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Global face mask pollution: threats to the environment and wildlife, and potential solutions

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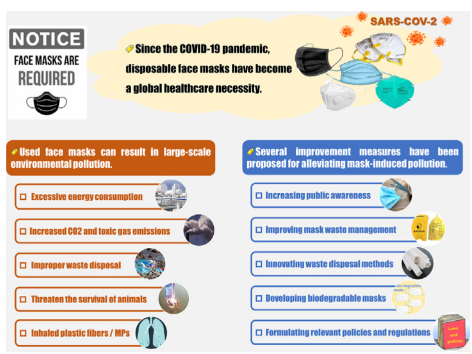
HIGHLIGHTS

- Mask production requires 15 g fuel-based polymers and releases 32.7 g CO_2-equivalent.
- ~15 trillion face masks are used globally each year, resulting in 2 megatons of waste.
- Mask waste disposal leads to secondary MPs and the release of hazardous substances.
- Five solutions are proposed here to alleviate the global crisis induced by mask use.
- Green routes toward developing new materials and recycling mask wastes are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Face masks are an indispensable low-cost public healthcare necessity for containing viral transmission. After the coronavirus disease (COVID-19) became a pandemic, there was an unprecedented demand for, and subsequent increase in face mask production and use, leading to global ecological challenges, including excessive resource consumption and significant environmental pollution. Here, we review the global demand volume for face masks and the associated energy consumption and pollution potential throughout their life cycle. First, the production and distribution processes consume petroleum-based raw materials and other energy sources and release greenhouse gases. Second, most methods of mask waste disposal result in secondary microplastic pollution and the release of toxic gases and organic substances. Third, face masks discarded in outdoor environments represent a new plastic pollutant and pose significant challenges to the environment and wildlife in various ecosystems. Therefore, the long-term impacts on environmental and wildlife health aspects related to the production, use, and disposal of face masks should be considered and urgently investigated. Here, we propose five reasonable countermeasures to alleviate these global-scale ecological crises induced by mask use during and following the COVID-19 pandemic era: increasing public awareness; improving mask waste management; innovating waste disposal methods; developing biodegradable masks; and formulating relevant policies and regulations. Implementation of these measures will help address the pollution caused by face masks.

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Contents

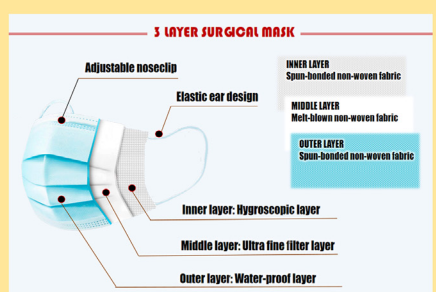
1. Introduction

Disposable face masks have emerged as a crucial measure in public health against respiratory infectious diseases, owing to their ability to reduce the likelihood of airborne infections (Box 1; Tan et al., 2021). The coronavirus disease (COVID-19) outbreak has further emphasized the importance of using these low-cost face masks, which have a limited effectiveness of only a few hours (Allison et al., 2020). Consequently, there has been a surge in their production worldwide to meet the growing demand (Shanmugam et al., 2021). The global usage of face masks reached a staggering 129 billion per month during the early stages of the pandemic. Thus, disposable face masks have become an indispensable healthcare necessity worldwide after the COVID-19 pandemic, with an unprecedented increase in demand and production (Table 1).

Both the production and distribution processes require petroleum-based raw materials and other energy sources (Das et al., 2020), leading to the release of greenhouse gases (Klemes et al., 2020; Giungato et al., 2021). Moreover, the disposal of face masks results in secondary microplastic pollution (MP, <5 mm), the release of toxic gases and organic substances, the loss of ecological integrity from buried waste (Fadare and Okoffo,

Box 1 What are face masks?

Face masks are common and effective devices that create a physical barrier to prevent small particles, such as dust and pathogens, from reaching the mouth or nose of wearers.



Raw materials: Most face masks are manufactured from petroleum-based non-renewable polymers (e.g., polypropylene).

Compositions: Three to five protective layers, an adjustable noseclip, and elastic ear loops. Surgical masks have three layers: (1) a waterproof outer layer composed of spun-bonded non-woven fabric; (2) a middle layer with an ultra-fine filter composed of melt-blown non-woven fabric; and (3) a hygroscopic inner layer, consisting of spun-bonded non-woven fabric. Surgical masks can also have four or five layers, and there are other masks (e.g., N95 or KN95) with four or five layers, which present an additional hot air sponge or another layer of melt-blown non-woven fabric for improving their filtering performance.

Types: Surgical, FFP, N95, and KN95 masks.

Applications: Protection from respiratory diseases, airborne pollen, dust particles, and cold weather.

Box 1. The basic information of face masks.

Table 1
Usage and demand of plastic-based face masks during the COVID-19 pandemic in various countries.

Mask usage and demand	Continent	Country	Number of masks	Reference
Consumption	Asia	Bangladesh	~455 million per month	ESDO, 2020
	South America	Brazil	~255 million per month	Urban and Nakada, 2021
	Asia	China	~ 900 million per day	Shanmugam et al., 2021
	Europe	France	~40 million per week	BoF, 2020
	Asia	India	~40 million per week ~4.6 million per month	Shanmugam et al., 2021
	Europe	Italy	~40 million per day	Shanmugam et al., 2021
	Global	Global	~129 billion per month	Prata et al., 2020
Production	Asia	China	~200 million per day	Shanmugam et al., 2021
	Asia	India	~8 million each week	Shanmugam et al., 2021
	Asia	Japan	~600 million per day	METI, 2020
	Europe	Italy	~90 million per month	Shanmugam et al., 2021
	North America	USA	~140 million in 3 months	Shanmugam et al., 2021
	Europe	UK	~421.8 million in five months	BBC, 2020
	North America	USA	~1.1 billion per year	Shanmugam et al., 2021

2020; Silva et al., 2021a; Li et al., 2022), and air pollution from increased waste incineration (Prata et al., 2020). The increase in used masks in the environment directly contributes to plastic pollutants, posing significant challenges to the environment and wildlife in various ecosystems (Das et al., 2020; Ma et al., 2022). Additionally, used masks may carry viruses, increasing the risk of viral pathogen transmission if not disposed properly

