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Environmental risks of disposable face masks during the pandemic of COVID-19: Challenges and management

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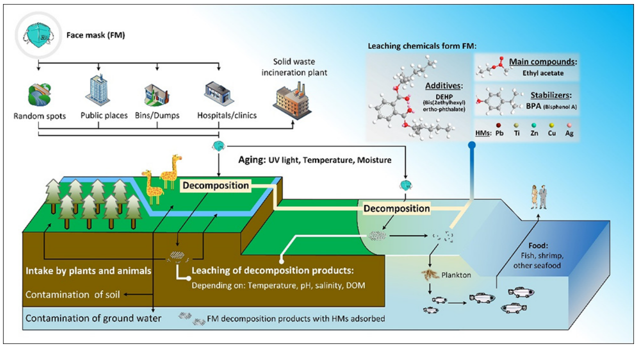
HIGHLIGHTS

- Global FM consumption during the COVID-19 pandemic is 449.5 billion.
- Organics and inorganics embedded in FM pose huge threats to the ecosystem.
- Urgent attention for FMs waste management is suggested in the near future.

GRAPHICAL ABSTRACT



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ABSTRACT

Since the COVID-19 outbreak in early 2020, face mask (FM) has been recognized as an effective measure to reduce the infection, increasing its consumption across the world. However, the large amount of at-home FM usage changed traditional medical waste management practices, lack of improper management. Currently, few studies estimate FM consumption at a global scale, not to say a comprehensive investigation on the environmental risks of FM from a life cycle perspective. Therefore, global FM consumption and its associated environmental risks are clarified in the present study. Our result shows that 449.5 billion FMs were consumed from January 2020 to March 2021, with an average of 59.4 FMs per person worldwide. This review also provides a basis to understand the environmental risk of randomly disposed of FM and highlights the urgent requirement for the attention of FMs waste management to prevent pollution in the near future.

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1. Introduction

Face masks (FM) are generally worn to filter air entering the mouth and nose to block harmful gases, odors, droplets, viruses and other substances. The efficacy of FMs toward viruses was documented during the SARS epidemic in 2003, where measures such as gloves, gowns, and handwashing offered no additional protection for FM wearers. During the COVID -19 pandemic, Howard et al. (2021) and Cheng et al. (2020) suggest that FM-wearing is a useful and low-cost adjunct to reduce viral spread (Chen, 2021). The World Health Organization (WHO) published interim guidance on personal protective equipment (PPE) and encouraged everyone to wear FM when taking public transportation and going to public areas (WHO, 2020a). As a result, most countries have encouraged people to wear FMs, while more and more countries, including France, the UK, Germany, Iran, Israel, China, Thailand, and the USA, have made FMs compulsory.

Disposable FMs were designed for healthcare professionals with further proper disposal after use, but with the COVID-19 pandemic, FMs became a mandatory part of daily life for a major part of the world population, making its disposal and associated environmental risks of significant concern. Aragaw and Mekonnen (2021) estimated that the global FM consumption could reach 129 billion per month, while the UK alone consumes 53 million FMs per day during the COVID-19 pandemic. Due to the lack of disposal guidance, the general public's extensive use of FMs could lead to severe plastic waste generation, which would enter soil and water and become a persistent pollutant (Wang et al., 2020a). For example, Haddad et al. (2021) documented a total of 689 PPE items along the coastline of Agadir, Morocco, while 96.81% of them are proven to be FMs. Similarly, PPE items occurred in 91.7% and 66.6% along the beaches of Peru and Argentina, with 94.5% and 48.8% found PPE are identified to be FMs. Marine Conservation Society (MCS) reported that FMs were found on nearly 30% of beaches in the UK (Laville, 2020), which might be mistakenly consumed as food by marine animals and seabirds (Dharmaraj et al., 2021). Furthermore, the improperly disposed FMs may contain viruses and particles that could pose a risk for virus transmission, becoming a microbial habitat and affecting environmental processes in aquatic ecosystems (Dussud et al., 2018). FMs could be entrapped by aquatic and riparian vegetation, accumulate at the surface of reservoirs, and transported through rivers to the ocean causing further pollution (Shumilova et al., 2019).

Moreover, most single-use FMs are made of nonrenewable petroleum-based polymers, such as polypropylene (PP) and polyethylene (PE), which can generate secondary microplastic (MPs) pollution (Aragaw, 2020; Chen et al., 2021; Fadare and Okoffo, 2020). MPs would pose huge threats to the ecosystem and public health due to their carcinogenic, mutagenic, and neurotoxic properties along the aquatic food chain (Zhang et al., 2021). Besides, the release of heavy metals and additives (e.g., stabilizers and plasticizers) from FMs would also induce environmental contamination. Although several recently published papers highlight the potential environmental risks caused by the extensive usage of FMs (Peng et al., 2021; Selvaranjan et al., 2021), few of them estimate the FM consumption at a global scale, not to say a comprehensive investigation on the environmental risks of FMs from a life cycle perspective.

To address the knowledge gap on the basic environmental relevant information of FMs, we investigate FMs' global consumption, release to the aquatic environment, transport, transformation pathways in their life cycles, and ecotoxicity based on literature. We aim to delineate the complications and challenges of FMs generated during the COVID-19 pandemic, clarifying the global status of FM consumption and the consequential environmental risks. Suggestions on FM management were also discussed to mitigate the potential ecotoxicological risks.

