×10^{-2} items/m^2 Kenya's urban beaches (Okuku et al., 2021). From the view of the city scale, population density, and intensive human activities, these regions are significantly less than that of Beijing. This suggested that the discarded PPEs in the environment, including face masks, are independent of the density of the local population, but mainly depend on the local sound solid waste management system. Of course, the collection frequency for waste in different regions could affect the current density of masks discarded in environments, resulting in overestimation or underestimation among studies. However, sound waste management should include litter collection in time, not accumulation over a long time in environments. So, the relative value could also mirror the contamination of masks discarded in environments. In the present study, garbage bins are also found to be set along the riversides at intervals according to the investigation on-site, and cleaning workers empty the trash timely every day. Additionally, the River and Lake Chief system, which is a river and lake management and protection system in China, is also strictly implemented in the Qing River to clean and remove river litter every day, resulting in the elimination of plastic waste along the river. Thus, perfect medical waste management in all nations and regions is especially vital to prevent plastic contamination from PPEs and other sources, although it is challenging.

At the same time, public environmental protection awareness and responsible consumption behavior are also crucial factors in eliminating the leakage of discarded face masks into the environment throughout the pandemic. For example, a recent study reported that the change in consumer-based actions could greatly promote to fight against the plastic contamination challenge (Marazzi et al., 2020). The *in situ* evidence showed that face masks on streets and beaches in Peru were probably driven by mismanagement and poor environmental awareness (Torres and De-la-Torre, 2021). Thus, it is necessary to raise public awareness in a broader community of the adverse environmental impacts of plastic pollution. After all, a policy highlighting responsibility can not be effectively implemented without active public education and participation partnerships actions. More importantly, all stakeholders should cooperate and coordinate tightly to address macro- and microplastic contamination in the principle of source prevention, including consumers and policy-makers.

Additionally, based on the present limited investigation data on-site, it is estimated that the daily flux of discarded face masks in Qing River was about 75 pieces along the Qing River from upstream to downstream due to improper disposal after use. Fortunately, these discarded face masks along the river were collected and removed daily for further harmfulness treatment, which would facilitate eliminating the potential environmental risk. Recently, Benson et al. (2021) estimated that approximately 3.4 billion single-use facemasks/face shields are discarded daily due to the global COVID-19 pandemic. From our present investigation on-site in Beijing city, one of the megacities worldwide, their results should be significantly overestimated because they were simply calculated based on the total population of a country and an

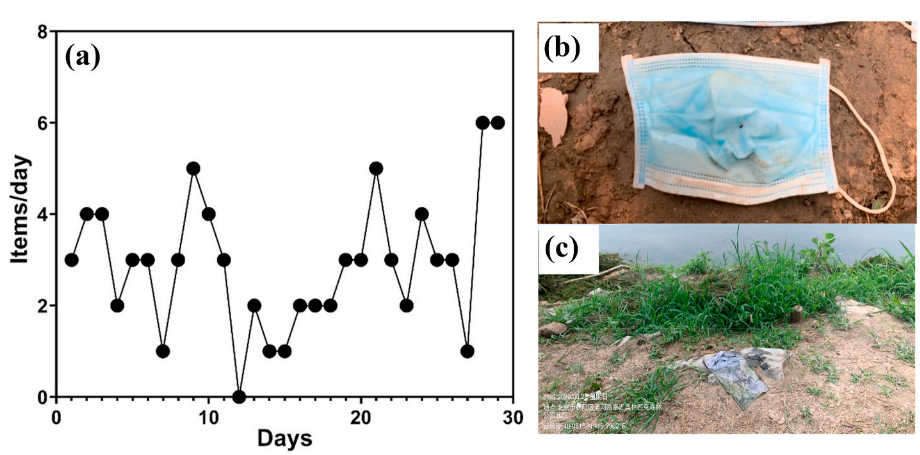

Fig. 3. Discarded face masks collected from Qing River. (a) Numbers of discarded disposable masks collected daily; (b) Newly discarded disposable mask; (c) Damaged discarded disposable mask.

arbitrary percent of facemask acceptance rate by the urban population (Benson et al., 2021) despite no available harmonized approach presently. Further evidence-based practices should be conducted to improve the data quality which is crucial for a policy decision.