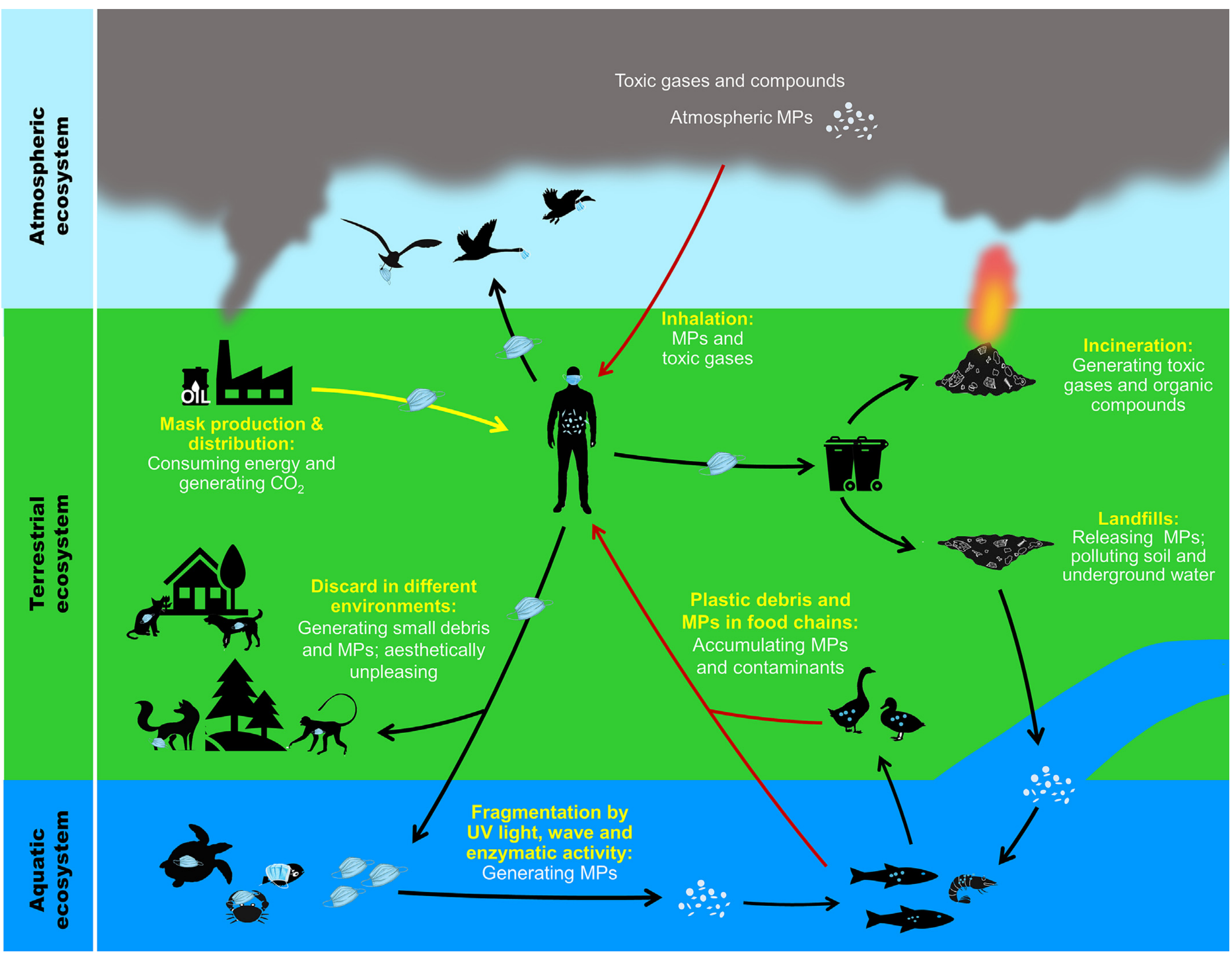


Fig. 1. Massive production and use of face masks have resulted in different pollutants and carbon dioxide (CO_2) emissions. Yellow arrow: face mask production and distribution require petroleum-based raw materials, petrol, workforce, and electricity, which consume energy and release CO_2. Black arrows: face masks discarded in waste containers are incinerated or landfilled with other plastic wastes, which generate harmful gases, toxic compounds, and microplastics (MPs), which can move through the soil and underground water environments. Red arrows: masks discarded in outdoor environments can generate small debris and MPs, which can move through terrestrial, aquatic, and atmospheric ecosystems, thus, threatening wildlife through entanglement and ingestion, causing injury or ecotoxicological effects. These pollutants can accumulate along food chains, thereby resulting in MP pollution in human food resources. Moreover, atmospheric MPs and other toxic gases can be inhaled by terrestrial animals, including humans.

(Ilyas et al., 2020; Orive et al., 2020; Yu et al., 2020). Hence, the generation, use, and disposal of face masks have rapidly transitioned from being a measure in a public health crisis to an economic, social, and ecological threat (Dharmaraj et al., 2021; France, 2022; Shukla et al., 2022).

To address these environmental concerns, it is crucial to adopt circular economy practices that promote sustainable production, use, and recycling of face masks. While some previous reports have highlighted how face masks pollute the environment (Pradit et al., 2021; Fukuoka et al., 2022; Tesfaldet and Ndeh, 2022), a dearth of comprehensive evaluations regarding their overall environmental impacts throughout their entire life cycle remains. This study reviews the global demand volume for face masks and the associated energy consumption and pollution potential throughout their life cycle and proposes solutions to mitigate further environmental problems (Fig. 1).