2. FMs consumption during the pandemic

There are several types of FM, such as surgical mask, N95 mask, anti-dust respirator (KN95), activated carbon mask and cotton mask, which could prevent COVID-19 transmission to a different extent. Most single-used medical FMs are multi-layered, including two outer waterproof layers (nonwoven fibers), one middle adsorption layer (melt-blown filter), elastic band, nose wire and other components. The PP nonwoven microfiber accounts for 90% of the waterproof and filter layers materials. Polyethylene terephthalate (PET) and polyurethane (PU) are common materials used in elastic bands, while PP/galvanized iron wire and PE/galvanized iron wire are commonly used for nose wire production.

Understating the magnitude of FMs consumption during the pandemic is essential to provide a baseline for consequential environmental risk evaluation, directing global attention to plastic waste management. However, there were huge gaps in data availability, which also exhibited significant variations across different countries and cultures. Researchers have proposed several scenarios to estimate FMs consumption. For example, Sangkham (2020) quantified the daily FMs usage in Asia by multiplying the total population, percentage of the urban population, and a constant FM acceptance rate (80%) in each country. Likewise, Akber Abbasi et al. (2020) adopted a varying acceptance rate between 50% to 80% and a daily FM use between 1 and 4 pieces to calculate FM consumption in the Arabian Peninsula. However, the above studies did not consider the willingness to wear FMs or the supply shortages. Furthermore, previous estimations also failed to address the significant reduction of FMs consumption during lockdowns. Thus, the total amount of FMs consumption could be overestimated, complicating environmental risk management.

To address the accuracy of FMs consumption, we estimate the global FMs usage by considering the following factors: the population, willingness to wear FMs, and the increase in supply in each country since the beginning of the pandemic. A detailed calculation is shown in Eq. (1):

$$C_{FM} = \sum_1^i \sum_1^{t_i} \left(P_i \times U_{Pi} \times D \times R_i \times SUP_i\right) \tag{1}$$

where C_{FM} is the amount of global FM consumption, i is the number of countries estimated, t_i is the number of days from the first occurrence of COVID-19 cases, P_i is the population in country i, and U_{Pi} is the urbanization rate in country i. We derived these values from the project Our World in Data (ourworldindata.org).

SUP_i is the FM supply rate, which is assumed to be increased from 0.05 to 1.00 with a daily increase of 0.01 since the first occurrence of the confirmed case in country i. R_i is the FM-wearing rate in country i, and it can be calculated using Eq. (2):

$$R_i = W_i \times PD_i \times (100 - S_i) \tag{2}$$

where W_i is the awareness of wearing an FM, which ranged from 0.01 to 0.80 in this research, with a daily increase of 0.01 since the first occurrence of the confirmed case. PD_i is the population density in country i. It is used as a penalty index for the estimation, where a higher population density represents a higher risk for virus circulation and thus a higher demand for wearing masks. S_i is the stringency index in country i; it is a composite measure based on nine response indicators, including school closures, workplace closures, and travel bans, rescaled to a value from 0 to 100 (e.g., 100 means strictest). We sourced the values of W_i and S_i from the project Our World in Data (ourworldindata.org).

We estimated FM consumption in 147 countries, covering 97.1% of the global population based on the available data. According to our calculations, the global FM consumption from January 21, 2020 to March 19, 2021 is 449.5 billion, with an average of 59.4 FMs per person across the world (Table S1). FMs used by the general population was found to be the highest in Asia, followed by Europe, Africa, South America, North America, and Oceania, accounting for 68.1%, 14.5%, 11.1%, 3.5%, 2.7%, and 0.1% of the global consumption, respectively. In particular, China is the largest consumer that used 98.4 billion FMs, followed by India (72.8 billion), Japan (26.9 billion), Indonesia (19.9 billion), Nigeria (19.9 billion), Pakistan (18.9 billion), Bangladesh (16.6 billion), Germany (13.9 billion), UK (11.4 billion) and the USA (8.6 billion).

Our estimation agrees with the previously reported FMs consumption. For example, it's reported that the UK sent 54.5 million single-use FMs to a landfill every day at its peak, and the UCL Plastic Innovation Hub estimated that FMs demand for the UK is around 24.37 billion per year. In comparison, the UK used 11.4 billion FMs in our estimation, which falls in the reasonable range considering the supply restriction and decreased FMs usage during the lockdown. Those large amounts of FM consumption would generate a surprising amount of plastic waste. By weighing 100 different brands FMs in the laboratory, we estimated the average weight of FM to be between 2 and 3 g. Uncollected and improper managed FMs (defined as FM loss) would end up in the grassland, streets and arable land (Fig. 2). When applying an FM loss rate of 20% (some regions would be higher due to the lack of FM disposal guidance), we estimated that at least 0.18 million tons of FMs plastic would be transported into the aquatic environment and finally entering the ocean (calculated by multiplying the FM consumption amount, average weight and the FM loss rate). As Lebreton et al. (2017) reported that 1.15 to 2.41 million tons of plastic waste entering the ocean every year from rivers, we estimated that FMs account for roughly 6.5% to 11.9% of the total plastics entering the ocean since the pandemic.