3.2. Structural and physicochemical characteristics

The face masks were observed under SEM to screen the change in fabric structure and surface characteristics. The structures of the inner layer and outer layer of both the new KN95 respirator and disposable mask were very flat. Moreover, the fibers of the KN95 respirator (Fig. 4 (a) and **(b)**) were more compact than the disposable mask (Fig. 4 (c) and **(d)**), and this might be related to their protective effectiveness of them. That is, at least 95% of airborne particulate matter must be filtered by KN95 respirators, while disposable masks can reduce the volume and spread distance of exhaled respiratory particles. However, the fiber diameter of both types was about 20 μm, which was consensus with the new face masks of 21.26 ± 6.08 μm reported by Wu et al. (2022), but thicker than the fibers from ecoparks disposable masks of about 30 μm (Wang et al., 2021). This might be explained by the different manufacturing processes that produce melt-blown fibers.

Additionally, these fibers in the inner and outer layers were remarkably intact and smooth, and no tiny particles were found to adhere to the surface of the fibers in these new face masks (Fig. 4(a)~(d)). However, the fibers of the inner and outer layers of discarded face masks collected from the Qing River became looser compared with these new face masks (Fig. 4(e) and **(f)**). And some tiny fragments appeared on the surface of the fibers, which might be natural substances attaching to the fibers or the exfoliated biofilm from the surface of fibers due to dried treatment. Moreover, the EDS showed that elements on the surface were also different between the new and old masks. That is, only carbon (C) and oxygen (O) were detected in the new disposable mask and KN95 respirator after immersion in ultrapure water for 24-h (Fig. 5 (a) and **(b)**). The ratio of the C element was significantly higher than that of the O element. Additionally, some potentially toxic elements such as Pb, Cd, and Sb, commonly used as chemical additives during plastic manufacture, were not found (Hahladakis et al., 2018). This might be related to the low detection limit of EDS analysis because Pb, Cd, and Sb had been detected in face masks using ICP-MS with high sensitivity (Sullivan et al., 2021).

Besides C and O, however, more elements were found on the surface of discarded face masks, such as Al and Fe (Fig. 5(c)), but these elements are not commonly used as chemical additives. It indicated that various contaminants in the aquatic environment easily adsorb to the surface of discarded face masks. Generally, oxygen-containing functional groups are formed on the surface of plastics during the weathering process, such as C=O, O–H, and C–O (Ding et al., 2020). This results in a significant increase in the adsorption capacity of inorganic contaminants and hydrophilic organic contaminants (Duan et al., 2021). Furthermore, multiple viruses and microorganisms from the surrounding environment might rapidly colonize the face masks during weathering because of the microbial colonization on the plastisphere and the formation of