2. Consumption and production of face masks

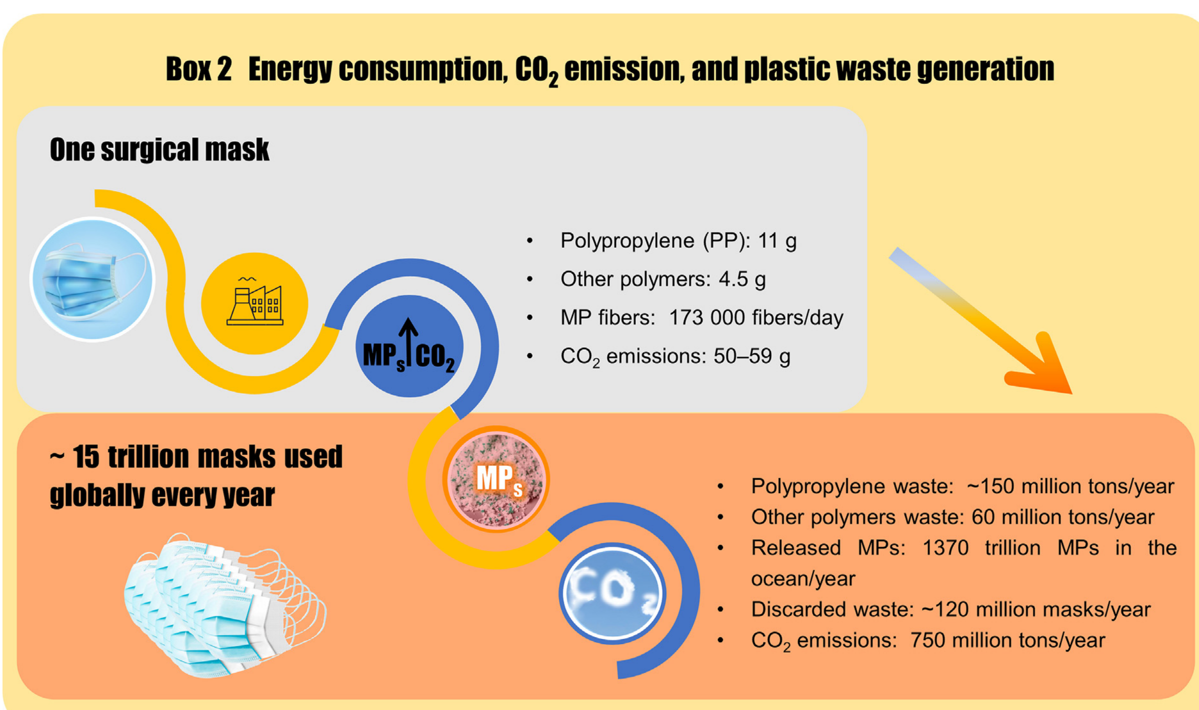
Most non-pharmacological face masks are manufactured from petroleum-based non-renewable polymers (Das et al., 2020). A single N95 mask or surgical mask contains approximately 11 g of polypropylene (PP) and 4.5 g of other polymers (ECOC, 2020). Moreover, the production of disposable masks includes the addition of other substances such as propylene, aluminum strips, fabric, and materials for the weaving process (Box 1; Du et al., 2022). The energy costs associated with their production include water, electricity, and labor. Therefore, increased production of face masks demands large amounts of energy. A previous study reported that the production of a surgical mask releases 32.7 g of CO_2-equivalent into the environment (Giungato et al., 2021). Throughout their life cycle — from production to disposal — an N95 or surgical mask releases 50–59 g CO_2-equivalent (Klemes et al., 2020). According to a report on energy consumption, the global warming potential of the 52 billion disposable masks produced in 2020 was estimated as ~2.6 million tons of CO_2 equivalent, which represents 22 terajoules (Turkmen, 2022). Therefore, face masks have become one of the main contributors in greenhouse gas emissions to the environment (Giungato et al., 2021). Therefore, the extensive production of disposable masks poses significant environmental challenges (Box 2).

3. Face masks: a new source of contaminants

Plastic waste pollution is one of the most significant environmental problems worldwide (Lebreton et al., 2017). Before the COVID-19 outbreak, the leading sources of plastic pollution were packaging materials, drinking bottles, and fast-food containers (Fadare et al., 2020). After the COVID-19 outbreak, hundreds of millions of disposable face masks have been discarded, with a rapid and dramatic increase in plastic waste (Table 1). If everyone wears a face mask every day, the pandemic could result in 15.5 trillion face masks being discarded globally every year (Prata et al., 2020), representing up to 2 million tons of plastic waste (15.5 g/mask; ECOC, 2020). Therefore, the large-scale use of disposable face masks has become a new source of plastic pollution globally. As the pandemic continues, the widespread use of disposable masks will further exacerbate global plastic pollution.

3.1. Direct effects of discarded masks on animals

Given the lack of compulsory measures for the recycling of face masks, inappropriate disposal has been observed in various environments, including urban areas (Gallo Neto et al., 2021), natural reserves (Prata et al., 2020), beaches (Aragaw, 2020), and even high mountains (Prata et al., 2020; Gallo Neto et al., 2021). Improperly disposed masks can be detrimental to animal survival and reproduction by limiting their mobility and feeding ability (Table 2). Recent studies have confirmed the physical, physiological, and ecotoxicological effects of discarded masks on domestic and wild animals (Pradit et al., 2021; Fukuoka et al., 2022; Tesfaldet and Ndeh, 2022). For instance, face masks or mask-derived plastic debris can be mistaken for food by various animals. The ingestion of plastic debris causes gastrointestinal disorders (Ray et al., 2022), such as digestive tract bleeding and blockage, ulcer, or perforation, which ultimately lead to starvation and mortality (Roman et al., 2019). Moreover, mask straps or debris become entangled in wild animals' appendages such as talons, beaks, necks, legs, and other body parts; these entanglements can lead to drowning, suffocation, or death (BBC, 2020; Facebook, 2020; Hiemstra et al., 2021). Furthermore, discarded face masks can be used as nest material by some birds, which



Box 2. The estimated energy cost and amount of pollutant generation during mask production and waste disposal.

Table 2
Adverse effects of discarded face masks on animals in different countries during the COVID-19 pandemic.

Negative effects	Species	Group	Country	Description	Reference
Ingestion	Sword prawn (*Parapenaeopsis hardwickii*)	Arthropods	Thailand	Mask-derived MPs (particularly PE and polyester fibers) in the gut.	Pradit et al., 2021
	Shrimp (*Metapenaeus brevicornis*)	Arthropods	Thailand	Mask-derived MPs (particularly PE and polyester fibers) in the gut.	Pradit et al., 2021
	Spotted catfish (*Arius maculatus*)	Fishes	Thailand	High occurrence of mask-derived MPs in the gut.	Pradit et al., 2021
	Sea turtle (*Chelonia mydas*)	Reptiles	Japan	Ingestion of drifted masks during feeding.	Fukuoka et al., 2022
	Magellanic penguin (*Spheniscus magellanicus*)	Birds	Brazil	A mask in the stomach of a dead penguin, may have caused its death.	Gallo Neto et al., 2021
	Long-tailed macaques (*Macaca fascicularis*)	Mammals	Malaysia	Multiple long-tailed macaques chewing on masks in Genting Sempah.	Hiemstra et al., 2021
Entanglement	Shore crabs (*Carcinus maenas*)	Arthropods	France	A dead shore crab entangled in a mask in lake Étang de Berre.	CGTN, 2021
	Checkered pufferfish (*Sphoeroides testudineus*)	Fishes	USA	A dead checkered pufferfish entangled in a mask in Miami Beach.	Hiemstra et al., 2021
	Gull (*Larus* sp.)	Birds	UK	A gull with a mask tangled around its legs in Essex. A young gull with a mask tangled around its beak in Dover.	Hiemstra et al., 2021
	Mute swan (*Cygnus olor*)	Birds	Italy	A mute swan with a mask entangled around its beak in Rome.	Hiemstra et al., 2021
	Peregrine falcon (*Falco peregrinus*)	Birds	UK	A juvenile peregrine falcon with its talons entangled in a mask in Yorkshire.	Hiemstra et al., 2021
	Mallard (*Anas platyrhynchos*)	Birds	Italy	A mallard with its neck entangled in a mask in Casentino.	Hiemstra et al., 2021
	American robin (*Turdus migratorius*)	Birds	Canada	A dead American robin entangled in a mask in Chilliwack.	Facebook, 2020
	European hedgehog (*Erinaceus europaeus*)	Mammals	Netherlands	A European hedgehog entangled in a mask.	Hiemstra et al., 2021
	Serotine bat (*Eptesicus serotinus*)	Mammals	Netherlands	A serotine bat entangled in two masks in Nijmegen.	Hiemstra et al., 2021
	Red fox (*Vulpes vulpes*)	Mammals	UK	A red fox entangled in a mask.	BBC, 2020b
Others	Common coot (*Fulica atra*)	Birds	Netherlands	Disposable masks in the nest of a common coot could lead to entanglement or ingestion by chicks or adults.	Facebook, 2020

