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Review

Assessing face masks in the environment by means of the DPSIR framework

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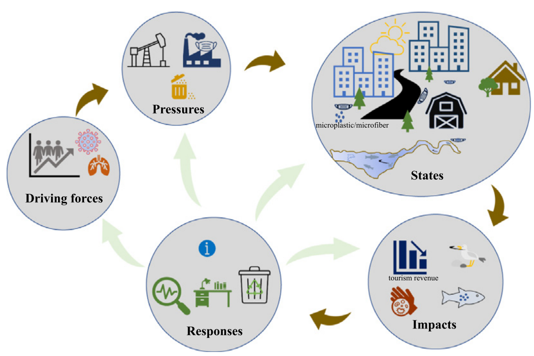
HIGHLIGHTS

- Face masks in the environment are examined using the DPSIR framework.
- The historical background and the driving forces of face masks are reviewed.
- Societal responses to mitigate the environmental impacts are presented.
- Policy indicators are discussed, and further work is outlined.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of face masks outside the health care facility dates back a century ago. However, face masks use noticeably soared due to the COVID-19 (Coronavirus disease 2019) pandemic. As a result, an unprecedented influx of discarded face masks is ending up in the environment. This review paper delves into face masks in the environment using the DPSIR (driving forces, pressures, states, impacts, and responses) framework to simplify and communicate the environmental indicators. Firstly, the historical, and briefly the economic trajectory of face masks are discussed. Secondly, the main driving forces of face masks use with an emphasis on public health are explored. Then, the pressures exerted by efforts to fulfill the human needs (driving forces) are investigated. In turn, the state of the environment due to the influx of masks along with the impacts are examined. Furthermore, the upstream, and downstream societal responses to mitigate the environmental damages of the driving forces, pressures, states, and impacts are reviewed. In summary, it has been shown from this review that the COVID-19 pandemic has been causing a surge in face mask usage, which translates to face masks pollution in both terrestrial and aquatic environments. This implies proper usage and disposal of face masks is paramount to the quality of human health and the environment, respectively. Moreover, further research on eco-friendly face masks is indispensable to mitigating the environmental damages occurring due to the mass use of surgical masks worldwide.

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1. Introduction

As the name implies, single-use face masks are intended to be used once and then disposed of. While polypropylene is the most common material used to make face masks, other alternatives include polystyrene, polycarbonate, polyethylene, or polyester (Chellamani et al., 2013). Surgical face masks are multilayered consisting of an outer, middle, and inner layer (Fig. 1). In addition, the face masks contain either aluminum or plastic nose clips, and two elastic cords. The outer and inner layers are made from non-woven cloth, while the middle layer is made from textile fibers (Adanur and Jayswal, 2020; Chellamani et al., 2013). The inner layer is made of an absorbent material that captures droplets exhaled from the wearer, while the outer layer is hydrophobic in nature (Salvi, 2020). The middle layer which provides the most filtration is made from melt-blown material. The mask filtration efficiency depends on different parameters such as the fiber size, the mode of synthesis, the web structure, and the fiber's cross-sectional shape (McCarthy, 2011). Additionally, breathing comfort levels are adjusted by lowering the pressure drop, a measure of the resistance to airflow (Arumuru et al., 2021). Thus, single-use face masks are prevalent among health workers and the public due to their high filtration capacity, lightweight, affordability, convenience, breathability, and disposability.

Products fashioned out of polypropylene typically take 20–30 years to be completely degraded. Irrespective of whether the condition of degradation is aerobic or anaerobic, photodegradation and thermo-oxidative degradation remain the traditional route of disintegration for polyethylene (Canopoli et al., 2020). Knicker and Velasco-molina (2021) estimation of the amount of carbon dioxide exclusively produced following biodegradation of single-use polypropylene-based face masks revealed an additional annual contribution of 41 to 68 t year^{-1} provided 0.1% masks end up in the soil. Furthermore, they pointed out that the mean residence time for these masks in soil ranged from 2 to 3 days and between 7 and 18 years for easily decomposable and non-easily decomposable masks fragments, respectively. It is expected that factoring in other abiotic pressures will accelerate the disintegration process.

The rise of air pollution across developing countries has shot up the production and consumption of face masks among the public. The numbers in face masks usage have further soared due to the COVID-19 (coronavirus disease 2019) pandemic. Hence, this has brought about an unprecedented influx of used COVID-19 masks winding up in the environment (Beckage et al., 2021; Haque et al., 2021; Wang et al., 2020a).

A few review articles on the impacts and mitigations of the COVID-19 related medical wastes in the environment have been written. However, a synthesized understanding of face masks in the environment and the interaction between societal drivers and the environment is still lacking. Therefore, to fill in the gap this paper reviewed articles on face masks using an environmental indicator in a structured manner to communicate the complex interaction between different facets of society and the environment. Structured into two parts, this study critically reviews the data for face masks usage and different facets of disposal through the DPSIR (driving forces, pressures, states, impacts, and responses) framework. The first part dwells on the historical development and economic components of the face masks industry, while the second part discusses all the components of the DPSIR framework within the context of a spike in face masks usage, its environmental ramifications, and measures of turning the tides on the adverse implications. In this review, unless specified, the term face masks (single-use face masks or surgical masks) refers to three-layer disposable face mask. Moreover, microplastic refers to plastic particle size <5 mm.