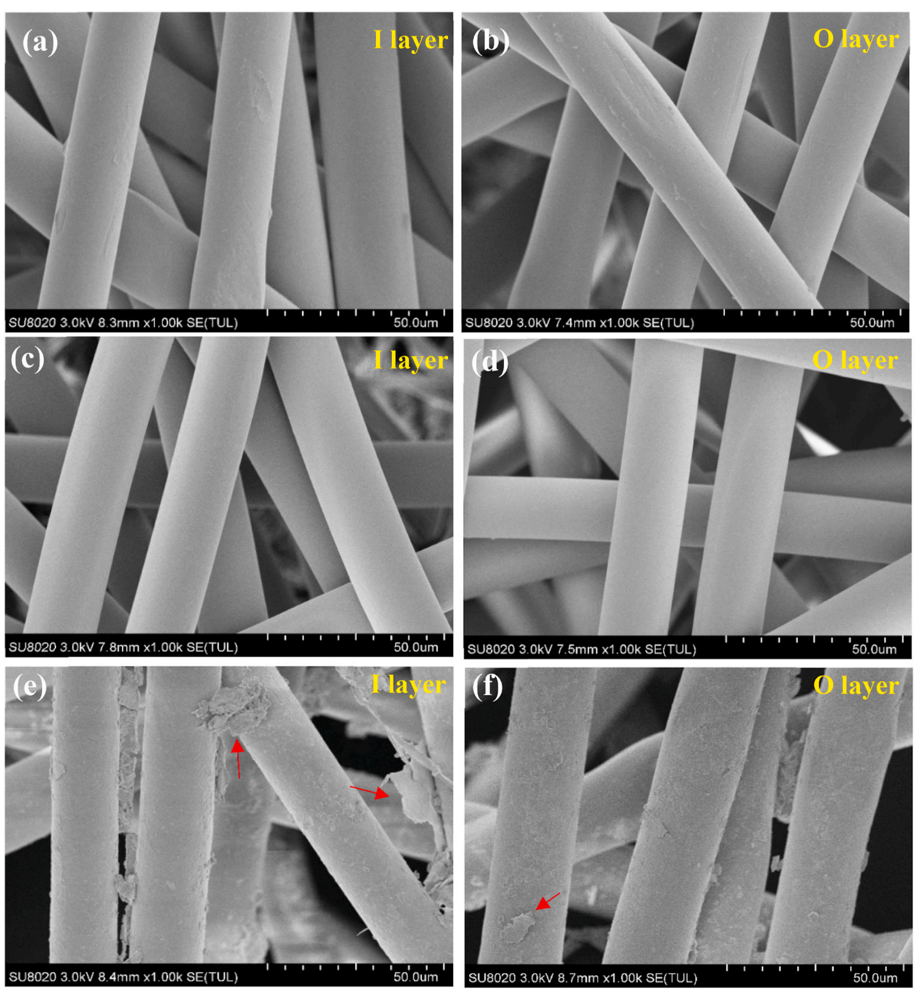

Fig. 4. Microscopic analysis of face masks. (a). Inner layer of KN95; (b). Outer layer of KN95; (c). Inner layer of virgin disposable mask; (d). Outer layer of virgin disposable mask; (e). Inner layer of discarded disposable mask; (f). Outer layer of discarded disposable mask. Red arrows indicate the fragments in fibers from discarded disposable masks. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