can affect the fitness of their offspring. For example, face masks in bird nests can entangle the chicks, or be ingested by chicks, as well as the adults, thereby compromising their nutritional requirements and development (Hiemstra et al., 2021). In addition, microbial colonizers (e.g., Rhodobacteraceae, Flavobacteriaceae, and Vibrionaceae) and fouling organisms (e.g., calcareous tubeworms) can massively accumulate on masks (Ma et al., 2022), resulting in the alternation of micro-environments.

3.2. Microplastic pollution and ecological threats

Masks discarded in open environments are likely to undergo fragmentation by physicochemical (e.g., UV radiation, wind, and currents) and biochemical (enzymatic activity) processes (Fadare and Okoffo, 2020; Prata et al., 2020; Wang et al., 2021a), which lead to the generation of small plastic particles, such as MPs (Fig. 2). According to experimental data, a single face mask can release 110–540 MPs after 24 h of simulated breathing, and over 1000 MPs when immersed in water, although this is largely dependent on mask type and treatment (Table 3). When a surgical face mask is exposed to UV light for 180 h and then subjected to vigorous stirring in artificial seawater, it can release as many as 173,000 MPs (Saliu et al., 2021). Approximately 1.56 billion face masks were estimated to have been released into the oceans in 2020, which would have resulted in the release of over 1370 trillion MPs into coastal marine environments (Bondaroff and Cooke, 2020). This can lead to the circulation of plastic waste derived from used masks in terrestrial, aquatic, and atmospheric environments (Rillig and Lehmann, 2020; Zhang et al., 2020; Huang et al., 2021).

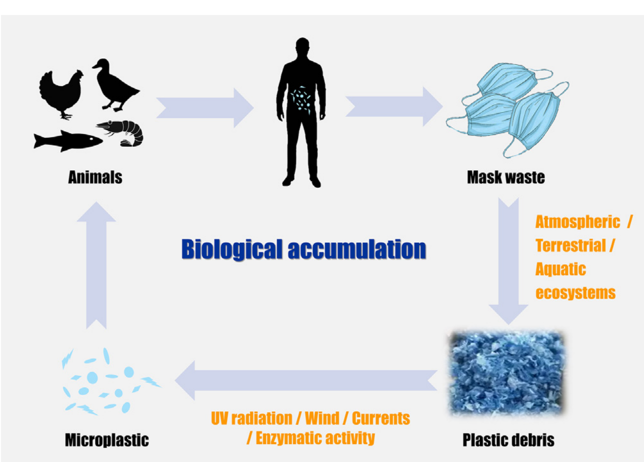


Fig. 2. A schematic diagram of the transmission of microplastics into the environment and through the food chain.

Wearing face masks for long durations (over 4 h) can lead to the inhalation of fibrillary MPs (Li et al., 2021). MPs inhaled from masks can appear in the lung tissue of patients causing prolonged inflammation and other serious health problems (Jenner et al., 2022). MPs can enter internal organs or tissues and even reach fetuses through the placenta (Ragusa et al., 2021; Vethaak and Legler, 2021). Through circulation, MPs can also affect the digestive (Lu et al., 2018; Jin et al., 2019; Li et al., 2020; Sun et al., 2021), reproductive (Hou et al., 2021; Wei et al., 2021, 2022), nervous (Lee et al., 2022; Yang et al., 2022) and immune systems (Li et al., 2020; Mu et al., 2022; Table S1).

MPs can also adsorb various viruses, bacteria, heavy metals, and organic compounds owing to their hydrophobic nature, relatively large surface area ratio, and extraordinary vector capacity (Rathi et al., 2019). This adsorption process can worsen the bioaccumulation of pollutants in the food chain, leading to ecotoxicological effects (Fig. 2). This phenomenon has been observed in recent studies (Lin et al., 2022; Ray et al., 2022). Furthermore, the fibrous nature of face mask microplastics makes them more toxic and capable of higher adsorption than conventional granular microplastics (Chen et al., 2021). In conclusion, masks waste in various environments can exacerbate the existing plastic pollution crisis, posing a significant threat to both wildlife and humans (Wang et al., 2021b).

Table 3
A summary of the number of microplastics (MPs) released from different face masks under various conditions.

Mask type	Number of MP release per mask	Treatment method	Reference
Activated carbon mask	540	Breathing simulation for 24 h	Li et al., 2021
	1600 ± 237	Immersing and shaking in water for 24 h	Jiang et al., 2022
Disposal medical mask	1043 ± 155	Immersing and shaking in water at 15 °C for 24 h	Jiang et al., 2022
	2940 ± 392	Immersing and shaking in water at 40 °C for 24 h	Jiang et al., 2022
	1447 ± 218	Immersing and shaking in water for 24 h	Jiang et al., 2022
	1246.62 ± 403.50	Immersing and shaking in water for 24 h	Chen et al., 2021
N95 mask	110	Breathing simulation for 24 h	Li et al., 2021
	3700 to 4400	Rinsing with water for 30 min	Ma et al., 2021
	31.33 ± 0.57	Immersing in water for 24 h	Wang et al., 2022a
	1339 ± 166	Immersing and shaking in water for 24 h	Jiang et al., 2022
	899 ± 65	Kept at 45 °C for 30 days	Gupta et al., 2023
Surgical mask	55,000- 173,000	Under UV for 180 h with vigorous stirring in seawater	Saliu et al., 2021
	137–264	Breathing simulation for 24 h	Li et al., 2021
	2600 ± 700	Shear stress tests in water for 1 s	Morgana et al., 2021
	28,000 ± 5000	Shear stress tests in water for 120 s	Morgana et al., 2021
	3600–5400	Washing in water for 24 h	Shen et al., 2021
	1300 to 2900	Leaching in water for 30 min	Ma et al., 2021
	50.33 ± 18.50	Immersing in water for 24 h	Wang et al., 2022a
	4716	Leaching in water for 24 h	Zuri et al., 2022
	1038 ± 65	Kept at 45 °C for 30 days	Gupta et al., 2023