2. Historical background

The idea of nose and mouth covering to stem the spread of disease dates as far back as the early middle ages in Europe (Matuschek et al., 2020). Medical professionals wore beak-like masks stuffed with spices to protect against miasma in their dealings with sufferers of the bubonic plague. Attention to this practice somewhat took a nosedive in the subsequent century with greater emphasis informed by remarkable strides in the understanding of germ theory birthing a resurgence in the 19th century (Strasser and Schlich, 2020). The contributions of Louis Pasteur, the postulation of Joseph Lister on the importance of creating an antiseptic environment in

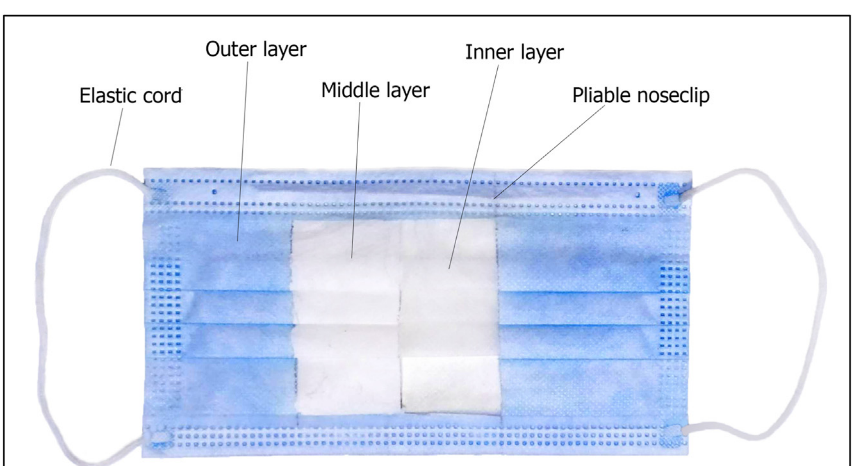

Fig. 1. Components of surgical face masks.

operating rooms, and Carle Flugge's experiment demonstrating respiratory droplets contained bacteria paved the way for a new generation of surgeons like Johann Mikulicz and Paul Berger to start wearing face masks in 1897 (Belkin, 1997). The popularity of the mask surged outside the traditional area of use, the surgery room, following the Manchurian plague of 1910–11 and the influenza pandemic of 1918–19 (Brienen et al., 2010; Rogaski, 2021). These two cases somewhat crystallized the idea of the mask as a means of protecting health workers and patients from infectious diseases outside the surgery room into the public psyche. The consensus on the function of the mask encouraged its evolutionary design away from multiple layers of cotton gauze, the first of which was patented in 1919, to disposable paper masks in the 1930s (Hauser, 2020). The 1960s were marked by the growing usage of single-use masks made from synthetic material. By the middle of the subsequent decade, reusable cotton masks had fallen out of favor among health care workers thanks to aggressive marketing and industry-backed studies extolling the superiority of synthetic single-use masks.

Over the years, the nature of materials used, and design has evolved in response to infectious disease outbreaks and the rise of air pollution. For example, before the COVID-19 pandemic, the last two decades saw a large-scale surge in mask use in response to the SARS (Severe Acute Respiratory Syndrome) epidemic of 2003 and increasing air pollution problems in parts of Asia (Sim et al., 2014; Zhang and Mu, 2018). However, the numbers in economic terms pale in comparison with respect to market demand for masks since the onset of the current pandemic. Furthermore, growth in consumer awareness on the importance of masks, ease of purchase, and positive marketing campaigns on online platforms account for the meteoric rise in demand. According to certain estimates, the face mask market grew from USD 737 million in 2019 and is expected to hit USD 22,143 million at the close of 2021 (Markets and Markets, 2020). As measures to rein in the infection grows, the same report projects that the global market will experience a sharp decrease to USD 3021 million by 2025.

3. Face masks in the environment: a DPSIR analysis

The DPSIR framework was first developed by European Environment Agency in 1995, aiming to deliver information on environmental indicators to policymakers (European Environment Agency (EEA), 1995). The framework is designed to communicate the causal relationships between society and the environment to raise public awareness for policy measures. According to European Environment Agency (Gabrielsen and Bosch, 2003), the components of the DPSIR framework are defined as: a) driving forces are the societal changes that shape the need, consumption, and consumption pattern, b) pressure is the emissions and resources deployed to satisfy the driving forces, c) state describes the status of the physicochemical and biological process both quantitative and qualitative aspects, d) impact are the changes on the functioning of the ecosystem such as loss of biodiversity, revenue, and well-being, and e) response indicator includes the initiatives by society and governments to prevent, mitigate, and adapt to the state of the environment. The DPSIR framework has been applied to various kinds of environmental problems such as the effect of climate change on biodiversity (Omann et al., 2009), microplastic in the environment (Miranda et al., 2020), and social-ecological systems of coastal environments (Gari et al., 2015). In all studies, the complex interactions between the society, economy, and the environment were communicated via the DPSIR framework, which is vital information for policymakers. Similarly, Tscherning et al. (2012) correctly argues that the DPSIR framework is a practicable tool to support decision making. The DPSIR framework of face masks in the environment is summarized in Fig. 2.

3.1. Driving forces

From inception, face masks were largely reserved for use by health care professionals in surgical wards and those at the forefront of battling transmittable respiratory type diseases. In the years that have since followed, skepticism on its effectiveness in curbing the rate of respiratory infection has been sufficiently squashed. The result of that has been the widespread embrace of single-use masks beyond traditional users to include members of the public. In recent years, the usage of these face masks among the public has been remarkably increased due to air pollution and various types of infectious diseases. While masks wearing does not offer absolute prevention, this nonpharmaceutical measure reduces the risk of exposure to infections and air pollutants (Bai, 2020). As such, it is both useful in everyday disease prevention and it is the first-line measure among others in the event of an outbreak caused by novel pathogens (Sim et al., 2014). A case in point is the current COVID-19 pandemic which has somewhat normalized the global use of face masks outside hospital environments in many