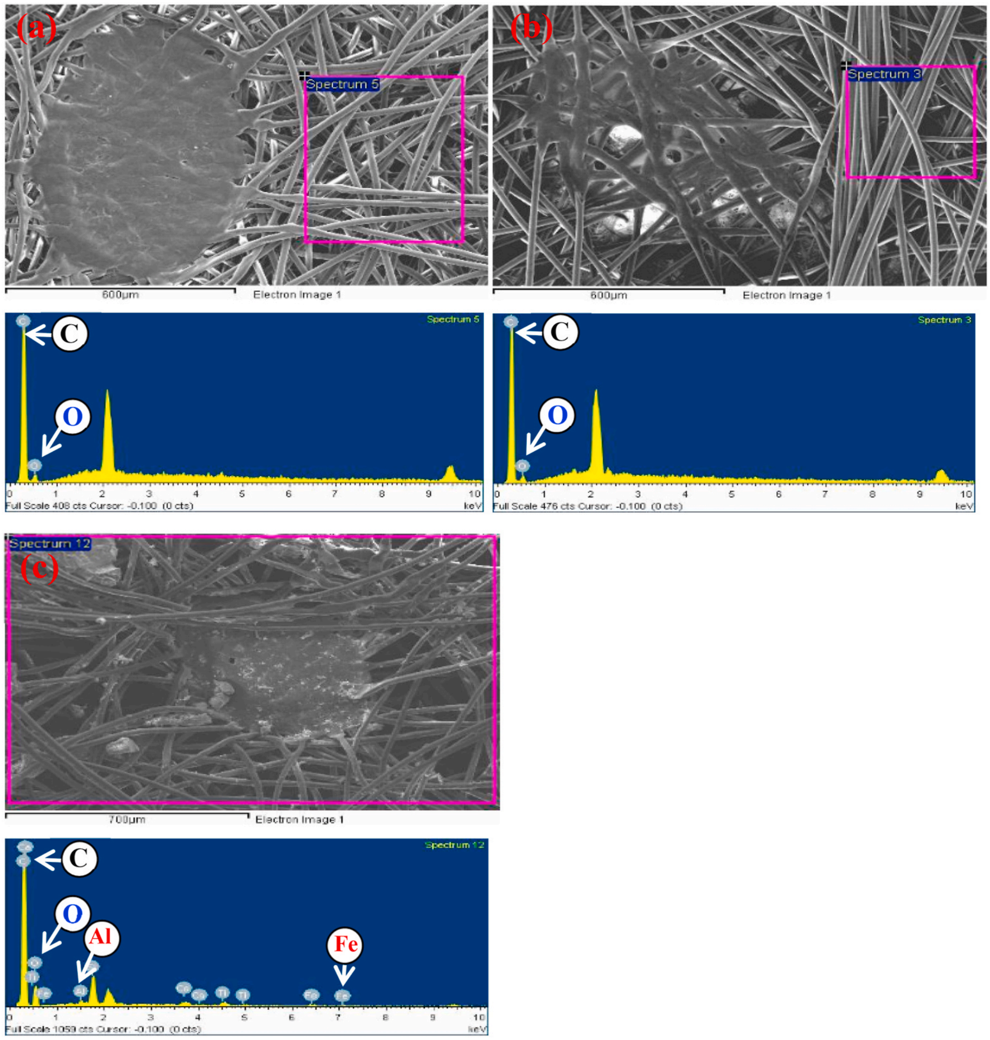

Fig. 5. Elements attached to the surface of fibers. (a). New KN95 respirator; (b). New disposable mask; (c). Discarded disposable masks from Qing River.

microbial biofilms (Sooriyakumar et al., 2022); subsequently, the discarded face masks act as vectors for transmitting pathogens or bacteria because of the persistent inner feature of the plastic substrates in environments. Consequently, the adsorption ability of discarded face masks to environmental contaminants would pose more health hazards to wild organisms through various pathways. At the same time, the fibers shedding from these discarded face masks could aggregate the present environmental microplastic contamination. Thus, as a necessary precaution, more attention in the future should reinforce the medical waste management of these used face masks to prevent microfiber contamination and control pathogens spreading wildly.

3.3. Microfiber shedding from face masks

As predicted, many microfibers (Fig. 6(a)) and a few tiny particles (Fig. 6(b)) shedding from new face masks were also confirmed to be PP. The number of microfibers shedding from disposable masks with an average of 50.33 ± 18.50 items/mask was higher significantly than the KN95 respirator of 31.33 ± 0.57 items/mask ($p < 0.05$) (Fig. 6(c)). At the same time, the average sizes of microfibers shedding from the disposable mask were 565.19 ± 411.93 μm, ranging from 59 μm to 2248 μm. Similarly, the size of the microfibers was also equal to the microfibers from KN95 with an average size of 607.12 ± 474.01 μm, ranging from 94 μm to 2882 μm. However, the size of microfibers in the present study was less than the document of 183.00 ± 78.42 particles/piece from 18 brands of disposable masks (Chen et al., 2021). Surprisingly, the number of microfibers obtained from the present results was significantly lower than the 1300–4400 microfibers (>1 μm) per face mask (Ma et al., 2021), which might be explained by the lowest size of microfiber detected in different investigations. More microfibers would be detected with the increase of the detection limits of particle size, such as from micrometer to nanometer. It could be concluded that these microfibers and microplastics should be generated during the production of masks but not aged or weathered face masks themselves during immersion. They generally adhere to the surface of the face masks and then shed once used. For example, 25–172 fiber-like microplastics inhalation was observed based on a 2-h of simulated respiration using different new face masks, and the amount of microfiber inhalation increased with the wearing time (Li et al., 2021). Consequently, these microfibers in new face masks might be directly breathed into human bodies. Ma et al. (2021) also detected microplastics in the nasal mucus of mask wearers, implying that these microplastics in masks could be inhaled when wearing, especially, a new face mask. Thus, it is necessary to evaluate the potential health hazards caused by microfibers shedding from face masks when wearing new face masks. By the way, it should point out that the tiny plastic particles with irregular shapes should be the by-product of manufacturing face masks, and they were not counted in the present study due to the small number. However, the ingestion of these particles through inhalation should be paid more attention to when wearing new face masks.