3. Life cycle of disposable FMs

Since a massive amount of FMs was released into the environment, it is essential to thoroughly understand the life cycle of FMs. As shown in Fig. 1, generally, used FMs should be treated and properly disposed to eliminate any residual virus. The WHO recommends that used FMs should be pretreated with disinfectants and followed by incinerated to destroy residual pathogens (WHO, 2020b, p. 19). However, as limited FMs collection facilities are available in most countries, used FMs can be found littering the streets (Xu and Ren, 2021), which could be easily flushed into rivers, lakes and bays by rainfall and wind (Hasan et al., 2021). The management of FMs used by the general public poses a huge challenge to the environment. In Bangladesh (Rahman, 2020) and Hongkong (Fig. 2), used FMs were found in random spots, such as hospitals, police stations, and footpaths. Plastic FMs were found in offices, universities, airports, public gardens, streets, and even coastlines in European countries (Patrício Silva et al., 2021) and even developed Hongkong (Fig. 2). Besides, due to insufficient treatment capacity, sanitary landfills are still the most common practice for FM disposal in many developing countries, including India, Bangladesh, Thailand, and Malaysia (Kulkarni, 2020). Those buried FMs would decompose and generate secondary contaminants to the surrounding environment (i.e., groundwater, soil).

The improper disposal of FMs would be degraded into MPs via UV radiation and mechanical or biological intervention in both terrestrial and aqutic environment. These secondary MPs generated by the improper disposable FMs would enter and accumulate in the aquatic environment via multiple biogeochemical processes (e.g., runoff water, tidal movements), posing great ecotoxicological risks to aquatic environment (Hasan et al., 2021). MPs directly affect living organisms by releasing inorganic and organic contaminants and impair human health through ingestion and food chain accumulation (Feng et al., 2019; Wu et al., 2020). Degraded FMs pose additional threats to public health and safety because they may adsorb co-existing pollutants or become carriers for bacteria and viruses. Mechanisms of pollutant leaching during FM degradation are also outlined in Fig. 1, with detailed information summarized and discussed in Section 4.

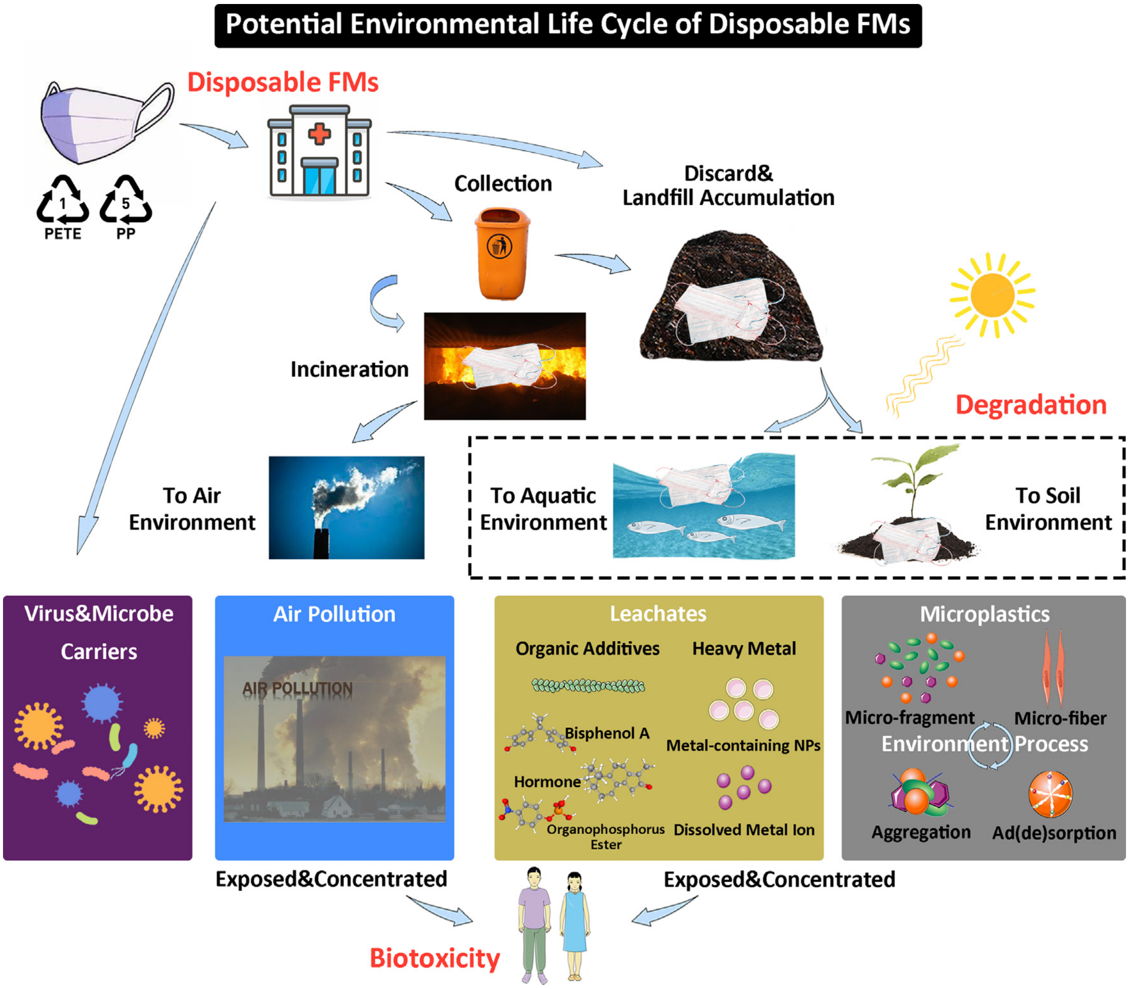


Fig. 1. The life cycle of disposable FMs in the environment.