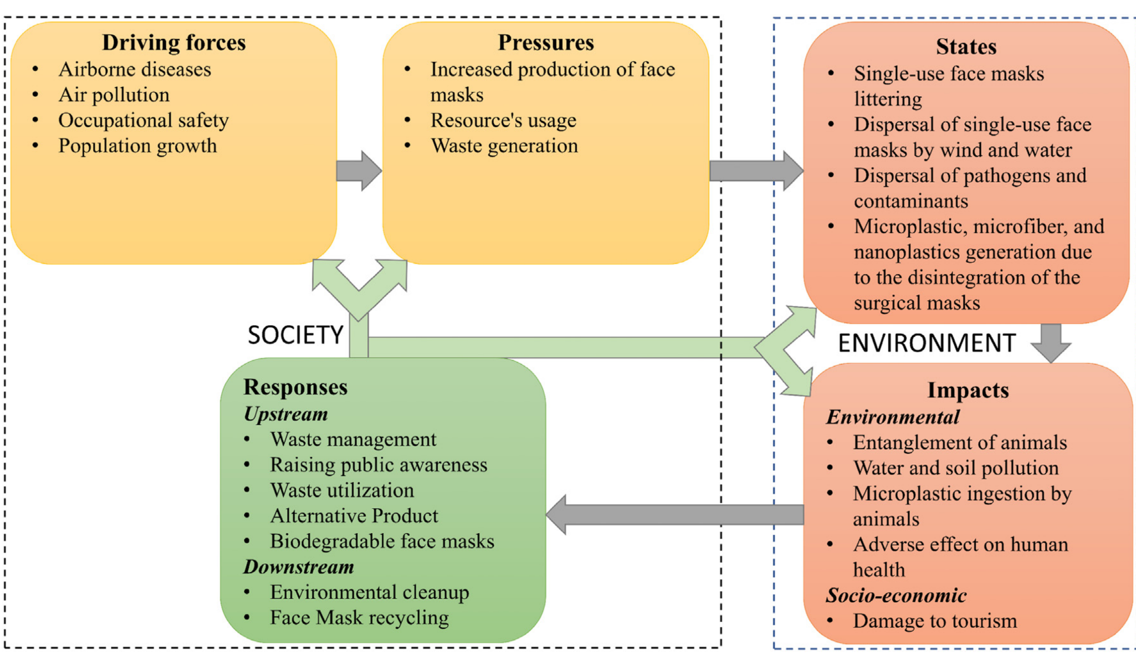

Fig. 2. The DPSIR framework of face masks in the environment.

parts of the world. However, the sight of people wearing face masks in many parts of Asia has always been commonplace; becoming somewhat like an entrenched culture (Joung, 2020). This is owed to past spates of respiratory infections and the problem of fine particulate matter ($PM_{2.5–10}$). Be it the increasing prevalence of air pollution or the response to limit respiratory infection by adopting single-use masks, industrialization, mass transportation, and mass media seem to be the common denominators in enabling these two primary drivers (Li et al., 2016; Tomes, 2010).

3.2. Pressures

The non-woven fabric of surgical masks is usually made from polypropylene which is sourced from petroleum oil. Metals are an equally crucial raw material in the face mask value chain (OECD, 2020). Other less commonly used materials include polystyrene, polycarbonate, polyethylene, and polyester (Table 1). With respect to other types of nonwovens, spunbond nonwoven fabric, especially those made from polypropylene are in high demand in the medical field. Market estimates in 2020 valued it at USD 18.7 billion and it is expected to hit USD 23.8 billion by 2025 (GlobeNewswire, 2020). Data that accounts for how much of the estimated growth is or will be directly linked to single-use face mask production is not readily available. However, it is safe to assume that the global demand for this item has driven the acquisition of related raw materials in its manufacture such as wood for cardboard in packaging. Life cycle assessment estimates of single-use surgical masks indicate that the most severe environmental impact incurred occurs primarily at the raw material procurement stage (Lee et al., 2021). The accompanying waste generated due to the global pandemic mounts additional pressure on routine waste management procedures (Adyel, 2020). This, in turn, increases the incidence of unsuitable waste management strategies such as local burning and landfills. Zooming in further, some estimates indicate that if 1% of face masks were improperly disposed, it will account for about 40 tons of plastics per month in nature (WWF, 2020).

Also, government policies that mandate every citizen to wear face masks when outdoors are playing a key role in mass usage and production of masks. As of the writing of this article, mask-wearing in public is currently mandated in over 170 countries (Masks for All, 2021). This means the amount of medical waste generated globally is unparalleled to anytime in history. The consequence of this is both environmental and health-related if proper care is not taken in the storage, transportation, and handling processes (Sangkham, 2020). In certain cases, it is inextricably linked to the sheer volume of waste generated, lack of expertise, and the capacity to handle specialized waste, especially in developing countries. For example, incineration will adversely impact air quality while distillation sterilization leaves behind a massive wastewater and waste residue footprint (Michael, 2013; Wang et al., 2020b). The overall environmental impact can be well understood through the life cycle assessment of face masks. As Lee et al. (2021) illustrated, assuming the face mask is used for two days, it can cause up to 0.290 kg CO_2-eq climate change impact, and can generate up to 0.002 kg of waste.

Table 1
Chemical composition of face mask.

Parts of face mask	Chemical composition	Weight percentage (wt%)
Outer and inner layer[a]	PP	73.33
Middle layer[a]	PE	13.77
Elastic cord[a]	Nylon	8.27
Pliable noseclip[a]	Metals	4.63 (Fe: 4.58, Zn: 0.02, Ti: 0.01, Ca: 0.01, and Mn: 0.01)
Complete surgical mask[b]	(C: 84.37 ± 0.22, H: 14.93 ± 0.04, O: 0.70 ± 0.09, H/C ratio: 2.12, O/C ratio: 0.01) (mean % ± std.)	

n.d. below detection limit.
[a] (Jung et al., 2021).
[b] (Brillard et al., 2021).

3.3. States

The mass use of single-use face masks, lack of awareness, poor waste management system is inducing face mask littering. Littered single-use face masks can end up as litter in street lanes, sewage systems, water channels, and aquatic environments. A typical example is the global face mask littering since the early months of the COVID-19 pandemic. The occurrence and potential disaster to the environment and solid waste management system has been reported by numerous researchers worldwide (Anastopoulos and Pashalidis, 2021; Aragaw, 2020; Benson et al., 2021; De-la-Torre et al., 2021; Fadare and Okoffo, 2020; Kalina et al., 2020; Kassam, 2020; Patrício Silva et al., 2020; Roberts et al., 2020).