3.3. Additive-derived organic pollution

Disposable face masks contain various additives that enhance their properties, such as antiviral and antibacterial barriers, dye compounds, and fragrances (Du et al., 2022). Therefore, in addition to the release of MPs, face masks also slowly release potentially hazardous chemicals (organic pollutants) from these additives (Prata et al., 2020). During production, organophosphate esters (OPEs) are added as flame retardants and plasticizers to face masks (Deng et al., 2018). OPEs, such as tri-n-butyl phosphate and tris (1,3-dichloro-2-propyl) phosphate, are suspected carcinogens with various ecotoxicological effects, including the disruption of nervous system development and endocrine and immune functions (Du et al., 2022). Some dispersive dyes added during face mask production include commonly used organic compounds. When these dyes eventually degrade, they generate highly toxic aromatic compounds such as mutagenic and carcinogenic substances (Vikrant et al., 2018) or prevent cell transcription processes (Du et al., 2022).

3.4. Other indirect effects

The accumulation of face masks in various environments can be indirectly detrimental to socioeconomic development (Tesfaldet and Ndeh, 2022). Discarded face masks are aesthetically unpleasing. Additionally, discarded masks in public areas and natural environments can discourage tourism (De-la-Torre et al., 2021; Haddad et al., 2021) and incite depression among residents because of the fear of contracting COVID-19 and other infectious diseases (Wang et al., 2021c; Daly and Robinson, 2022). These aspects can potentially decrease the economic revenue from tourism activities and affect the psychological well-being of residents (France, 2022; Li et al., 2022).

4. Global challenges for mask disposal

4.1. Challenges of indiscriminate disposal of masks

While used masks are generally disposed of in waste containers, some are carelessly discarded (Silva et al., 2021b). Studies suggest that although only 1 % of used face masks are improperly disposed of, this still amounts to approximately 10 million masks per month, resulting in 30–40 tons of plastic waste being released into the environment (Kwak and An, 2021). As discarded masks cannot be easily transported and recycled quickly, they can spread to various ecosystems (Das et al., 2020; Ma et al., 2022), exacerbating plastic pollution in different environments (Hellewell et al., 2020).

Previous studies have documented that untreated contaminants carrying severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) remain highly contagious for up to seven days (Ilyas et al., 2020). Consequently, face masks that have been disposed by infected individuals could serve as a source of infection, further exacerbating the risks of COVID-19 transmission (Yu et al., 2020). As a result, indiscriminate disposal of masks could give rise to a resurgence of infectious diseases, posing a significant threat of pathogen transmission to both humans and other organisms (Orive et al., 2020).

4.2. Challenges of mask waste disposal

Used face masks can be disposed of as solid waste into waste containers (Robertson et al., 2022). The masks are then handled in accordance with laws and policies related to solid waste management, with the majority ultimately being buried in landfills, incinerated, or recycled (Parashar and Hait, 2021; Silva et al., 2021a; Robertson et al., 2022). Landfilling is currently the most common practice of waste management strategy for face masks (Vaverková, 2019; Silva et al., 2021a). When mask waste is buried in landfills, it degrades into MPs after undergoing a series of transformations, including temperature fluctuations, pH changes, and fragmentation due to microbial activity (He et al., 2019). The disposal of masks in landfills has been found to have a range of adverse effects on the environment and living organisms. For instance, MPs containing hazardous chemicals are released (Saliu et al., 2021; Sullivan et al., 2021), and air pollution is caused by biogas and leachates (Vaverková, 2019; Quecholac-Piña et al., 2021). It can also alter the local microclimate and have impacts on soil and adjacent aquatic ecosystems (Silva et al., 2021a).

When face masks are incinerated with other mixed wastes, they can release greenhouse gases (GHG), such as CO_2 and methane (CH_4), as well as hazardous compounds, such as heavy metals, dioxins, polychlorinated biphenyls (PCBs), and furans (Silva et al., 2021a). These toxic gases and compounds affect air quality, exacerbating the current burden of environmental pollution and global climate change (Prata et al., 2020; Silva et al., 2021b). As an alternative to landfills and incineration, recycling of mask waste is an essential eco-friendly strategy. However, because face masks are lightweight, cheap, simple, undegradable, become scattered, and may carry other infectious viral pathogens, they are difficult to recycle on a large scale.

It is predicted that at least 60,000 tons of contaminated plastic waste would be generated if every citizen uses one face mask daily in UK (Allison et al., 2020). Globally, the escalating usage of disposable face masks aggravates the capacities of waste management through landfill and incineration methods (Silva et al., 2021a). Considering that both landfills and incineration can have detrimental effects on the environment in the medium to long-term (Silva et al., 2020, 2021a), proper management of the increasing mask waste has become a pressing global issue (Gertsman et al., 2020; Saadat et al., 2020).

5. Improvement measures

The COVID-19 pandemic has resulted in a significant increase in the production of medical and household waste, leading to a crisis in municipal solid waste and hazardous biomedical waste management (Govindan et al., 2021; Silva et al., 2021a, b). Several studies have proposed various measures to improve waste management capacity while reducing environmental impacts (Kulkarni and Anantharama, 2020; Silva et al., 2020, 2021a; Vanapalli et al., 2021; Mahyari et al., 2022). Instead of classifying used masks as medical solid waste, they are often treated as household waste. Therefore, it is essential to develop effective strategies that minimize plastic pollution from mask production and usage. However, there is a lack of specific policies for the appropriate collection, disposal, and management of face masks. As such, it is imperative to undertake effective measures to mitigate the adverse environmental effects of plastic pollution caused by the widespread use of masks. We propose the following five solutions (Fig. 3).

