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Review

Risks of Covid-19 face masks to wildlife: Present and future research needs

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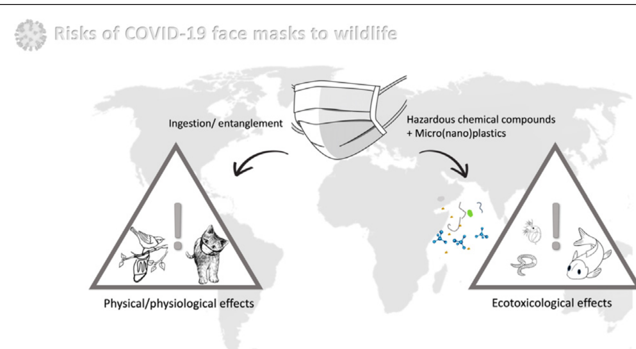
HIGHLIGHTS

- Thousands of COVID-19 disposable masks may enter the environment daily.
- Wildlife interactions with disposable masks have been reported in several countries.
- Disposable masks release contaminants with the potential for ecotoxicological effects.
- Monitoring and ecotoxicological studies should be prioritised.
- Mitigation measures should be implemented to control plastic (including masks) pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of disposable face masks became essential to fight against the COVID-19 pandemic, resulting in an unprecedented rise in their production and, unfortunately, to a new form of environmental contamination due to improper disposal. Recent publications reported the abundance of COVID-19-related litter in several environments, wildlife interaction with such items, and the contaminants that can be released from such protective equipment that has the potential to induce ecotoxicological effects. This paper provides a critical review of COVID-19 face mask occurrence in diverse environments and their adverse physiological and ecotoxicological effects on wildlife. It also outlines potential remediation strategies to mitigate the environmental challenge impose by COVID-19-related litter.

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Contents

1. Introduction

The fast spread of the SARS-CoV-2 virus via respiratory droplets and the resulting coronavirus disease (COVID-19) pandemic has led to a significant increase in the demand for disposable face masks globally (Fadare and Okoffo, 2020). Primarily made to protect healthcare workers from preventing occupational hazards, the use of disposable masks also became a preferential option for non-medical professionals based on their higher filtration capacity over reusable alternatives (Prata et al., 2021). In South Korea, for instance, 91% of mask-wearing citizens opt by own-will for disposable masks (e.g., N95, KF masks, surgical masks) (Won So, 2020); but the preference for disposable masks (surgical masks, 40%) also prevails in other countries such Australia, U.S., U.K. Singapore, Sri Lanka and India (Selvaranjan et al., 2021). In France, Austria, Germany, and some U.S. states, the use of disposable masks in public places were even imposed by national or local governments (Prata et al., 2021; CDC, 2021).

Disposable masks are essentially made of polypropylene and high density of polyethylene, and might contain other polymeric materials such as polyesters, polyurethane, polystyrene, and polyacrylonitrile (Prata et al., 2021). Such face masks mostly rely on three layers: an inner layer composed of soft fibres; a middle layer consisting of a melt-blown filter; and an outer layer consisting of nonwoven fibres that confirms water-resisting properties (Fadare and Okoffo, 2020). With a great contribution from petrochemical polymers with high molecular weight, disposable face masks do not readily (bio)degrade in open environments (Prata et al., 2020).

Incorrect disposal of disposable face masks has been reported worldwide, in urbanised areas (streets, gardens, parks), natural reserves, beaches, and even high mountains (e.g., Ammendolia et al., 2021; Neto et al., 2021; Prata et al., 2020); intensifying plastic pollution. This is not surprising, as, in an international online survey (Australia, U.S., U.K., Singapore, Sri Lanka and India), 19% of individuals assumed that they recklessly throw away their disposable face masks (Selvaranjan et al., 2021). Even when considering improper disposal of just 1% of disposable face masks by the world population, it would release to the environment ~10 million face masks (30,000–40,000 kg) (WWF International, 2020). To this share can add up face masks leaked from landfill facilities due to their lightweight, particularly in developing countries where such an end-of-life option is preferable for treating municipal solid wastes from COVID-19 (Corburn et al., 2020; Gandhiok, 2021; Sabour et al., 2020). Wildlife interactions with littered disposable masks have been reported daily, with the potential for adverse effects in a short- and long-run (Fig. 1). This paper provides an overview of the presence and abundance of COVID-19 mask in urbanised and natural environments, their direct adverse effects on wildlife, and discusses the potential ecotoxicological effects imposed by the released particles and leached hazardous chemicals recently reported for such items.