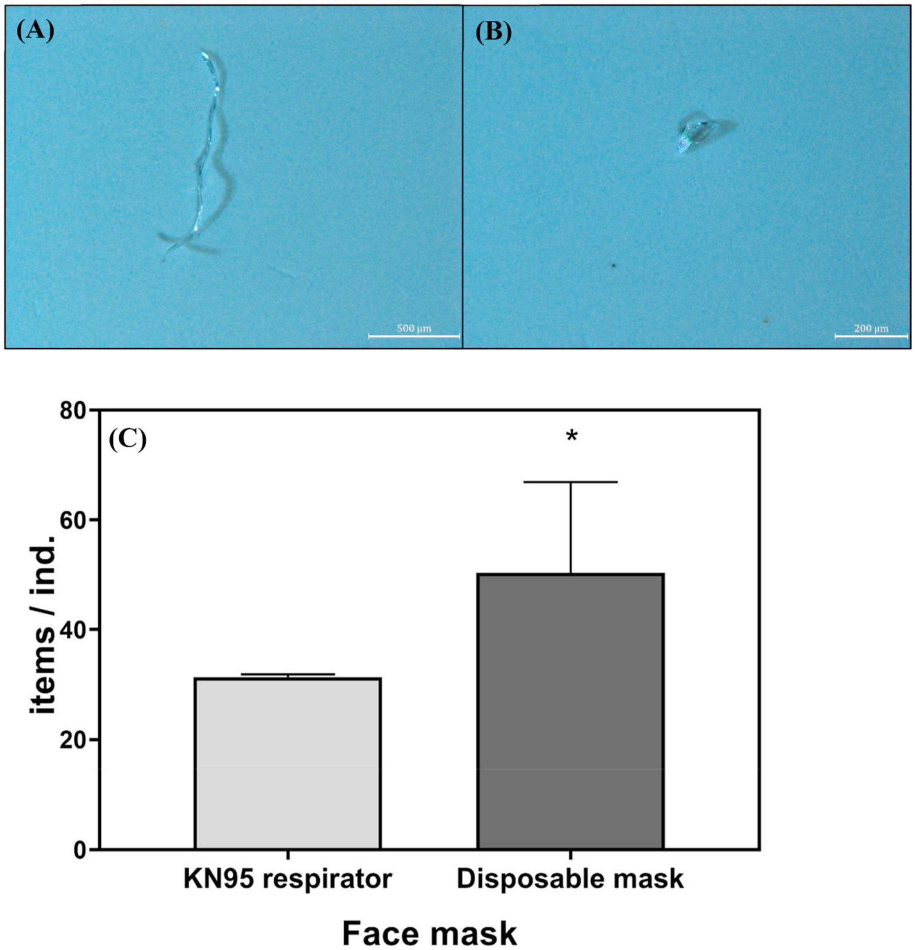

Fig. 6. Microfiber and particles shedding from new face masks. (A). Microfiber; (B). Microplastics. (C). Numbers of microfibers and microplastics. Asterisk indicates statistical significance ($p < 0.05$) between the two types.

Most importantly, these microfibers and microparticles attaching to the surface of fabrics of new masks would be released into environments once used. So, new face masks are the potential source of microplastic contamination in environments, especially in urban regions where many face masks are used daily due to concentrated population and intensive activities. Although we didn't accurately evaluate the release of microfiber from these discarded face masks, there is no doubt that more microfibers could be generated and then released into the environment due to wear and tear and aging, as demonstrated by earlier studies (Chen et al., 2021; Ma et al., 2021; Wu et al., 2022). At the same time, these face masks in the environment might threaten wildlife and the ecosystem in the land and aquatic environment once discarded into the environment. For example, Hiemstra et al. (2021) reported that fish was entrapped in a medical glove, and these discarded medical face masks were also found to be used as nesting materials by birds in the Netherlands, implying that the discarded PPEs are a new threat to wildlife for a long time. Regrettably, it is estimated that 1.56 billion face masks had entered the oceans in 2020 (Chowdhury et al., 2021), which accounted for a large proportion of the 25.9 ± 3.8 thousand tons of pandemic-associated medical plastic waste leakage into global oceans (Peng et al., 2021). As an emerging microfiber source, these discarded face masks would produce extra microplastic contamination in the environment, including freshwater and marine environment. Consequently, COVID-19 causes public health emergencies and aggravates plastic contamination due to the dramatic increase of used personal protective equipment, particularly face masks which are mandatory to wear daily during the pandemic.

On the premise of the prevention principle, more effective waste management measures should be implemented to avoid these discarded face masks and prevent microfiber contamination from sources, such as improving recycling consciously by incentives and raising public awareness through education. Alternatively, using a reusable face mask is also a solution for markedly reducing the amount of discarded face masks in environments. At the same time, the microfibers and microparticles attaching to new face masks should also be controlled and eliminated before on sale to prevent them from releasing into the environment. Most importantly, more emphasis on responsible consumption should be strengthened to collect and return the used face masks for proper disposal. This should be a priority in solving the challenge of microfiber contamination. After all, a recent study reported that consumer-based actions could significantly reduce plastic contamination in rivers (Marazzi et al., 2020). Of course, these time-consuming and high-cost measurements should be ruled out despite effectiveness, such as disinfection and segregation, due to technical barriers in most countries. Just as recommended by Sarkar et al. (2022), it is crucial to implement stringent environmental regulations and the development of appropriate infrastructure and economically sound, environmentally sustainable, and socially acceptable plastic waste management strategies for addressing the issue of plastic and microplastic contamination, which is also the goal of UN SDGs by 2030.