5.1. Increasing public awareness of the proper use and disposal of masks

To prevent viral transmission, millions of people have been advised or required to wear face masks to protect themselves against transmission in public areas (Fadare and Okoffo, 2020; Cheng et al., 2021). Although some public places have specific containers for mask recycling, in most cases, people discard masks at will, without taking any precautionary measures, along with other common household garbage in a regular bin (Tunon-Molina et al., 2021). In some cases, masks are even carelessly discarded in open environments (De-la-Torre et al., 2021; Haddad et al., 2021). The inappropriate disposal of used masks has become a common issue globally (Chen et al., 2021). However, limited guidance has been provided to the public regarding the safe disposal of masks and their potential recyclability (Rousseau and Deschacht, 2020). Governments have a responsibility to establish appropriate institutional frameworks and employ effective communication channels to increase public awareness regarding environmental issues. The public must be encouraged to dispose of used masks in an eco-friendly manner. This can be achieved by developing educational curricula and sensitizing the public to the environmental impact of discarded masks and eco-friendly methods of disposing face masks. To further cultivate socially and environmentally conscious citizens,

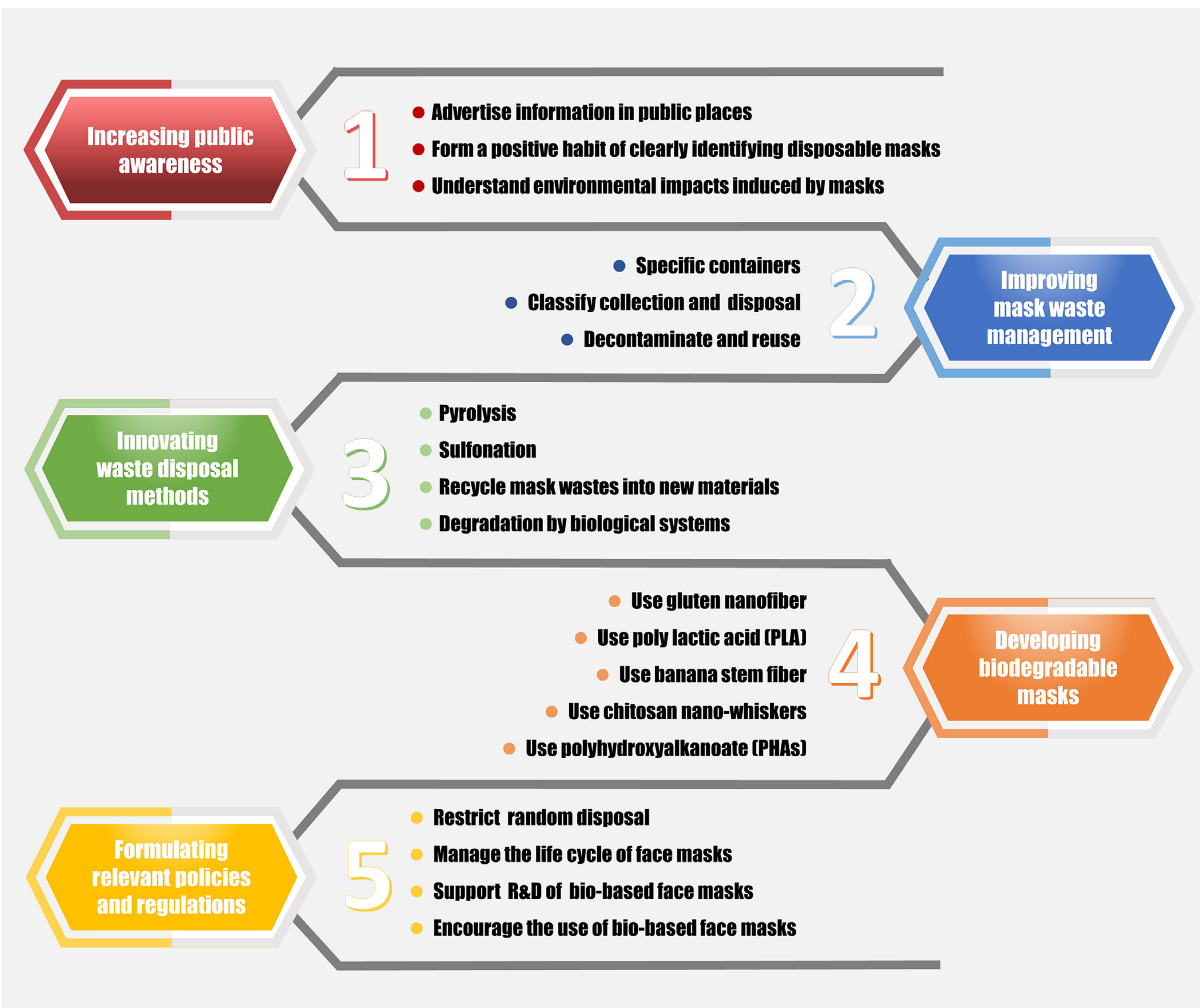


Fig. 3. Practical strategies to improve face mask disposal during and after the COVID-19 pandemic.

these materials, as a part of environmental science education, should be fully disseminated in public spaces such as local communities, kindergartens, and schools through public advertising as a long-term strategy to combat mask pollution.

5.2. Improving mask waste management

As face masks might be contaminated with infectious pathogens, they should be collected, transported, stored, and treated separately from other waste (Saadat et al., 2020). The World Health Organization (WHO) advised that used face masks should be collected in clearly marked lined containers, stored in black bags, and sealed properly before a unified collection (WHO, 2020). Incineration is often the best option to dispose of large volumes of waste (>10 t/day; WHO, 2020; Silva et al., 2021b), whereas chemical or physical disinfection (microwave or high-temperature steam) are good options for the treatment of smaller waste volumes (<10 t/day; Gertsman et al., 2020). Masks used by COVID-19 patients should not be recycled; rather they should be treated by autoclaving or incinerating at high-temperatures (Table 4; EC, 2020; WHO, 2020; Silva et al., 2021b). Therefore, municipalities responsible for waste collection and treatment should create guidelines and procedures to be applied during pandemics, and these guidelines should include waste reduction recommendations, protective measures, collection frequency, and end-of-life management of masks.

Face mask decontamination can extend their life cycle, thereby preventing excessive consumption and ensuring adequate supply (Silva et al., 2021a; Schumm et al., 2021). For PPE and N95 masks, the use of UV-C light, vaporized hydrogen peroxide (VHP), ozone gas, ionized hydrogen peroxide, and microwave- and dry heat-based methods are considered valid decontamination approaches that improve their reusability and reduce waste production (Table 4; Gertsman et al., 2020; Schumm et al., 2021). Dry heat and VHP, two commonly used decontamination methods, have been confirmed to effectively inactivate pathogens and preserve the filtration efficiency and structural integrity of face masks. The use of these two methods to decontaminate and then reuse face masks costs 77 % and 89 % less than new masks, respectively (Tao and You, 2021).