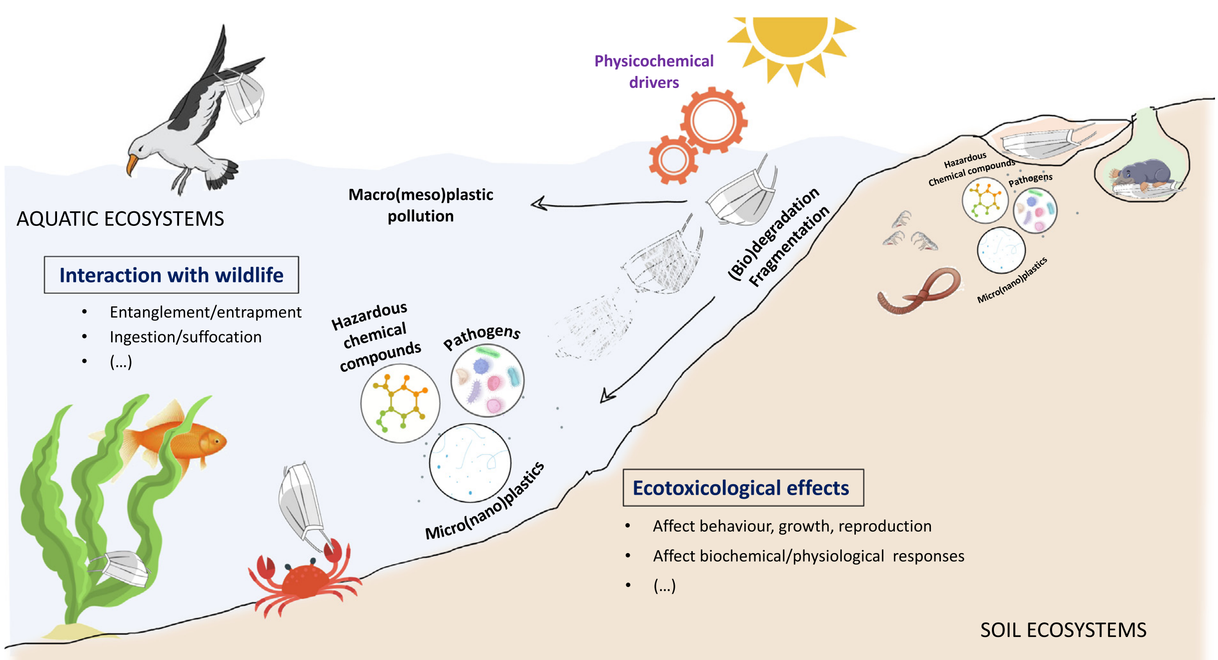

Fig. 1. Potential effects of disposable facemasks in aquatic and terrestrial organisms.