4. Conclusions

The present study firstly reported the presence of discarded face masks in an urban river with a density of $(8.28 \pm 4.21) \times 10^{-5}$ items/m^2, which was significantly lower than other sites reported recently. It suggested that the density of discarded face masks in the environment mainly depends on the local sound solid waste management, but not the density of the population. Moreover, the new face masks could release microfibers with microplastics, while the discarded masks in the aquatic environment would release more microfibers and adsorb various contaminants. Consequently, this might aggravate threats to the aquatic ecosystem as an emerging contamination source. Therefore, effective waste management measures for used face masks by strengthening solid waste recovery and raising public responsible consumption behavior are crucial to prevent microfiber contamination and avoid the ecological disaster caused by face masks after COVID-19.

Credit author statement

Wang F.F.: Writing – original draft and Methodology; Wu H.W.: Investigation and Visualization; Li J.N.: Investigation and Visualization; Liu J.L.: Methodology; Xu Q.J.: Conceptualization, Writing – review & editing;:AN L.H. Conceptualization, Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

This paper was supported by the Central Public-interest Scientific Institution Basal Research Fund, Chinese Research Academy of Environmental Sciences (2020YSKY-002). We thank the anonymous reviewers for their insightful and constructive comments that helped improve this article.

References

Akhbarizadeh, R., Dobaradaran, S., Nabipour, I., Tangestani, M., Abedi, D., Javanfekr, F., Jeddi, F., Zendehboodi, A., 2021. Abandoned Covid-19 personal protective equipment along the Bushehr shores, the Persian Gulf: an emerging source of secondary microplastics in coastlines. Mar. Pollut. Bull. 168, 112386 https://doi.org/10.1016/j.marpolbul.2021.112386.

Ammendolia, J., Saturno, J., Brooks, A.L., Jacobs, S., Jambeck, J.R., 2021. An emerging source of plastic pollution: environmental presence of plastic personal protective equipment (PPE) debris related to COVID-19 in a metropolitan city. Environ. Pollut. 269, 116160 https://doi.org/10.1016/j.envpol.2020.116160.

Aragaw, T.A., 2020. Surgical masks as a potential source of microplastic pollution in the COVID-19 scenario. Mar. Pollut. Bull. 159, 111517 https://doi.org/10.1016/j.marpolbul.2020.111517.

Badillo-Goicoechea, E., Chang, T.H., Kim, E., LaRocca, S., Morris, K., Deng, X., Chiu, S., Bradford, A., Garcia, A., Kern, C., Cobb, C., Kreuter, F., Stuart, E.A., 2021. Global trends and predictors of face mask usage during the COVID-19 pandemic. BMC Publ. Health 21 (1), 2099. https://doi.org/10.1186/s12889-021-12175-9.

Bailey, R.I., Cheng, H.H., Chase-Topping, M., Mays, J.K., Anacleto, O., Dunn, J.R., Doeschl-Wilson, A., 2020. Pathogen transmission from vaccinated hosts can cause a dose-dependent reduction in virulence. PLoS Biol. 18 (3), e3000619 https://doi.org/10.1371/journal.pbio.3000619.

Benson, N.U., Bassey, D.E., Palanisami, T., 2021. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Heliyon 7 (2), e06343. https://doi.org/10.1016/j.heliyon.2021.e06343.

Boroujeni, M., Saberian, M., Li, J., 2021. Environmental impacts of COVID-19 on Victoria, Australia, witnessed two waves of Coronavirus. Environ. Sci. Pollut. Res. 28 (11), 1–10. https://doi.org/10.1007/s11356-021-12556-y.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Publ. Health 17 (4), 1212. https://doi.org/10.3390/ijerph17041212.

Chen, X., Chen, X., Liu, Q., Zhao, Q., Xiong, X., Wu, C., 2021. Used disposable face masks are significant sources of microplastics to environment. Environ. Pollut. 285, 117485 https://doi.org/10.1016/j.envpol.2021.117485.

Chowdhury, H., Chowdhury, T., Sait, S.M., 2021. Estimating marine plastic pollution from COVID-19 face masks in coastal regions. Mar. Pollut. Bull. 168, 112419 https://doi.org/10.1016/j.marpolbul.2021.112419.