5.3. Innovating mask waste disposal methods

To decrease the negative impacts of face mask pollution, green, productive, and effective routes to recycle mask waste into value-added or new materials must be developed. To date, several innovative methods — including pyrolysis, sulfonation, and biodegradation, among others — have been used to develop new materials (e.g., membrane material, battery electrode, gas sensors, and chemical products; Table 4). Pyrolysis is an emerging disposal method for plastic waste, including medical waste, and it does not require material-based segregation (Qin et al., 2018). Pyrolysis can degrade long-chain polymer molecules into simpler and smaller molecules at high pressures and temperatures in the absence of oxygen (Jain et al., 2022), and it generates high yields of new energy resources, such as liquid and gas fuels (Lee et al., 2021). For example, the pyrolysis of PP face masks and polyvinyl chloride (PVC) surgical gloves in a reactor at 400 °C for 1 h generated ~75 wt% crude oil and 10 wt% char (Aragaw and Mekonnen, 2021). Although studies on mask waste pyrolysis are still in the preliminary stage, this appears to be a promising approach in the near future.

Waste masks can be sulfonated as a carbon source (sulfonation) and converted into a dense hollow fiber porous structure after heat treatment, and the final products can be developed into high-performance supercapacitor

Table 4
Known strategies to improve municipal waste management and develop biodegradable masks.

Overall solution	Specific strategy/materials	Strategy description	Reference
Improving municipal waste management	Specific waste collection bins	Specific waste bins for disposable masks in public places, with daily collection.	Benson et al., 2021
	Proper treatment of discarded masks	Separate collection, transportation, storage, and disposal of non-infected and infected masks.	Facebook, 2020; WHO, 2020; Silva et al., 2021a, 2021b
	Reprocessing and reuse of discarded masks	Decontamination using autoclaving, UV irradiation, chemical treatment, hydrogen peroxide vapor, dry heat pasteurization, or dry and moist heat treatments can retain the filtering capacity and successfully reduce the infectivity of masks.	Gertsman et al., 2020; Schumm et al., 2021
Innovating mask waste disposal methods	Construction material	Waste mask fibers can be used as additives in diverse construction materials to enhance their tensile/bending strengths and crack resistance.	Ahmed and Lim, 2022; Saberian et al., 2021
	Membrane material	The nanofiltration membranes prepared from waste masks by green solvents (e.g., p-cymene) as extractants had superior chemical stability and were suitable for organic solvent nanofiltration.	Cavalcante et al., 2022
	Fuel	Waste masks can be transformed into fuels through pyrolysis, possessing high calorific value, including gasoline, jet fuel, diesel, motor oil, bio-char, and non-condensable gases.	Aragaw and Mekonnen, 2021; Park et al., 2021
	Battery electrode	The functionalized porous carbons prepared from waste masks by microwave-assisted solvothermal method had good electrochemical performance.	Hu and Lin, 2021; Chao et al., 2022
	Adsorbent	The activated carbon adsorbents prepared from waste masks by sulfonation chemistry and thermal stabilization technology can be used for oil adsorption and removing organic pollutants from aqueous.	Chao et al., 2022; Robertson et al., 2022
	Gas sensors	The waste mask fibers/ZnS sensor prepared from waste masks and ZnS nanoparticles by one-step hydrothermal method had high sensitivity to target vapors.	Wang et al., 2022b
	Catalytic supports	Waste mask fabrics can be used as a free-standing catalytic support for the deposition of titanium dioxide (TiO_2), iron oxide (FexOy), and cobalt oxide (CoOx) metal oxide nanoparticles.	Muhyuddin et al., 2022; Reguera et al., 2022
	Useful chemical products	Waste masks can be successfully converted into useful chemical products through a combination of tandem catalysis and biodegradation (e.g., enzymes present in the saliva of wax worms).	Sullivan et al., 2021; Sanluis-Verdes et al., 2022
Developing biodegradable masks	Gluten nanofiber	Wheat gluten biopolymers, a by- or co-product of cereal industries, can be transformed into electrospun nanofiber membranes and compressed molded gluten for the development of biodegradable face masks.	Das et al., 2020
	Poly lactic acid (PLA)	Electrospinning and 3D printing have been used to strut PLA polymer on a PLA nanofiber web to fabricate face masks.	Patil et al., 2021; Soo et al., 2022
	Banana stem fiber	Masks produced by banana stem fibers extracted from banana peel can be recycled and biodegraded easily.	Sen et al., 2021
	Chitosan nanowhiskers	Two biodegradable microfiber and nanofiber mats can be integrated into a mask and coated by cationically charged chitosan nanowhiskers. The mask can completely decompose within four weeks in composting soil.	Choi et al., 2021
	Polyhydroxyalkanoates (PHAs)	PHA face masks are characterized by the solidity and porosity of the polymer, non-stick features, and biodegradability.	Al-Hazeem, 2021

electrode materials (Hu and Lin, 2021; Chao et al., 2022). Recycled masks can also be shredded and utilized as construction materials (Saberian et al., 2021; Ahmed and Lim, 2022). The addition of shredded face masks (1–3 %) to concrete aggregates in road base and subbase applications improves the strength, stiffness, ductility, and flexibility of the blends (Saberian et al., 2021). Therefore, a viable option to reduce pandemic-generated waste is the recycling of face masks with other waste materials for civil construction. This would also reduce the costs of civil construction (Ahmed and Lim, 2022). Finally, plastic degradation by biological systems, followed by the re-utilization of by-products, can be another solution to the global threat of plastic waste accumulation. Recently, novel techniques have successfully converted plastic wastes into useful chemical products through a combination of tandem catalysis and biodegradation (Sullivan et al., 2021), or oxidized and depolymerized plastic through enzymes present in the saliva of wax worms (Sanluis-Verdes et al., 2022). Similarly, used masks can be converted to useful materials through biodegradation.

Overall, these techniques present significant economic and environmental benefits and decrease environmental pollution associated with plastic waste management via bio-recycling/upcycling methods. Although certain innovative disposal options are still in the experimental stage and cannot be universally applied at present, they do offer novel pathways for improving mask waste management and illuminate mechanisms for the synthesis of new materials.

5.4. Developing biodegradable masks

As most face masks are non-biodegradable and composed of non-renewable resources, they are prone to inflicting long-term adverse effects on the environment (Dharmaraj et al., 2021). Therefore, there is an urgent need to develop biodegradable materials or alternative reusable materials for the production of face masks to mitigate plastic pollution. In a circular economy context, bio-based plastics have emerged as sustainable but short-term alternatives to conventional plastics, as they replace fossil fuels with renewable resources. Over the past three decades, the use of new degradable bio-based polymer plastics in biomedical applications has increased (Shen et al., 2020; Babaahmadi et al., 2021). Compared to traditional plastics, natural biodegradable polymers (e.g., chitosan, alginate, collagen, and gelatin) have better biocompatibility, whereas synthetic biodegradable polymers (e.g., such as polyvinyl alcohol, PVA; polyethylene oxide, PEO; polycaprolactone, PCL; polylactic acid, PLA) are easier to process and have better mechanical properties (Lakshmi and Cato, 2007). Therefore, blending natural and synthetic biodegradable polymers is potentially a favorable option for producing more environmentally friendly face masks.