2. Occurrence of disposable face masks in outdoor environments

Plastic pollution is one of the greatest environmental challenges, with known adverse ecological, economic and human health effects (De-la-Torre et al., 2021). Plastic mismanagement during the COVID-19 pandemic has escalated plastic pollution worldwide. Several reports have evidenced the occurrence of personal protective equipment such as disposable masks in lakes and beaches in Africa (Aragaw, 2020; Okuku et al., 2021), coastal cities of South America (Ardusso et al., 2021), and cities in Europe (e.g., Prata et al., 2021). But only recently, monitoring studies have been released, although remaining scarce. Disposable masks have been found in urban areas, with densities of approximately 0.001 items m^{-2} in Canada (Ammendolia et al., 2021) and Peru (De-la-Torre et al., 2021), and <0.3 item m^{-2} in Kenya (Okuku et al., 2021) (Table 1). Items densities seem dependent on sampling areas, weather conditions (wind, precipitation), and populational density. The number of disposable face masks in rivers and beaches seems considerably higher than in any other place, acting as highways and sinks, respectively. For example, In Jakarta, Indonesia, approximately 250 disposable masks might be entering aquatic environments daily (Cordova et al., 2021). In Kenya, beaches presented 10 times more disposable masks than in the streets (Okuku et al., 2021) (Table 1). In urbanised areas, hospital and parking lots seem to present 5 times higher levels of disposable face masks than in residential areas (Ammendolia et al., 2021) (Table 1).

Although the percentage of COVID-19 face mask litter seems to be considerably lower than single-use plastics (e.g., packaging), their constitution (e.g., layers of polymeric material; ear-hook) and composition (additives and plasticisers) raises equal environmental concerns if their use and consumption patterns remain considerably high for the coming years (as in 2020–2021). Besides, thousands of disposable masks are ending up on landfills or open dumps along with mixed wastes daily (as it is occurring in developing countries such as India and Indonesia; Corburn et al., 2020; Gandhiok, 2021; Sabour et al., 2020), and if not properly contained and due to their lightweight, such items can easily leak to the environment. It is estimated that approximately 0.15 million tons to 0.39 million tons of mismanaged COVID-19 plastic waste could end up in global oceans within a year (Chowdhury et al., 2021). Thus, if no remediation strategy is put into place, it is expected to increment their numbers in natural environments, with the potential for adverse effects at different biological organisation levels.

3. Disposable masks can directly threaten wildlife

It is widely recognised that plastic pollution can directly affect wildlife (e.g., via ingestion and entanglement), regardless of their habitat, physiology, behavioural patterns. Over 200 species, including marine mammals, sea turtles, and seabirds, are reported to have been entangled or ingested plastic litter (Kühn et al., 2015). Both ingestion and entanglement can be detrimental to the organisms' survival and reproduction by limiting their mobility and feeding ability. Additionally, plastic marine litter can act as a substrate, favouring some species over others, creating unique communities in these persistent and drifting substrates (Zettler et al., 2013). COVID-19 related litter adds to the pressures already caused by common plastic items, such as single-use plastics (e.g., plastic bags). Face masks have a particular interest as the dominant COVID-19 related litter found in the environment (as discussed in Section 2). Interactions with COVID-19 litter, particularly masks (and, to a lesser extent, latex gloves and disposable wipes), have been reported by academics, ordinary citizens, and wildlife stakeholders, for several aquatic and terrestrial species (Hiemstra et al., 2021). For instance, Neto et al. (2021) recently reported the death of an adult Magellanic penguin (*Spheniscus magellanicus*) found on Juquehy Beach, São Sebastião, Brazil, potentially related to the ingestion of an FFP-2 protective face mask. This mask was present in the penguin's stomach, which may have restricted the organisms feeding activity and resulted in starvation. A considerable percentage of Magellanic penguins (~36%) in Brazil, actually display evidence of being negatively affected by the ingestion of solid (plastic) waste, with acute (death) and chronic (reproductive failure, delayed ovulation) effects (Brandão et al., 2011). Therefore, they may be more susceptible to the adverse effects of littered face masks.

Similarly, species that feed on landfills may be particularly exposed to disposable masks disposed of by the public, as these are disposed of as municipal solid wastes. For example, the white storks (*Ciconia ciconia*) have been reported to feed on landfill wastes, which comprises 68.8% of the diet of these animals in Spain (Avila, Salamanca, Zamora) (Peris, 2003). A considerable amount of landfill waste was also observed in the gut of overwintering gull species (*Larus smithsonianus*, *Larus marinus*, *Larus glaucoides*) (Seif et al., 2018). Thus, it is reasonable to expect that some plastic waste is ingested along with food waste, affecting survival, feeding, health status, and fitness. In addition to the physical effects, plastics wastes adsorb and act as vectors for heavy metals,

Table 1
Occurrence and density of disposable face masks during COVID-19 pandemic in urbanised and natural environments.