Furthermore, due to environmental processes, littered face masks can be transported to surface water where they could relocate farther into marine environments. Stormwater flooding, rivers, and wind are the main pathways of face masks recovered in marine environments. According to estimation by Prata et al. (2020), worldwide consumption of face masks is 129 billion each month since the start of the COVID-19 pandemic. Assuming the loss rate and weight of face masks are 3% and 4 g, respectively, monthly around 17,000 tons of face masks end up in the marine environment. These data must be interpreted with caution because the estimation does not take account of the packaging, which in some cases individual masks are packaged in plastic bags. Similarly, the estimation does not separate the proportion of people who use reusable face masks. There is a growing body of literature that recognizes the presence of single-use face masks in the marine environment (Akber Abbasi et al., 2020; Akhbarizadeh et al., 2021; Bondaroff and Cooke, 2020; Dharmaraj et al., 2021). During the early days of the COVID-19 pandemic, Oceans Asia, the marine pollution advocate organization published a pioneer report about the presence of single-use face masks in the marine environment. The investigation reported that 70 single-use face masks along the remote beaches of Soko Islands, Hong Kong were found in February 2020 (Bondaroff and Cooke, 2020). This finding was pivotal in calling the attention of environmental scientists regarding the fate of discarded single-use face masks. Later on, Akhbarizadeh et al. (2021) investigated discarded face masks along the Persian Gulf in a four-day sampling campaign. The research found the highest and lowest face masks count of 574 and 252, respectively. Similarly, De-la-Torre et al. (2021) determined the distribution of discarded face masks along the densely populated beaches of Lima, Peru. The study found around 121 face masks representing 87.7% of all PPE observed in 12 sampling campaigns. The research was significant in incorporating the effect of beach activities on the nature of face masks littering. The research reported that recreational beaches were the most polluted areas than their counterpart fishing and surfing areas. The finding points to the importance of research on beach-based sources of face masks littering, which is lacking from the literature. A summarized table showing the presence of PPE in different environments is presented in Table 2.

Face masks discarded in the environment break down by physical and chemical processes and generate microplastics and microfiber that contaminate both soil and water. There is evidence that face masks produced by electrospinning are potential sources of microplastics, nanoplastics, and microfibers in the environment (Aragaw, 2020; Chen et al., 2021; Fadare and Okoffo, 2020; Ma et al., 2021) (Table 3). Moreover, Saliu et al. (2021) simulated the degradation of face masks in marine environments by exposing single-use face masks to UV light and soaking in artificial seawater. The sample was continuously steered to resemble the natural environment. The demonstration showed that each face mask can generate up to 173,000 fibers a day, which represents 26% of the total mass of the face mask. The research was significant to understanding the potential impacts of discarded face masks on the environment. Once the surgical face mask is disintegrated into microplastics, it has a sorptive potential for contaminants such as metals and DEHP (Di 2-ethyl hexyl phthalate) (Dobaradaran et al., 2018; Takdastan et al., 2021).

In the case of face masks as potential carriers of infectious viruses, studies by Dargahi et al. (2021) found SARS-Cov-2 (Severe Acute Respiratory Syndrome Coronavirus-2) on both sides of single-use face masks collected

Table 2
The occurrence and density of PPE associated with COVID-19 in different environments.

Location	State of the environment	Sampling sites	Reference
Agadir; Morocco	During and after the lockdown, the average PPE density ranged from 0 to 5.78×10^{-5} items/m^2 and 5.81×10^{-6} to 5.60×10^{-4} items/m^2, respectively.	11 sites were observed along the beach	(Haddad et al., 2021)
Bangkok; Thailand	Cumulative mask flux rate was 0.30 items/km/day.	Three streets in the city (13 km total path)	(Tesfaldet et al., 2022)
Bushehr; Iran	574 face masks observed on the first day of sampling along the shores of Bushehr.	9 observation sites on sandy and rocky beaches	(Akhbarizadeh et al., 2021)
Cilincing, Marunda; Indonesia	Face mask abundance in March and April 2020 increased by 1.51% and 1.36% at Cilincing and Marunda outlet, respectively.	Two river outlets	(Cordova et al., 2021)
Cox's Bazar; Bangladesh	The density of PPE ranged from 3.16×10^{-4} to 2.18×10^{-2} items/m^2.	13 sites were observed along the beach	(Rakib et al., 2021)
Ile-Ife; Nigeria	Face mask littering along a highway and drainage system.	Highway and drainage system.	(Fadare and Okoffo, 2020)
Kwale, Kilifi, Mombasa; Kenya	<0.1 items/m COVID-19 related litter along streets, 0.1 items/m^2 on the beach, and 66 items/km^2 floating litter.	Street, beaches, and floating litter on the ocean	(Okuku et al., 2021)
Kumasi, Abenase; Ghana	The density of face mask ranged from 0.04 to 0.42 items/m.	A metropolitan, municipal, community and an institution were surveyed (total length = 1720 m)	(Amuah et al., 2022)
Mersin, Adana, Niğde; Turkey	The density of face masks was 170, 210, and 166 items/km^2 in Mersin, Adana, and Niğde, respectively.	3 cities were observed for face mask littering	(Akarsu et al., 2021)
Northern, central; Chile	The average density of face masks along the sandy beaches was 2.75 items/km and along the rocky shore was 0.74 items/km.	4 coastal areas: two sandy beaches and two rocky shores	(Thiel et al., 2021)
Soko Islands; Hong Kong	70 face masks encountered along the beach.	100 m stretch of the beach	(Bondaroff and Cooke, 2020)
Quebec; Canada	The density of mask litter was 0.0001 ± 0.00006 items/m^2.	A walking pilgrimage of 3 m wide and 250 km length	(Maderuelo-Sanz et al., 2021)
Toronto, Ontario; Canada	The cumulative sum of face masks in each sampling site ranges from 10 to 165 items.	Residential area, commercial grocery store parking lots, a recreational trail, and a hospital district	(Ammendolia et al., 2021)