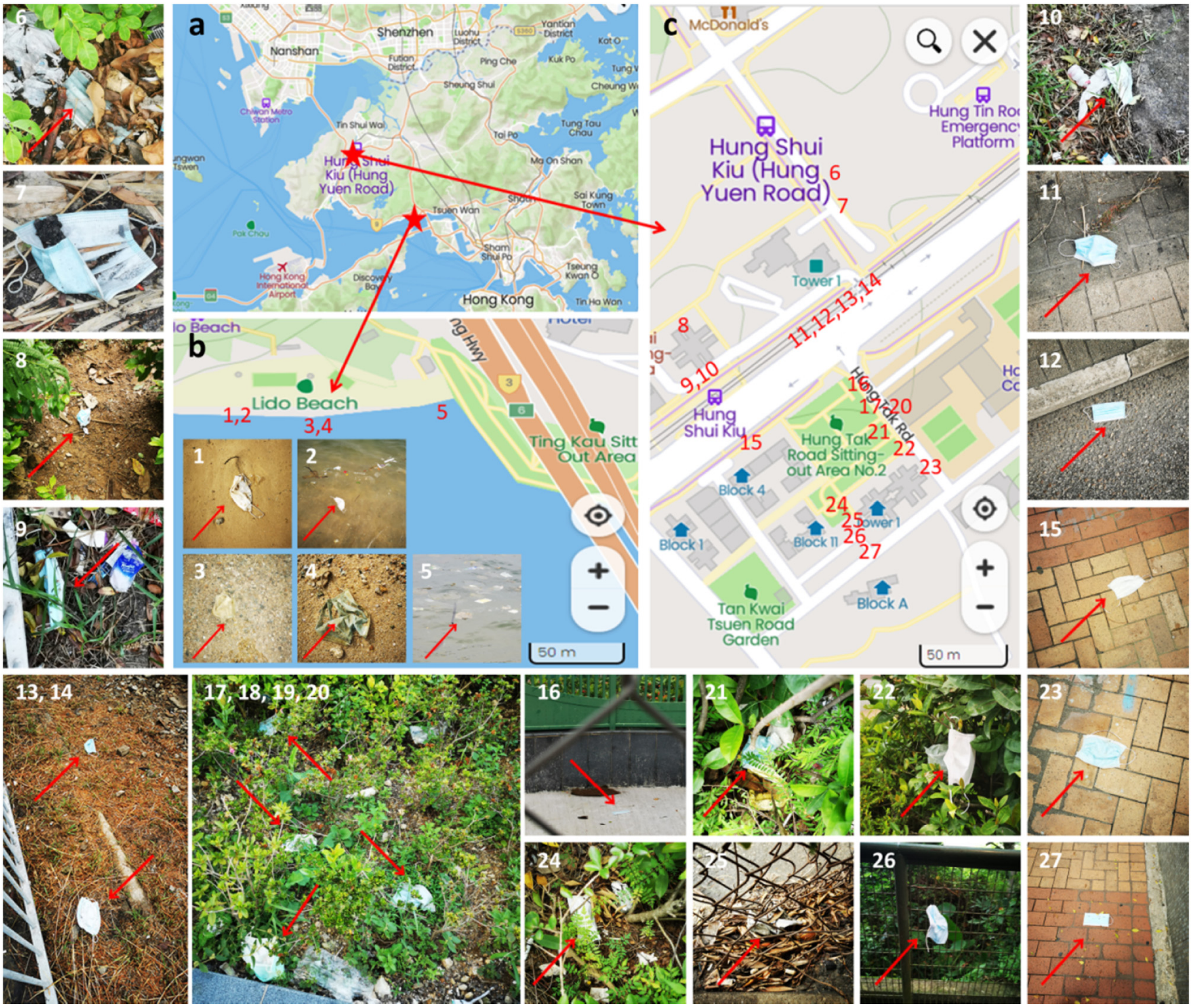


Fig. 2. Used FMs found at Hongkong (a) coastal beach (b) and local environment (c). Note: 5 used FMs found at a very small beach (b) in one afternoon; 22 used FMs were randomly found at a very small local environment (c, including street, bus station, play and rest area, pet garden, et al) in one week.

4. Environmental risks caused by disposable FMs

4.1. *Causes of animal death*

Carelessly discarded FMs can be fatal to wild animals, including swans, coots, penguins, shore crabs, bats, hedgehogs, macaques, fish, and the common octopus (Hiemstra et al., 2021). The FMs can disturb breathing and gill structures and hinder swimming, thus reducing animals' food intake and utilization rate while increasing their energy expenditure (Hasan et al., 2021). For example, in marine environments, widelifes easily mistake FMs and gloves for prey, filling their stomachs with undigestible materials. In the UK, the feet of seabirds were bound in elastic strings, immobilizing the birds for a week. In September 2020, an intact undigested N95 FM was dissected from the stomach of a dead penguin found off the coast of Brazil.

4.2. *Toxic chemicals from disposable FMs*

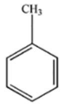
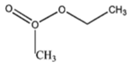
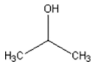
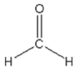
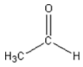
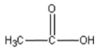
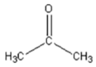
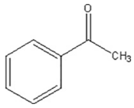
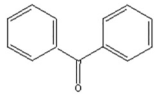
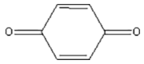
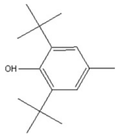
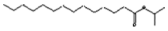
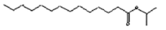
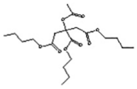
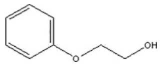
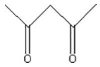
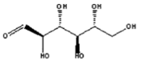
4.2.1. *Fabric dyeing leachates*