Location	Sampling sites	Number of items	Observations	Reference
Lima; Peru	11 beaches	138 items (7.44×10^{-4} items/m^2), 66.4% representing disposable masks (surgical, KN95)	Recreational beaches presented the highest number of items (73%), followed by surfing (24.6%), fishing and inaccessible beaches (< 1%).	De-la-Torre et al., 2021
Soko island; Japan	100 m beach	70 disposable masks (7×10^{-3} items/m^2)		Stokes, 2020
Kwale, Kilifi, Mombasa; Kenya	Beaches (sediments and water), and streets	Streets: 0.01 item/m Beaches: 0.1 items/m^2	Mombasa presented a higher number of masks in the streets; Kwale beaches presented more items than Kilifi.	Okuku et al., 2021
Jacarta bay; Indonesia	Cilincing and Marunda river mouths	4500–5000 items (~254.7–246 items/day), 5.36–4.92% representing face masks	COVID-19 waste increased 5% the debris found in riverine sediments.	Cordova et al., 2021
Toronto; Canada	Parking lots, hospitals, residential areas	1306 items, 31% representing face masks. Parking lots and hospitals ($1.60–1.33 \times 10^{-3}$/m^2) Residential areas ($2.9–2.7 \times 10^{-4}$ /m^2)	Parking lots and hospitals had higher numbers of face masks.	Ammendolia et al., 2021
Cox's Bazar; Bangladesh	One beach (13 sampling sites; 12 weeks)	6.29×10^{-4} /m^2, 97.9% representing face masks		Rakib et al., 2021
Bushehr, Iran	Sandy beaches (S1, S4, S7-S9) Rocky beaches (S3, S5, S6)	1578 face masks and 804 gloves were found over a cumulative area of 43,577 m^2 during 40 days	S4, S5, S7 (most populated beaches) were the most polluted sites	Akhbarizadeh et al., 2021

organic compounds (Anastopoulos and Pashalidis, 2021), and pathogens (Luksamijarulkul et al., 2014), potentially even SARS-CoV2 (Kasloff et al., 2020). Thus, despite later regurgitation, frequent ingestion of plastic wastes in landfills by overwintering seagulls has been associated with death and a significant decrease in their reproduction due to chemical body-burdens (Seif et al., 2018).

The entrapment of organisms in plastic litter has been frequently documented. For instance, hermit crabs *Coenobita perlatus* are known to get entrapped in marine plastic litter (e.g., inside bottles) (Lavers et al., 2020). The presence of marine debris, including plastics, also increases turtle hatchlings times to reach the sea, favouring predation (Aguilera et al., 2018). Several cases of wildlife species entangled in disposable face masks have been reported worldwide, including entanglement in talons, beak, neck, legs, or other body parts (Hiemstra et al., 2021). Species include seagulls (*Larus sp.*), peregrine falcons (*Falco peregrinus*), swans (*Cygnus olor*), mallards (*Anas platyrhynchos*), American robins (*Turdus migratorius*), crabs (*Carcinus maenas*), bats (*Eptesicus serotinus*), foxes (*Vulpes vulpes*), hedgehogs (*Erinaceus europaeus*), checkered pufferfish (*Sphoeroides testudineus*) (as reviewed by Hiemstra et al., 2021; and data available at https://www.covidlitter.com). Organisms' entanglement can result in immediate death through immobilisation (as observed in the American robin *T. migratorius*), or by suffocation or drowning. It can also result in chronic effects, for instance, by restricting feeding to the point of starvation, facilitating predation, exhausting the animal, causing strangulations, infections, severe wounds, and even amputations. Besides entanglement, the availability of face masks may have unexpected effects. For instance, a disposable face mask and other personal protective equipment were observed in the nest of a common coot (*Fulica atra)* in Leiden, Netherlands (Hiemstra et al., 2021). The presence of such items in bird nests can later result in the entanglement or ingesting by the chicks (or the parents), compromising nutritional requirements and development (Tavares et al., 2016). Ingestion (even of relatively low quantities) of plastic debris by seabird *Ardenna carneipes* induced a significant negative effect on bird morphometrics and blood calcium levels, along with an increment in the uric acid, cholesterol, and amylase concentrations (Lavers et al., 2019), revealing that it may have a negative impact on fitness. The presence of plastic waste in the nest's structure could also alter thermal and drainage properties, influencing reproductive success (Thompson et al., 2020).