from patients with coronavirus admitted at the hospital. The research is crucial to emphasize the possible dangers imposed by improperly disposed face masks. Similarly, Chin et al. (2020) confirmed the presence of SARS-Cov-2 at the inner and outer parts of the face masks. The study further showed that the virus can survive up to seven days and more than seven days in the outer and inner face masks layers, respectively. The finding is pivotal in that it recognizes the dangers posed to the public and specifically to waste handlers. In this regard, the most vulnerable people are street sweepers and garbage collectors. Since the use of PPE by solid waste collectors is not standard across the globe, where in some countries it is hardly used, the occupational risk is inevitable. In addition, once the mask is discarded, it may interact with different components of the ecosystem and can be relocated farther. A critical review done by Tran et al. (2021) indicated that the presence of discarded masks in the environment might contribute to the presence of infectious viruses in water and wastewater. Although the presence and survival of SARS-Cov-2 for days on face masks support the claim, it is imperative for it to be supported by further rigorous research. The survival of SARS-Cov-2 in wastewater depends on many physical and chemical parameters of water. A number of authors have found SARS-Cov-2 in wastewater inflow (Bivins et al., 2020; Giacobbo et al., 2021; Ihsanullah et al., 2021; Westhaus et al., 2021), while SARS-Cov-2 amplification test showed their absence in treated wastewater outflow (Rimoldi et al., 2020).

On the other hand, discarded face masks can act as pollutant carriers. Anastopoulos and Pashalidis (2021) indicated that single-use face masks can act as the transporters of dye chemicals specifically, crystal violet and malachite green in the aquatic environment. The study offers some important insights into the sorption of pollutants in single-use face masks. Since the breakdown of face masks produce microplastic which is small and capable of traveling long distances, they can be an effective carrier of contaminants and pathogens. However, the knowledge about single-use face masks as potential carriers of heavy metals and POPs (Persistent Organic Pollutants) is still lacking in literature and is an important issue for future research.

Table 3
Number of microplastics (MP) and nanoplastics (NP) counted from 100 μL well-mixed face mask leachate identified by scanning electron microscope (Ma et al., 2021).

Mask type	Country of production	MP ≥ 1 μm (10^3 per mask)	NP < 1 μm (10^9 per mask)	Mean diameter of NP < 1 μm (nm)
Surgical	China	1.8 ± 0.1	2.6 ± 0.3	108 ± 19.0
Surgical	China	1.6 ± 0.3	2.1 ± 0.1	135 ± 10.3
Surgical	China	1.5 ± 0.2	2.0 ± 0.4	144 ± 20.5
Surgical	China	1.3 ± 0.1	1.6 ± 0.2	139 ± 16.7
Surgical	Vietnam	1.7 ± 0.1	1.9 ± 0.4	112 ± 22.7
Surgical	Korea	1.7 ± 0.2	3.8 ± 0.5	103 ± 10.2
Surgical	Japan	1.7 ± 0.2	1.9 ± 0.5	101 ± 35.7
Surgical	Japan	2.9 ± 0.1	2.0 ± 0.1	115 ± 25.8

3.4. Impacts

At present, research and reports regarding the impact of face masks are steadily coming out. The obvious reason could be due to the easing of restrictions imposed during the COVID-19 pandemic; moreover, the impacts are beginning to be more pronounced with the increasing usage of single-use face masks. The physical, physiological, and ecotoxicological damage of discarded masks to domestic and wildlife has been recognized by researchers (Hiemstra et al., 2021; Patrício Silva et al., 2021). For example, the entanglement of two shore crabs (*Carcinus maenas*) at lake Étang de Berre, France, where one crab was seen perniciously entangled by face masks. In the same vein, the entanglement of the American robin (*Turdus migratorius*) by face mask is another case in point (Hiemstra et al., 2021). The ingestion of face masks by both animals and humans has also been reported in various parts of the world (BBC, 2020a; Hiemstra et al., 2021; Kaur, 2020; Klein, 2020). According to wildlife bosses, Seagulls struggling over discarded face masks thinking it was food has been a common occurrence at the Weymouth beach, UK (Klein, 2020). Similarly, discarded coronavirus face masks mistakenly eaten for food by domestic pets were also reported by Kaur (2020). In most cases, the ingestion of face masks by animals leads to death or emergency surgery, which signals the severity of discarded face masks (Gallo Neto et al., 2021). Furthermore, BBC (2020a) reported an incident where a six-year-old child ingested a chicken nugget containing a face mask bought from a MacDonald's branch in Hampshire, UK. Taken together, these studies support the notion that unless robust intervention is put in place, the incidence of animal death and entanglement due to discarded face masks will most likely increase with the current skyrocketing usage of face masks across the globe. Moreover, since face masks contain a plastic layer and fiber, ingestion by animals translates to entry into the food web. For instance, studies conducted by Akhbarizadeh et al. (2020) found microplastics in canned fish. Situations like this ultimately leads to the accumulation of microplastics and microfibers in apex predators such as humans. Table summarizing incidences of interaction between animals and discarded face mask reported worldwide are presented in Table 4.

The socio-economic damage of discarded face masks is hardly found in the literature. However, extensive research has shown that marine debris negatively affects the aesthetic of the beaches as well as reduces tourism revenue (Botero et al., 2017; Jang et al., 2014; Krelling et al., 2017; Qiang et al., 2020; Williams et al., 2016). Similarly, the presence of discarded face masks on beaches will apparently affect the aesthetics of the beaches. Hence, the presence of discarded masks at the beaches could also cause panic and discourage tourists (beachgoers) from swimming or engaging in activities at the beach due to the fear of contracting COVID-19. This ultimately affects the revenue that can be collected from coastal tourism.