A variety of colored FMs are available in the market, but their embedded inks and dyes pose a risk to human health and the environment (Hassaan and Nemr, 2017). The inhalation of dye particles may cause allergic skin reactions, sneezing, and sore eyes. Long-term wear of dyed masks may also affect the nervous and reproductive systems, damaging lungs, liver, and kidneys (Kumar et al., 2018). Those health issues are attributed to VOCs (e.g., benzene, ethylbenzene, and xylenes, known as BTEX) and organic solvents (e.g., ethyl acetate and isopropanol) in dyes and inks (Alabdulhadi et al., 2019). Table 1 summarizes the ecological risks of compounds in inks and dyes during FMs manufacturing. For instance, propanone can significantly decrease the locomotive activity of Sprague Dawley rats (Dianne), while butyraldehyde and 2,5-Cyclohexadiene-1,4-dione affect lungs, thorax, and the respiratory system of rats. When FM is exposed in the aquatic environment, those identified compounds could also be released and affect the environment negatively. For example, Dobaradaran et al. (2021) documented that BTEX may leach into water samples, although the detected concentrations of BTEX did not exceed the Water Framework Directive guidelines, but it can still be a threat for aquatic creatures when considering its large amount from various sources. However, the investigation on specific chemicals released from FM and their relative toxicities is still missing, which requires further in-depth study.

4.2.2. *Organic additives*

Various types of chemicals, including plasticizers, antioxidants, stabilizers, lubricants, and heavy metals, are used during FMs production (Tables 2 and 3). For example, ethylene oxide (EO) is commonly used to inactivate most microbial macromolecules and maintain the structural

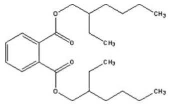
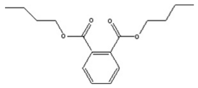
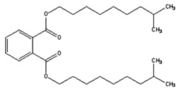
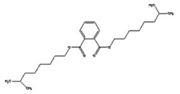
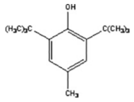
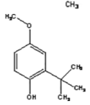
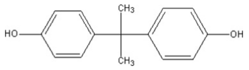
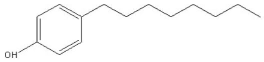
Table 1
Health and ecological effects of the main compounds in inks and dyes (Schmid and Speit, 2007; Jammalamadaka and Raissi, 2010; Neghab et al., 2015; Crowell et al., 2015).

Compounds	Structure	Organism	Remarks
BTEX		Human	Evident dysfunction in kidney and liver.
Ethyl acetate		Rats, human	Decreased respiratory rate and tidal volume; Impair neurological function; Lower blood concentrations.
Isopropanol		Human	Nausea, vomiting, abdominal pain, gastritis, headache, dizziness, confusion, stupor, and coma.
Formaldehyde		Human	FA-induced cytotoxicity (measured as reduction of the nuclear division index) possibly prevented division of damaged cells.
Acetaldehyde		Human	The deficient expression of aldehyde dehydrogenase (ALDH) I will cause elevated concentrations of acetaldehyde in blood, exhibiting characteristic clinical symptoms, such as peripheral vasodilation, flushing, changes in heart rate, difficulties in breathing, and muscle weakness.
Acetic Acid		Budding Yeast	A mechanism of acetic acid toxicity in yeast is related to the induction of growth signaling pathways and oxidative stress. These mechanisms are relevant to aging in all eukaryotes.
Propanone		Sprague–Dawley Rats	Markedly decreased locomotor activity in animals on acetone-paired days compared to air-paired days.
Acetophenone		Rabbit	Standard Draize test; Severe reaction severity.
Diphenyl ether		Rabbit	Standard Draize test; Mild reaction severity.
2,5-Cyclohexadiene-1,4-dione		Mouse	Tumorigenic in lungs, thorax, or respiration, skin, and appendages.
Butylated Hydroxytoluene		Mouse	Tumorigenic in lungs, thorax, or respiration, skin and appendages.
Isopropyl myristate		Guinea Pig	Standard Draize test; Administration onto the skin; Moderate reaction severity.
Isopropyl palmitate		Rabbit	Standard Draize test; Administration onto the skin; Moderate reaction severity.
Pyrene		Mouse	Tumorigenic in skin and appendages.
Tributyl acetylcitrate		Mouse	Pigmented or nucleated red blood cells; Blood changes in erythrocyte (RBC) count; Weight loss or decreased weight gain.
Ethanol, 2-phenoxy-		Rat	Changes in bladder weight; Weight loss or decreased weight gain; Death.
Octane, 1,1′-oxybis-		Mouse	LD50: 1183 mg/kg.
Butyraldehyde		Rat	Other changes in lungs, thorax, or respiration; transaminases; Death.
Acetylacetone		Rat	Changes in thymus weight; Weight loss or decreased weight gain.
D-glucose		Rat	Lethal dose, 50% death; Oral; 25,800 mg/kg dose; Coma; Cyanosis; Gastrointestinal hypermotility or diarrhea.

integrity of FMs. However, the residual EO may induce health concerns, including hemolysis, allergic reactions, and carcinogenesis, which was revealed as moderate toxicity with nonpersistent bio-oxidation (Conway et al., 1983).