De-la-Torre, G.E., Rakib, M.R.J., Pizarro-Ortega, C.I., Dioses-Salinas, D.C., 2021. Occurrence of personal protective equipment (PPE) associated with the COVID-19 pandemic along the coast of Lima, Peru. Sci. Total Environ. 774, 145774 https://doi.org/10.1016/j.scitotenv.2021.145774.

Ding, L., Mao, R., Ma, S., Guo, X., Zhu, L., 2020. High temperature depended on the ageing mechanism of microplastics under different environmental conditions and its effect on the distribution of organic pollutants. Water Res. 174, 115634.

Duan, J., Bolan, N., Li, Y., Ding, S., Atugoda, T., Vithanage, M., Sarkar, B., Tsang, D.C.W., Kirkham, M.B., 2021. Weathering of microplastics and interaction with other coexisting constituents in terrestrial and aquatic environments. Water Res. 196, 117011 https://doi.org/10.1016/j.watres.2021.117011.

Fadare, O.O., Okoffo, E.D., 2020. COVID-19 face masks: a potential source of microplastic fibers in the environment. Sci. Total Environ. 737, 140279 https://doi.org/10.1016/j.scitotenv.2020.140279.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard Mater. 344, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014.

Hasan, N.A., Heal, R.D., Bashar, A., Haque, M.M., 2021. Face masks: protecting the wearer but neglecting the aquatic environment? - a perspective from Bangladesh. Environ. Chall. 4, 100126 https://doi.org/10.1016/j.envc.2021.100126.

Hiemstra, A.F., Rambonnet, L., Gravendeel, B., Schilthuizen, M., 2021. The effects of COVID-19 litter on animal life. Anim. Biol. Leiden 71 (2), 1–17. https://doi.org/10.1163/15707563-bja10052.

Hutten, I.M., 2007. Chapter 5 Processes for Nonwoven Filter Media. Handbook of Nonwoven Filter Media, pp. 195–244. https://doi.org/10.1016/b978-185617441-1/50020-2.

Jung, S., Lee, S., Dou, X., Kwon, E.E., 2021. Valorization of disposable COVID-19 mask through the thermo-chemical process. Chem. Eng. J. 405, 126658.

Leonas, K.K., Jones, C.R., 2003. The relationship of fabric properties and bacterial filtration efficiency for selected Surgical mask. J. Text. Appar. Technol. Manag. 3 (2), 1–8.

Li, L., Zhao, X., Li, Z., Song, K., 2021. COVID-19: performance study of microplastic inhalation risk posed by wearing masks. J. Hazard Mater. 411, 124955 https://doi.org/10.1016/j.jhazmat.2020.124955.

Ma, J., Chen, F., Xu, H., Jiang, H., Liu, J., Li, P., Chen, C.C., Pan, K., 2021. Face masks as a source of nanoplastics and microplastics in the environment: quantification, characterization, and potential for bioaccumulation. Environ. Pollut. 288, 117748 https://doi.org/10.1016/j.envpol.2021.117748.

Marazzi, L., Loiselle, S., Anderson, L.G., Rocliffe, S., Winton, D.J., 2020. Consumer-based actions to reduce plastic pollution in rivers: a multi-criteria decision analysis approach. PLoS One 15 (8), e0236410. https://doi.org/10.1371/journal.pone.0236410.

Matuschek, C., Moll, F., Fangerau, H., Fischer, J.C., Zänker, K., van Griensven, M., Schneider, M., Kindgen-Milles, D., Knoefel, W.T., Lichtenberg, A., Tamaskovics, B., Djiepmo-Njanang, F.J., Budach, W., Corradini, S., Häussinger, D., Feldt, T., Jensen, B., Pelka, R., Orth, K., Peiper, M., et al., 2020. Face masks: benefits and risks during the COVID-19 crisis. Eur. J. Med. Res. 25 (1), 32. https://doi.org/10.1186/s40001-020-00430-5.

Okuku, E., Kiteresi, L., Owato, G., Otieno, K., Mwalugha, C., Mbuche, M., Gwada, B., Nelson, A., Chepkemboi, P., Achieng, Q., Wanjeri, V., Ndwiga, J., Mulupi, L., Omire, J., 2021. The impacts of COVID-19 pandemic on marine litter pollution along the Kenyan Coast: a synthesis after 100 days following the first reported case in Kenya. Mar. Pollut. Bull. 162, 111840 https://doi.org/10.1016/j.marpolbul.2020.111840.