The physiological and psychological burden associated with protracted mask usage has been reported to decrease work efficiency and the time put into activities while donning masks (Johnson, 2016). The ramifications of this are lower productivity and economic output. Numerous studies have highlighted the downsides of prolonged mask usage on the health of individuals. According to (Rosner, 2020), her respondents of healthcare professionals reported adverse effects such as headaches, acne, skin rash, and impaired cognition. A shortcoming of the research is that it failed to consider the underlying conditions of the respondents. While this might be a ground for skeptics to discount the potential long-term impacts of extended mask use, this could not be further from the truth. A similar study in India with a pool of healthcare workers selected on the basis of being highly active and healthy, showed overlapping adverse effects such as difficulty breathing on exertion and acne on the face (Purushothaman et al., 2021). Along the same lines, a study by Techasatian et al. (2020) indicated that wearing surgical masks less than 4 h/day has reduced adverse effect on skin than wearing for longer hours. Other reported effects included dry mouth sensation, sore throat, nasal discomfort, and pain behind the earlobe. Furthermore, there is increased danger to disseminate infectious pathogens due to the discomfort that comes from prolonged mask use which encourages frequent touching by the wearer. In the same context, L. Li et al. (2021) investigated the risk of inhaling microplastics by wearing face masks. The study revealed that wearing face masks causes the risk of microplastic inhalation to the wearer, and the risk increases with the increasing frequency of mask-wearing. Likewise, Han and He (2021) observed loosely attached debris that resembles fibers and particles of micron to submicron size in the outer part of new face mask. Together, these studies indicate that wearing face mask poses the risk of inhaling microplastics or microfiber. Furthermore, the current research highlights the need of assessing human exposure to microplastics from face mask by employing the technique of nasal lavage (Torres-Agullo et al., 2021).

3.5. Responses

Due to the growing presence of face masks in the environment, especially the marine environment, the need to reduce the risk associated with poorly disposed of PPE is imperative. As a result, several strategies can be put in place to reduce the environmental and health impact that comes with mass mask generation. Generally, the responses can be categorized into two as upstream and downstream responses.

Table 4
Reported impacts of face mask on animals.

Location	Animal	Impact	Reference
Chelmsford; UK	Gull sp. (*Larus* sp.)	Entangled	(BBC, 2020b)
Dover; UK	Gull	Ingesting	(Singer, 2021)
Yorkshire; UK	Peregrine falcon	Entangled	(BBC, 2020c)
Dromana; Australia	Silver gull	Ingesting	(MP News Group, 2021)
Phang; Malaysia	Macaque monkeys (*Macaca fascicularis*)	Ingesting	(Rasfan, 2020)
Sao Sebastiao; Brazil	Magellanic penguin (*Spheniscus magellanicus*)[a]	Ingested	(Gallo Neto et al., 2021)

[a] Face mask recovered from dead body.

3.5.1. Upstream responses

Upstream responses include all the preventive actions and recommendations put in place to reduce the influx of face masks into the environment such as waste management, waste utilization, alternative products, and biodegradable face masks.

3.5.1.1. Waste management. Once the face mask serves its purpose it will be regarded as waste. When properly disposed of, the discarded face masks can end up in either incinerators or landfills, while improperly disposed face masks can end up in the environment as litter. Face masks waste has become prevalent during the COVID-19 pandemic. According to (WHO, 2020), healthcare professionals require 89 million single-use face masks for every month of the COVID-19 pandemic. Considering the world population of 7.5 billion, Prata et al. (2020) estimated that the world consumes 129 billion single-use face masks monthly. Assuming the weight of each single-use mask is 4 g, that would be 516,000 tons of waste generated globally for each month. Based on the WHO (2014) waste management guidelines, discarded face masks can be considered as part of healthcare waste (infectious waste) because the waste is suspected to contain pathogens. Therefore, discarded masks require separate collection and disposal systems to prevent further transmissions of pathogens. For example, installing bins designated for face masks in public places and public transportation systems are essential measures to reduce the influx of face masks into the environment (Tesfaldet et al., 2021).

Furthermore, the IoT (Internet of things) based waste collection system proposed by H. Li et al. (2021) can be an efficient alternative. Since the system is accompanied by a sterilization system and provides real-time information to the respective recycling facility, it is an efficient and safe option. Public awareness promoting the use and proper disposal of face masks are also an inevitable part of the waste management arsenal to reduce the environmental and health impact. For instance, promoting good practices of mask handling and usage, disinfecting the mask using alcohol-based sanitizer before disposal, safe disposal methods, and subsidizing environmentally friendly face masks. Within the framework of disposal and handling, the current widespread use of masks means those in the waste management sector not formally trained in handling these materials are at risk as well as the population at large. To reduce potential dangers, the waste management handling chain can be strengthened by evaluating the knowledge, practice, and attitude of waste handlers with respect to medical waste and dispensing the necessary training to fill in the gaps.