Likewise, polybrominated diphenyl ethers (PBDEs) are used to improve the heat resistance of FMs, while nonylphenol (NP) and triclosan are used to resist oxidation and biodegradation, they could also be released to the environment during FM degradation. However, few studies have investigated the additives leached from FMs, while plastic additives' environmental behavior and implications have been widely reported. For example, Luo et al. (2019) investigated the leaching behavior of fluorescent additives in polyurethane in both natural (rivers, lakes, wetlands, and seawater) and simulated water (acidic water, saline, and alkaline water), and found increasing in pH and soak time promoted pollutant release. Solar radiation was also demonstrated to be an essential factor that would promote the release of endocrine interferon (EDCs) from MPs (Chen et al., 2019). The plastic additives also significantly contribute to abnormal embryonic development of sea urchins (Nobre et al., 2015) and cause the deaths of *N. spinipes* (Bejgarn et al., 2015). Thus, the organic additives in FMs, especially those floating on the sea surface and directly exposed to solar radiation, are likely to leach into the environment and cause toxicological effects.

Table 2
Potential risks of additives used in plastic production.

Compound	Structure	Organism	Remark	Ref.
Plasticizers				
DEHP		Catfish	Damage liver; ROS; lipid peroxidation, immunosuppression.	(Mo et al., 2019)
DEP		*Caenorhabditis elegans*	Shorten the lifespan and decreased reproduction rate.	(Pradhan et al., 2018)
DIDP		Zebrafish (*Danio rerio*)	Oxidative stress reactions; Disruption in circadian rhythm.	(Poopal et al., 2020)
DINP		Zebrafish (*Danio rerio*)	Effects on oocytes growth maturation, gonadal development and reproduction; Impair endocannabinoid system.	(Forner-Piquer et al., 2018)
Antioxidants				
BHT		Zebrafish (*Danio rerio*)	Cardiotoxicity and developmental toxicity.	(Sarma et al., 2020)
BHA		Rat liver	ROS production.	(de Oliveira Pateis et al., 2018)
Stabilizers				
BPA		Zebrafish (*Danio rerio*)	Acute metabolic effects in larvae; Effects on hatchability and heart rates; Craniofacial deformity; Elongation of head length.	(Huang et al., 2020)
NP		Mullets	Adverse impact on cell membrane and cellular metabolism.	(Salamat and Derakhshesh, 2020)

DEHP: Di-(2-ethylhexyl) phthalate; DEP: diethyl phthalate; DIDP: Diisodecyl phthalate; DINP: Diisononyl phthalate;
Halogen: Bromine and chlorine; BHT: 2,6-di-tert-butyl-4-methylphenol; BHA; Butyl hydroxyanisole; BPA: Bisphenol A.

4.2.3. Heavy metals

Heavy metals in FMs are usually distributed in antimicrobial agents, nose clips, etc. For instance, galvanized iron wire or aluminium strips are the main material used for nose clips, while metal ions like Zn, Mg, Cr, Fe, and Al can be used as cross-linkers to accelerate sulfur vulcanization during plastic production. Recently, metal-based nanoparticles, such as nano-silver (Nano-Ag) (Chen et al., 2016), silver compounds (Ag^+) (Li et al., 2006), nano-copper (Nano-Cu), and other metal oxides nanoparticles like ZnO, TiO_2, and Al_2O_3 (Chua et al., 2020) are incorporated into the FM layers (both disposable and reusable) as an antimicrobial agent. Nano-Ag, Nano-Cu, and Nano-Zn are the most commonly used antimicrobial agents in commercial N95 FMs (Chua et al., 2020). Hiragond et al. (2018) found that direct coating of Nano-Ag onto FMs had broad-spectrum antimicrobial activities to control Gram-positive and Gram-negative bacteria.

Nevertheless, the engagement of heavy metals in FMs would increase the risks of leached compounds. Most of the leached heavy metal ions were reported to exhibit toxicity (Table 3). Chronic aluminium exposure may cause cognitive problems (Cao et al., 2020), while Zn, Cu, and Ti may damage the liver and pancreas (Li et al., 2011; Zhang et al., 2008). Zhang et al. (2015) reported that Ag^+ increased the mortality of zebrafish embryos and decreased the hatching rate, which demonstrated a significant correlation between hatching rate and Ag^+ concentration.

4.3. Fragmentation into microplastics

FMs are mainly made of plastics and fibers. Most FMs, including surgical masks, N95 masks, anti-dust respirators (KN95), activated carbon masks, and cotton masks (Table S2) are multi-layered, with two outer waterproof layers (nonwoven fibers) and one middle adsorption layer (melt-blown filter), as well as two elastic bands, nose wire, and other components. The polypropylene (PP) nonwoven microfiber accounts for 90% of the waterproof and filter layers materials. Polyethylene terephthalate (PET) and

Table 3
Ecological risks of heavy metals engaged within FMs.

Heavy metal	Organism	Remark	Ref.
Cr	Mouse	No mutagenic effect of $CrCl_3$; Severe acute toxicity of $K_2Cr_2O_7$ (as the mutagen).	(Masood and Malik, 2011)
Pb	Mouse	Significant reduction in serum testosterone, serum and testicular E2; Testicular testosterone increase.	(El-Magd et al., 2017)
Ti	*Daphnia Magna*	Toxic; Nano-TiO_2 could dissociate adsorbed As (V).	(Li et al., 2016)
Zn	*Misgurnus Anguillicaudatus*	A significant time and dose effect relationship between the heavy metal Zn^{2+} treatment and DNA damage in hepatopancreas of loach.	(Zhang et al., 2008)
Cu	*Oryzias Latipes*	Different degrees of liver tissue damage.	(Li et al., 2011)
Ag^+, Ag^{2+}, Ag^{3+}	Zebrafish	Increased mortality, decreased hatching rate, and delayed hatching with a concentration-dependent manner.	(Zhang et al., 2015)
Al	Human	An association between chronic Al exposure and impaired cognitive function in majority of domains including memory, processing speed, and working memory.	(Cao et al., 2020)
Fe	Medaka Fish	Different antioxidant balance by induced intracellular ROS in hatchlings with three iron species.	(Chen et al., 2013)

polyurethane (PU) are the common materials used in elastic bands, while PP/galvanized iron wire and PE/galvanized iron wire are commonly used for nose wire production. They may be broken down into numerous MPs (particle size smaller than 5 mm) along the environmental process (Law and Thompson, 2014), as shown in Fig. 1. Overall, the degradation of FMs highly depends on the environmental process, including the light, temperature, mechanical forces, etc.