In recent years, new bio-based face masks have been developed, and they possess equal or better efficacy than traditional surgical or N95 masks (Torres and De-la-Torre, 2021). Bio-based materials, such as gluten fiber, cellulose, PLA, banana stem fiber, chitosan whiskers, and polyhydroxyalkanoates, have been widely used to create biodegradable face masks by integrating modern techniques such as electrospinning, 3D printing, and nanotechnology (Table 4). Several of these bio-based face masks include vegetable seeds, and these masks eventually serve as compost. They decompose into nutrients or soil conditioners that can facilitate the germination of vegetable seeds (Das et al., 2020). Although bio-based materials and biodegradable polymers are more expensive than conventional plastics (Torres and De-la-Torre, 2021), they have received substantial international attention because they can alleviate the plastic pollution caused by the massive consumption of conventional masks. The large-scale use of bio-based face masks would reduce the consumption of non-renewable resources, curtail the emission of greenhouse gases and other toxic pollutants, and reduce conventional plastic pollution (Napper and Thompson, 2019). With support from governments and companies, bio-based plastic masks can provide an environmentally friendly option for the mask market in the future, which could decrease the conflict between the prevention of pathogen transmission and environmental pollution caused by the use of conventional face masks.

5.5. Formulating relevant policies and regulations

The global plastic pollution crisis has prompted many countries and regions to implement a series of measures to decrease plastic production, such as restricting, taxing, and even banning single-use plastic items (Schmidt and Laner, 2021; Mahyari et al., 2022). To address the urgency of the plastic crisis, considering the life cycle of plastic products (production, use, and disposal), 175 countries have adopted "End Plastic Pollution: Towards an international legally binding instrument" to develop a legally binding instrument in 2022 (CIEL, 2022). However, there are no specific laws, regulations, or restrictions regarding mask disposal. Therefore, relevant authorities should introduce policies to regulate face mask use throughout their life cycle. Notably, mismanaged plastic waste and marine pollution are higher in lower-income countries because of the lower number of waste management facilities (Chowdhury et al., 2021). Although some countries, such as China, Japan, and South Korea, have passed legislation on face masks and even issued precise guidelines (CIEL, 2022), the inappropriate disposal of used masks is still a common global problem. That is, relevant policies and guidelines to manage face masks throughout their life cycle are still lacking or not enforced. In this study, we proposed several potential policies and regulatory measures to prevent plastic pollution from face mask disposal.

National policies and laws should be established to support the development of new bio-based materials and increase the production volume of environmentally friendly (biodegradable or reusable) masks, e.g., through tax deductions or exemption policies (Patil et al., 2021; Sen et al., 2021; Soo et al., 2022). These policies can enable novel environmentally friendly materials to gradually penetrate the market share relative to traditional materials. Moreover, regulations, laws, economic disincentives, and financial support should be adopted to reduce the production and use of traditional face masks. Furthermore, corresponding policies guiding consumers to buy and use environmentally friendly masks are fundamental to prevent mask-induced plastic pollution, which in turn would promote the production of more sustainable masks. Other relevant policies should guide the public to appropriately discard traditional masks and implement specific waste collection and treatment in local communities (Rousseau and Deschacht, 2020). Moreover, a set of national guidelines should be established to address the problem of face masks already polluting the environment. Finally, to avoid inconsistent policies among regions or nations, it is critically important to establish international agreements on novel types of face masks and restrict the use of conventional ones. These policies and measures can contribute to enacting relevant laws and regulations to achieve the preliminary goal of reducing mask-induced plastic pollution on a global scale.

6. Conclusions and future perspectives

Since the beginning of the COVID-19 pandemic, face masks have become a worldwide healthcare necessity, and their demand and production reached unprecedented amounts. However, the entire life cycle of face masks, from production to disposal, requires huge resources and energy, and results in environmental pollution. Therefore, the widespread use of face masks has the potential to exacerbate environmental crises. Although disposable face masks are considered a low-cost indispensable measure for the prevention of respiratory diseases, they are composed of petroleum-based, non-degradable materials. Moreover, their frequent use increases the risk of MP inhalation into the lungs. Although some scholars recommend masks be collected in separate waste containers, most masks are treated as general waste and are landfilled or incinerated, which generates secondary MP pollution and releases toxic gases and compounds. Discarded masks have been observed globally in outdoor environments and have become a new plastic pollutant that poses significant challenges to the environment and wildlife in various ecosystems. Therefore, the use of disposable face masks has triggered a global and emerging issue that has rapidly evolved into an economic, social, and ecological environmental threat. More investigations on the environmental and wildlife health aspects related to the production, use, and disposal of face masks are urgently required.

Although wearing face masks can be beneficial in the long-lasting COVID-19 pandemic by effectively preventing viral transmission, they can also cause environmental issues. Even in a post-pandemic era, such a subtle healthcare necessity irreversibly elicits environmental issues worldwide, such as plastic and MP pollution, CO_2 emissions, and the release of toxic and hazardous substances, which negatively affect social and economic development. Therefore, the ecological impacts induced by the disposal of face masks are complex and the long-term effects remain to be determined. Considering that these environmental impacts have already caused an ecological crisis on a global scale, a series of practical measures must be immediately implemented to prevent further mask-induced environmental issues. The development of biodegradable materials and an increase in their production volume are potential solutions to balance their great demand and the consequent plastic pollution. Innovative and improved waste disposal and waste management strategies can critically address face mask-induced pollution of atmospheric, soil, and water environments. Finally, to prevent the global crisis induced by face mask pollution, stakeholders should increase public awareness, formulate and implement relevant policies, and promote international agreements on the production, use, and disposal of face masks.

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Data and materials availability

All data are available in the main text.

CRediT authorship contribution statement

Limin Wang: Conceptualization, Methodology, Investigation, Visualization, Funding acquisition, Writing – original draft. **Shengxuan Li:** Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **Ibrahim M. Ahmad:** Visualization, Writing – original draft. **Guiying Zhang:** Investigation. **Yanfeng Sun:** Investigation, Writing – review & editing. **Yang Wang:** Investigation, Writing – review & editing. **Congnan Sun:** Investigation, Writing – review & editing. **Chuan Jiang:** Investigation, Writing – review & editing. **Peng Cui:** Methodology, Writing – review & editing. **Dongming Li:** Conceptualization, Methodology, Investigation, Visualization, Funding acquisition, Supervision, Writing – original draft.

Data availability

No data was used for the research described in the article.

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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