3.5.1.2. Waste utilization. Repurposing discarded face masks within the theme of circular economy is also part of the response to bring the solid waste generated back to the economy. For instance, Saberian et al. (2021) demonstrated that shredded face masks can be an addition to recycled concrete aggregate for road base pavements without compromising the quality. The finding is significant in that it provides a way of utilizing discarded face masks. In the same vein, Kilmartin-lynch et al. (2021) suggested that the addition of 0.20% of shredded face masks improves the mechanical properties of concrete. Alternatively, Purnomo et al. (2021) proposed that discarded face masks can be utilized for energy sources using thermochemical conversion. The study further highlighted that incineration, pyrolysis, and gasification are the most feasible waste-to-energy conversion methods for face masks. Moreover, PP-based face masks can be effectively utilized for carbonaceous char using slow pyrolysis (Harussani et al., 2022). A question worth asking, however, is whether the environmental impacts of these waste-to-energy technologies are practicable and sustainable especially when taking into consideration that this approach does not reduce the overall demand for virgin material and contributes to the release of toxins to the air. Moreover, most of the experiments on the thermal conversion of face masks are done on unused face masks at the laboratory scale, which could translate poorly when it comes to large-scale waste utilization due to moisture variation (Dong et al., 2016) and a compromise in quality of discarded mask. Therefore, further research is inevitable to determine how to utilize the discarded masks to energy using the existing thermochemical conversion techniques. On the other hand, Hu and Lin (2021) investigated the safe and value-added utilization of polypropylene face masks. The study showed that sulfonating discarded polypropylene masks can produce high-performance porous carbon materials. Also, the prepared material results in good capacitance performance of the carbon electrode. To that effect, discarded face masks have been shown to be a valuable source of carbon nanomaterials. The authors of the study were able to obtain a maximum carbon yield of 64.4 g from 100 g of waste masks (Yu et al., 2021).

3.5.1.3. Alternative product. Prompting the use of cloth masks is one of the major campaigns directed at reducing the influx of single-use face masks worldwide. Various studies have assessed the efficacy of reusable masks (cloth masks) against respiratory droplets, bacteria, and particles (Ho et al., 2020; Rengasamy et al., 2010; Steinbrook, 2021). Several lines of evidence suggest that cloth masks have similar protection efficiency as single-use face masks. However, the type of material and the number of layers that compose the cloth mask has a great effect on the efficacy of the mask. As a result, the filtration capacity of cloth masks widely varies across studies. For instance, Davies et al. (2013) investigated the efficacy of several homemade cotton masks against bacterial and viral aerosols. The result showed that cloth masks markedly reduced the microorganisms released from the source. However, the same experiment done with single-use face masks showed three times higher efficacy than their counterpart homemade masks. In contrast to earlier findings, Ho et al. (2020) reported that there is no statistically significant difference in efficacy between cloth masks and medical-grade masks in microenvironments with air conditioning. Similarly, Teesing et al. (2020), Aydin et al. (2020), and Konda et al. (2020) argued that cloth masks can be a substitute for single-use face masks. Moreover, the Centers for Disease Control and Preventions, USA recommends the use of cloth masks in public places (NCIRD, 2021). Most of the studies indicated that the filtration capacity of cloth masks ranged from 60% to >95%, which heavily depended on the material used. One interesting finding was that the number of layers markedly improved the filtration capacity of the cloth masks (Clapp et al., 2021; Konda et al., 2020). Clapp et al. (2021) make the very valid point that modifying several aspects of cloth masks yields equal or higher filtration capacity compared to the equivalent medical masks. It is nevertheless necessary to ensure the low pressure drop and thus the good breathability of the mask. The finding is very impressive, and it provides direction for further research. The studies presented thus far provide evidence that cloth masks are the potential environmentally friendly substitute for single-use face masks. Allison et al. (2020), estimated the environmental impact of single-use face masks and cloth masks under different scenarios via life cycle assessment. The study revealed that cloth masks generate 85% less waste and 3.5 times lower impact on climate change than the counterpart single-use face masks. Moreover, cloth masks cost 3.7 times lower than the single-use face masks. Considering all this evidence, it seems that cloth masks are a good substitute for single-use face masks. Further work is indispensable to standardize the material to be used for making cloth masks; moreover, the life span or the duration of wearing of cloth masks need to be properly defined.

3.5.1.4. Biodegradable face masks. The pros to disposable PPE are the reduced risk of contamination spreading and affordability. On the other hand, the downside of it lies in the environmental harm non-recyclable varieties such as single-use face masks pose. Being typically non-degradable, they may end up in landfills, incinerators, or as terrestrial or aquatic litter after use. It is, therefore, necessary for more research to be poured into the development of biodegradable materials and bioplastics from renewable resources as an alternative to petroleum-based materials (Fouad and Farag, 2020). A viable biodegradable material equivalent should possess properties of polypropylene such as being lightweight, exhibiting high tensile strength, eco-friendly, and affordable (Selvaranjan et al., 2021). To address the environmental implication of non-degradable masks while concurrently maintaining high levels of functionality, Choi et al. (2021) developed a Janus membrane mask filter of polybutylene succinate and chitosan nanowhiskers. Their study revealed that the biodegradable polymer and bio-based material electrospun ensemble presented an impressive particulate matter removal efficiency of up to 98% and biodegraded in four weeks. The feasibility of creating compostable face masks has also been further demonstrated by the use of plant fibers from hemp, coffee, and sugar cane mulch (Ho, 2020; Layt, 2020; Reuters, 2020). While some of these biodegradable mask options show high filtration efficiency, more research ground needs to be covered in order to raise its quality to the standard of medical-grade masks. Furthermore, claims on the extent of the biodegradability of these compostable masks need to be ascertained. Even if current research still falls short in successfully nudging the transition to biodegradable plastics, the environmental burdens linked to suchlike disposable mask production can be alleviated by integrating tools like eco-design (González-García et al., 2016).

3.5.2. Downstream responses

Downstream responses comprise actions and studies that have been going on to remediate the environmental damages posed by discarded face masks such as environmental cleanups and face mask recycling.

3.5.2.1. Environmental cleanup. Environmental cleanup initiatives ranging from street sweeping to beach cleanup are essential measures to tackle the effects of discarded masks on humans and the environment. Face masks littered on the streets can be cleaned up by stepping up the sweeping frequencies. Similarly, the damage to the aquatic environment can be minimized using trash traps along the waterways. Moreover, organizing beach cleanups, and diving for marine debris are some of the activities that can reduce the impacts of discarded face masks, and raise public awareness.