4. Potential ecotoxicological effects

Once in open environments, single-use-masks will likely undergo fragmentation by physicochemical (e.g., UV radiation, wind, currents) and biochemical (enzymatic activity) processes (Fadare and Okoffo, 2020; Prata et al., 2020), resulting in a myriad of small particles such as micro- and nano-plastics (< 5 mm in size and < 1um in size, respectively; Frias and Nash, 2019). The few monitoring studies on PPE in the environment (summarized in Table 1) evaluated the weathered/deterioration levels of these items (FTIR, SEM), which suggests the release of plastic fibres and microplastics. However, none counted such debris in the environmental matrixes where such PPE were found.

Disposable face masks also contain additives to enhance some fashionable properties, such as antiviral and antibacterial barriers, dye compounds, fragrances. Thus, along with the release of microplastics, it is also expected that disposable face masks would slowly contribute to the release of potentially hazardous chemicals (Prata et al., 2020).

Saliu et al. (2021), Sullivan et al. (2021), and Wang et al. (2021) provided the first evidence on microfibers and micro and nanoplastics released from disposable face masks. Saliu et al. (2021) estimated the release of microfibres from surgical face masks into the marine environment, under the effect of UV light. Results indicated that one tested mask submitted to 180 h UV-light irradiation and vigorous stirring in artificial seawater could release up to 173,000 fibres/day. Authors also observed similar morphological and chemical degradation signature in surgical masks collected on Italian beaches (via SEM and micro-FTIR analysis), highlighting that similar processes could be happening in the natural marine environment (Saliu et al., 2021). Wang et al. (2021) estimated the release of microfibres from surgical masks also into the marine environment, now in the presence of UV light and sediments. According to the authors, higher mask-layers fragmentation into microplastics was observed in the longest UV light exposure (5-fold; up to 5 μg/L) and in the presence of sand (2 to 10 fold, depending on the mask-layer; up to 18 μg/L).

Based on these studies and considering that millions of disposable masks find their way into the freshwater waterways (where currents and turbulence can occur) and sea (where the waves' action can be quite sharp), one can predict that thousands of microfibres can be released daily. Microplastic fibres are already a reality in some environments, with high dominance over other shapes in aquatic environments and in concerning levels (as reviewed by Rebelein et al., 2021). So, the leakage or intentional littering of disposable masks from COVID-19 pandemic will scale up plastic microfibres contamination worldwide. For example, up to 102.4 fibres/kg was observed in shoreline sediment (75% represented by polypropylene and polyethylene, including from synthetic nonwoven materials) collected in the Magdalena River Huila, Colombia (Martínez Silva and Nanny, 2020). In Saigon river, Vietnam, synthetic microfibres concentration achieved up to 519,000 items/m^3 (Lahens et al., 2018).