Photolysis is considered the critical process to initiate plastic degradation, which usually involves free-radical–mediated reactions initiated by solar irradiation (Liu et al., 2022). Likewise, plastics would undergo thermo-oxidative reactions at high temperatures to break long polymer chains and generate radicals, which can self-propagate until the energy input is discontinued. Kamweru et al. (2011) reported synergic effects on plastic degradation between temperature and UV radiation, during which higher temperature leads to a higher oxidation rate. The extreme temperature change, for example, freezing and thawing in aquatic systems would also lead to the degradation of polyester and polyolefin plastics (Zhang et al., 2021). In addition, the mechanical forces caused by wind and waves would also contribute to the breakdown of plastics via collision and abrasion.

On the other hand, bacteria, fungi, and insects could induce plastic degradation via biochemical processes, such as enzymatic hydrolysis and oxidation (Dawson et al., 2018). For instance, enzymes generated by fungi could degrade nonhydrolyzable polymers like PP (Sánchez, 2020), while the aerobic biodegradation would further decompose plastics into CO_2 and H_2O. However, the lifetime of FMs, its degradation rate or kinetics, as well as its dominating influencing factors remain unclear, which are recommended to be addressed in the future study.

4.4. Pollutant and bacteria carrier

In addition to releasing additives, FMs themselves can also act as pollutant carriers since they can adsorb heavy metals and organics. Particularly, FMs will be transformed into MPs and nanoplastics (NPs), which have been shown to adsorb heavy metals, antibiotics, and other harmful substances (Nizzetto et al., 2016) (Table 4). For example, MPs can adsorb metals like Cd, Cs, Cu, Pb, and Zn in the marine environment, with heavy metal adsorption capacity varying according to plastic type (Turner and Holmes, 2015). The MP adsorption capacity of many persistent organic contaminants have also been widely investigated. It's found that MPs absorb PCBs, DDTs, and HCHs, with the hydrophobicity of pollutants directly affecting its adsorption (Karapanagiot, 2013; Lei et al., 2020; Heskett et al., 2012). Likewise, MPs also exhibited good adsorption capacity of pharmaceuticals (Razanajatovo et al., 2018). Wang et al. (2020a, 2020b) investigated commonly used pesticides on PE agricultural soil film, and concluded that HDPE microplastics had a relatively high adsorption capacity for epoxiconazole, tebuconazole, myclobutanil, and terbuthylazine, ranging from 427 to 963 ng/g. The co-adsorption of heavy metals and organics might pose higher risks of antibiotic resistance genes propagation than their individual species. As reported by Wang, co-exposure to air and UV light resulted in the release of phthalates (PAEs) in PE MPs, which could enhance the adsorption of Cu(II) while generating Cu-PAE and Cu-PAE-TC (tetracycline) complexes (Wang et al., 2021).

FMs and the consequential MPs can also become a substrate for microorganisms, and form biofilms (Fig. 1). The environmental transport of FMs and MPs would spread bacteria and change the microflora and function of whole ecosystems (Yu et al., 2021). For example, Zettler et al. (2013) detected pathogenic Vibrio on PP particles in the North Atlantic, indicating that MPs are vectors for horizontal transportation of antibiotic resistance at the DNA level. However, when Oberbeckmann et al. (2018) studied the effects of different environmental conditions (including nutrients) on the composition and specificity of bacterial communities on the surface of PS and PE, it suggested that MPs could not adsorb most pathogenic bacteria. Overall, no studies have investigated the adsorption and growth mechanisms of microorganisms on FMs yet.

5. Management of disposable FMs

With the lifting of lockdowns and the recovery of global trade, the public relies heavily on PPE to reduce viral transmission (Chen, 2021; Zhang et al., 2020), relying primarily on disposable FMs. Based on our estimation, the total number of FMs consumed globally from January 21, 2020 to March 19, 2021 is 449.5 billion, accounting for 6.5% to 11.9% of the total plastic entering the ocean since the beginning of the pandemic. Moreover, as FMs have been proven effective in preventing viral spread, the demand for FMs is predicted to progressively increase in the pandemic period until 2025 (Aragaw and Mekonnen, 2021). The seriously global spread of more contagious Delta and Omicron variants of COVID-19 (Du et al., 2022) will lead to a more strict FM-wearing policy or rule globally, which may evidently lead to a large amount of FM waste.

As discussed above, improper disposal of FMs can result in the generation of plastic waste, which would be fatal to wild animals, and further converted MPs and bioaccumulate via the food chain to ultimately induce adverse effects on ecosystems (Liang et al., 2021). It is worse that numerous organic and inorganic substances would be generated along the life cycle of FMs, posing huge threats to the ecosystem and public health. Moreover, degraded FMs could pose additional threats to environmental and public safety by adsorbing co-existing pollutants or becoming carriers for bacteria and viruses.