On the question of SARS-Cov-2 in municipal water systems, a study done by Rimoldi et al. (2020) identified the presence of SARS-Cov-2 in raw wastewater collected in the Milano Metropolitan Area. However, the virus was not detected in treated wastewater, suggesting the effectiveness of the existing treatment system. Similarly, Sherchan et al. (2020) identified the presence of SARS-Cov-2 in raw wastewater influents collected in Louisiana, USA. However, the secondary treated and the final effluent did not test positive for the virus. In contrast, Haramoto et al. (2020) detected SARS-Cov-2 in secondary treated water in one out of the five samples tested. Discrepancies in results can be accounted for by sample volume, method of isolation, and differences in the sensitivity of the marker genes (Haramoto et al., 2020; Rimoldi et al., 2020). In the same vein, a review article by Foladori et al. (2020) highlighted that the survival of SARS-Cov-2 decays in wastewater was due to the variability of the physicochemical parameters. Moreover, the virus reaches maximum inactivation when the wastewater is disinfected with free chlorine and UVC (Ultraviolet C). These results reflect those of Greaves et al. (2022) who also found that free chlorine disinfection is a practical way to reduce SARS-Cov-2 levels in deionized water and wastewater. Furthermore, Sunkari et al. (2021) review of wastewater disinfection in the context of developing countries suggested that the integration of ozonation, chlorination, UV irradiation, and sodium hypochlorite is an effective method to remove SARS-Cov-2 in water. However, there is no solid information on the best possible combination of disinfection techniques to reduce or eliminate SARS-Cov-2 in wastewater. Therefore, further research needs to be done on the synergism of disinfection techniques and to establish a standard protocol that benefits developing nations with fragile or nonexistent wastewater treatment infrastructures.

3.5.2.2. Face masks recycling. According to a 2015 estimate, only 20% of the global plastic was recycled while 25 and 50% were incinerated and discarded, respectively (Ritchie, 2018). A closer look at the recycling numbers with respect to the various types of plastics shows a disparity in recyclability. For example, in the US, only 3% of polypropene gets recycled yearly compared to about 29% of polyethylene terephthalate (Chasan, 2019). Some of the challenges faced in the recycling of polypropylene include difficulty to rid of offensive smells in post recycled products and the decrease in its aesthetic quality for reuse in packaging. The current surge in the utilization of single-use face masks and other personal protective equipment means a potential increase in the percentage of incinerated and discarded polypropylene-containing products. This situation also presents the opportunity to ramp up efforts in the recycling of the most abundant PPE used during the pandemic. The mode of recycling might be primary or secondary recycling. In primary recycling, the recovered material is used to derive similar products with an equivalent performance from those made from virgin materials. Secondary recycling entails transforming the recovered material into a variety of end products (Merrington, 2016). Initiatives such as those by the French firm Plaxtil which shifted its recycling efforts from clothes to single-use face masks by transforming them to plastic visors should be encouraged (FRANCE 24, 2020). Funding bodies such as The World Bank can create liaisons with other institutions dedicated towards effectively allocating funds to small and medium scale enterprises in this line of service. The potential to generate industrial-grade materials from disposable filtering masks by different recycling approaches has been shown by Battegazzore et al. (2020). The first approach involved processing all the three layers of face masks excluding the ear loop, while the second approach differed primarily by the inclusion of the ear loop. These two approaches proved most promising compared to the other techniques explored by the authors. As part of the way forward, the authors of the study recommend improving the performance of the recycled material by blending with virgin polymers, fillers, and other additives. Such a recommendation is useful especially when considering the comparative quality, filtration efficiency, and cost of brand-new masks viz-a-viz recycled masks (Chua et al., 2020). Conversely, Kakoria et al. (2021) demonstrated the feasibility of transforming waste PET bottles into nanofiber mats for facemasks and other air filtration applications. A 3-ply facemask prototype containing the nanofiber mat showed a high-performance filtration efficiency (>99%) following exposure to $PM_{0.1-2}$, ten cycles of handwashing, and sun drying, respectively. Furthermore, Maderuelo-Sanz et al. (2021) showed that surgical face masks possess great acoustical properties which can be utilized as sound porous absorbers in buildings.

4. Conclusion

This review has organized the main environmental indicators of face masks using the DPSIR framework. Due to human needs to protect against air pollution and infectious pathogens compounded by population growth and ease of mobility, the demand for face masks is increasing. As a result, the demand is putting enormous pressure on the face masks value chain. In particular, the COVID-19 pandemic has caused a substantial increase in single-use face masks production and usage worldwide. The favorability of single-use face masks over cloth masks is owed to positive media campaigns, ease of purchase, affordability, and comfort. This creates enormous pressure on the mass production of face masks and resource exploitation. Consequently, the state of the environment is dramatically changing with the influx of discarded face masks in both terrestrial and marine ecosystems. The impact of discarded masks on the environment is widespread. Entanglement of terrestrial and aquatic animals, ingestion of face masks, and the potential buildup of degraded mask plastics in the food chain are some of the reported incidences and wider implications. As a response, different strategies have been proposed to alleviate the associated environmental damage. The responses include waste management and utilization, diversification in the materials used for face masks with a bias towards eco-friendly type options, and environmental cleanups. The current knowledge on the efficacy of face masks needs to be further researched to include the quality of the materials to be used while striking the balance with functionality. In this light, more potential stakeholders like small and medium-sized firms can be brought on board by engaging intermediary entities that facilitate these kinds of investments in them by large funding bodies. Moreover, studies on the impact of discarded face masks on aquatic flora and fauna should be extended to quantify the risk. Similarly, further work needs to be done to understand the socio-economic impact of littered face masks on coastal environments. In sum, if there are any lessons to be taken out of this pandemic, especially with respect to mask use, there is an urgent need to foster research collaboration on alternative materials with high functionality, alongside effective outlets, and strategies to disseminate information to the public on the importance of personal responsibility on matters of the environment.

CRediT authorship contribution statement

Yacob T. Tesfaldet: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Visualization. **Nji T. Ndeh**: Writing - Original Draft, Writing - Review & Editing, Visualization.

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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