Peng, Y., Wu, P., Schartup, A.T., Zhang, Y., 2021. Plastic waste release caused by COVID-19 and its fate in the global ocean. Proc. Natl. Acad. Sci. USA 118 (47), e2111530118. https://doi.org/10.1073/pnas.2111530118.

Sarkar, B., Dissanayake, P.D., Bolan, N.S., Dar, J.Y., Kumar, M., Haque, M.N., Mukhopadhyay, R., Ramanayaka, S., Biswas, J.K., Tsang, D.C.W., Rinklebe, J., Ok, Y. S., 2022. Challenges and opportunities in sustainable management of microplastics and nanoplastics in the environment. Environ. Res. 207, 112179 https://doi.org/10.1016/j.envres.2021.112179.

Shen, M., Zeng, Z., Song, B., Yi, H., Hu, T., Zhang, Y., Zeng, G., Xiao, R., 2021. Neglected microplastics pollution in global COVID-19: disposable surgical masks. Sci. Total Environ. 790, 148130 https://doi.org/10.1016/j.scitotenv.2021.148130.

Shruti, V.C., Pérez-Guevara, F., Elizalde-Martínez, I., Kutralam-Muniasamy, G., 2020. Reusable masks for COVID-19: a missing piece of the microplastic problem during the global health crisis. Mar. Pollut. Bull. 161 (Pt B), 111777 https://doi.org/10.1016/j.marpolbul.2020.111777.

Sooriyakumar, P., Bolan, N., Kumar, M., Singh, L., Yu, Y., Li, Y., Weralupitiya, C., Vithanage, M., Ramanayaka, S., Sarkar, B., Wang, F., 2022. Biofilm formation and its implications on the properties and fate of microplastics in aquatic environments: a review. J. Hazard. Mater. Adv. 6, 100077 https://doi.org/10.1016/j.hazadv.2022.100077.

Sullivan, G.L., Delgado-Gallardo, J., Watson, T.M., Sarp, S., 2021. An investigation into the leaching of micro and nano particles and chemical pollutants from disposable face masks - linked to the COVID-19 pandemic. Water Res. 196, 117033 https://doi.org/10.1016/j.watres.2021.117033.

Tesfaldet, Y.T., Ndeh, N.T., 2022. Assessing face masks in the environment by means of the DPSIR framework. Sci. Total Environ. 814, 152859 https://doi.org/10.1016/j.scitotenv.2021.152859.

Torres, F.G., De-la-Torre, G.E., 2021. Face mask waste generation and management during the COVID-19 pandemic: an overview and the Peruvian case. Sci. Total Environ. 786, 147628 https://doi.org/10.1016/j.scitotenv.2021.147628.

Wang, Z., An, C., Chen, X., Lee, K., Zhang, B., Feng, Q., 2021. Disposable masks release microplastics to the aqueous environment with exacerbation by natural weathering. J. Hazard Mater. 417, 126036 https://doi.org/10.1016/j.jhazmat.2021.126036.

World Health Organization, 2020. Shortage of personal protective equipment endangering health workers worldwide. Saudi Med. J. 41 (4), 441.

Wu, P., Li, J., Lu, X., Tang, Y., Cai, Z., 2022. Release of tens of thousands of microfibers from discarded face masks under simulated environmental conditions. Sci. Total Environ. 806 (Pt 2), 150458 https://doi.org/10.1016/j.scitotenv.2021.150458.

Yang, L., Qiao, F., Lei, K., Li, H., Kang, Y., Cui, S., An, L., 2019. Microfiber release from different fabrics during washing. Environ. Pollut. 249, 136–143. https://doi.org/10.1016/j.envpol.2019.03.011.

Yim, W., Cheng, D., Patel, S.H., Kou, R., Meng, Y.S., Jokerst, J.V., 2020. KN95 and N95 respirators retain filtration efficiency despite a loss of dipole charge during decontamination. ACS Appl. Mater. Interfaces 12 (49), 54473–54480. https://doi.org/10.1021/acsami.0c17333.

Yong, C.Q.Y., Valiyaveettil, S., Tang, B.L., 2020. Toxicity of microplastics and nanoplastics in mammalian systems. Int. J. Environ. Res. Publ. Health 17 (5), 1509. https://doi.org/10.3390/ijerph17051509.