Thus, managing plastic FMs and the consequential MPs pollution due to the COVID-19 pandemic has become a global challenge (Tan et al., 2021). It is important to regulate and control the improper disposal of FMs in public places to prevent release into environments and disruption of ecosystems (Liang et al., 2021). In practice, most FMs in hospitals were properly collected and disposed of, but it is difficult to manage the disposal of household FMs. It is essential to set up collection sites on the streets and in

Table 4
The adsorption capacity of heavy metals and organic pollutants by microplastics.

Pollutants		Adsorption particles	Adsorption capacity (μg/g)	Remarks	Ref.
Heavy metals	Pb	PE MPs; PP	/	Cr and Pb: Stronger adsorption capacity to PE; PP: Pb > Cd > Cu.	(Besson et al., 2020; Godoy et al., 2019; Turner and Holmes, 2015)
	Cd	LDPE microbeads; PE MPs; PP	10.1; <0.8		
	Cr	LDPE microbeads; PE beads	1.7; 1360		
	Cu	PE MPs; PP	31.2; 42.6; <0.8		
	Zn, Cs	PE MPs	<0.8		
Organic contaminants	PAHs	LDPE; PE, PVC	69.8–159.5	Phenanthrene: Strongest adsorption capacity to LDPE; Nonylphenols: CIP: Strongest adsorption capacity to PP; CIP: Strongest adsorption capacity to PE; levofloxacin and DIFE: Strongest adsorption capacity to PVC.	(Liu et al., 2019; Razanajatovo et al., 2018; Wang et al., 2018, 2020a, 2020b; Mato et al., 2001)
	PCBs, DDE, and NP	PP	1.6×10^{-4}–16		
	Pharmaceuticals	PE, PVC	46.1–1740		
	Pesticides	PE	2.9–273.2		
	Antibiotics	PE	61–963		

PAHs: Polycyclic aromatic hydrocarbons; HDPE: High-pressure polyethylene.

PCBs: Polychlorinated biphenyls; DDE: 1,1-Bis (*p*-chlorophenyl) - 2,2-dichloroethylene; Pharmaceuticals: including sulfamethoxazole(SMX), propranolol (PRP), sertraline (SER), amoxicillin (AMX), ciprofloxacin (CIP); trimethoprim(TMP) and levofloxacin; Pesticides: including carbendazim(CAR), dipterex (DIP), diflubenzuron (DIF), malathion (MAL) and difenoconazole (DIFE).

other public areas and to encourage citizens to dispose of FMs in specific mask bins, rather than into ordinary bins or carelessly discarded. Governments should prioritize legislation to prevent littering and educate the public on responsible FM handling. Moreover, the reuse and recycling of FMs should be prioritized. Wang et al. (2020a) Wang et al. investigated a simple reuse approach that used hairdryers after a hot water soak (56 °C for 30 min) to recover filtration effects of FMs. Innovations on FMs materials and fabrication should be encouraged to facilitate biodegradable and reusable of FMs. For example, FMs made with bioplastics can be fully degraded with no harmful by-products (Karan et al., 2019). In addition, regarding resource recovery, converting the used FMs to fuels is a promising management approach. In particular, pyrolysis might be an effective approach for used FMs management (Makarichi et al., 2018). Aragaw and Mekonnen (2021) demonstrated that used FMs and gloves could be transformed to fuel energy via pyrolysis at 400 °C for 1 h.

Since numerous organic and inorganic substances could be generated along the life cycle of FMs, it is essential to identify the species and quantify the concentration of FM leachate, which also remains as huge challenges to thoroughly understand environmental behavior and the fate of FMs. With the development of high-resolution mass spectrometry, non-target analysis has been frequently used for unknown contaminants (Hollender et al., 2017). The non-target screening approach could effectively reveal the unknown FM leachates, which should be addressed more in the future studies.

6. Conclusions

A comprehensive investigation of the environmental risks of disposed FMs from a life cycle perspective is currently limited. The disposed FMs would be degraded into microplastics and release toxic chemicals into the environment, even acting as carriers for pollutants and bacteria. However, in-depth investigation on the environmental fate and transport as well as the consequential risks of disposed FMs is still missing. Therefore, timely understanding of the impacts with ongoing studies is essential before important strides are clearly being made to advance knowledge regarding the environmental risks of FMs in the early stages of their development as an emerging pollutant. Continuing, strengthening, and systematizing these efforts will allow the public to avoid the costs associated with identifying important health and environmental impacts of FMs. This review provides a basis to understand the environmental risks of randomly disposed FMs, and highlights urgent requirements for the attention of FMs waste management to prevent pollution in the near future.

CRediT authorship contribution statement

Bing Li: Conceptualization, Methodology, Data collection, Formal analysis, Writing - Original Draft. **Yuxiong Huang:** Methodology, Formal analysis, Resources, Writing - Original Draft. **Dengting Guo:** Methodology, Data collection, Formal analysis, Writing - Original Draft. **Yuzhi Liu:** Methodology, Writing - Review & Editing. **Ziyi Liu:** Methodology, Writing - Review & Editing. **Jincheng Han:** Methodology, Writing - Review & Editing. **Jian Zhao:** Resources, Writing - Review & Editing. **Xiaoshan Zhu:** Conceptualization, Methodology, Data collection, Formal analysis, Writing - Review & Editing. **Yuefei Huang:** Conceptualization, Formal analysis, Writing - Review & Editing. **Zhenyu Wang:** Methodology, Writing - Review & Editing. **Baoshan Xing:** 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.

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Appendix A. Supplementary data

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