The ingestion and consequential effects of microfibres (particularly PP, PE, and polyesters – which are also the most common polymers found on disposable face masks) have been reported in several organisms from aquatic environments and with different feeding guilds, such as crabs (*Carcinus maenas, Eremita analoga*), small crustaceans (*Hyalella Azteca, Gammarus fossarum*, *Daphnia magna*), and bivalves (*Mytillus edulis, Corbicula fluminea*) as filtrators; anemones (*Aiptasia pallida*) and fish (*Danio rerio*) as predators; annelids (*Tubidex tubidex*) as sediment-dwelling (detritivores) (as reviewed by Kutralam-Muniasamy et al., 2020; Singh et al., 2020). Terrestrial organisms also proved to ingest microfibres, such as the soil-dwelling (detritivore), annelids (*Lumbricus terrestris*) and the shredder snails (*Achatina fulica*) (Kutralam-Muniasamy et al., 2020) (Table 2). The ingestion of microfibres (although at concentrations relatively higher than the ones encountered in the field) is often related to behavioural alterations (e.g., burrowing activity of the annelids; or sink activity of crustaceans), decreased feeding activity (as observed in bivalves and crabs), reduced growth/body mass (particularly in crustaceans), increased deformities/damages (as in fish), reduced reproductive output and embryonic development (as for crabs), induced inflammatory processes (in anemone), oxidative stress (in annelids and shredders) (Kutralam-Muniasamy et al., 2020) (Table 1). Indeed, adverse effects of microplastics are often related to the formation of reactive oxygen species and consequent oxidative stress as the major molecular initiating event (Jeong et al., 2017). When compared to other particles shape (e.g., bead or powdered shape), fibre-shaped particles tend to induce generally higher ecotoxicological effects compared with (Kutralam-Muniasamy et al., 2020), particularly when such microfibres are weathered (e.g., with UV radiation) (Liu et al., 2021). Plastics include a myriad of additives to produce colour (e.g., dyes made of organic compounds, inorganic or organic pigments) or improve their physicochemical properties (e.g., antioxidants), some with known adverse effects (Christie, 1994). For instance, Bisphenol A, used in polycarbonate plastics (i.e., polypropylene, polyethylene) as a stabiliser and antioxidant, can leach from plastics and induce toxicity under low concentrations as an endocrine disruptor (i.e., by mimicking hormones) (Nam et al., 2010). Disposable face masks also contain these additives to enhance their properties, such as antiviral and antibacterial barriers, dye compounds, fragrances. Thus, it is also expected that disposable face masks would slowly contribute to the release of potentially hazardousness chemicals (Prata et al., 2020).

Sullivan et al. (2021) evaluated the emission of micro- and nanoplastics from 7 disposable face masks brands in aquatic compartments

Table 2
Summary of the adverse effects microfibres (from polymers found on disposable face masks; i.e., PE, PP, PA, PET, polyesters) on wildlife (as reviewed by Kutralam-Muniasamy et al., 2020; Singh et al., 2020).

Test organism	Polymer & size	Exposure conditions (concentration; time of exposure)	Ecotoxicological effects	Reference
Carcinus maenas (Decapoda)	PP (500 um) obtained from ropes	Up to 2 mg; 30 days	Reduction in feeding activity	Watts et al., 2015
Hyalella azteca (Amphipoda)	PE and PP (20–70 × 20 Ø um) obtained from a 3 y old rope	Up to 90 items/mL; 30 days	Compromised growth and reproduction	Au et al., 2015
Gammarus fossarum (Amphipoda)	PA (500 × 20 Ø um)	Up to 13,380 items/cm; up to 16 h	Reduction in the food intake	Blarer and Burkhardt-Holm, 2016
Daphnia magna (Cladocera)	PET (62–1400 × 31–528 Ø um) obtained from a PET fabric	Up to 100 mg/L; 48 h	Increased mortality	Jemec et al., 2016
Nephrops norvegicus (Decapoda)	PP (3–5 mm × 0.2 Ø mm) obtained from ropes	5 items included in 1.5 g of squid; 8 months	Compromised feeding rate, body mass, and metabolic rate	Welden and Cowie, 2016
Ceriodaphnia dubia (Branchiopoda)	Polyester (100–400 um) obtained from clothing	Up to 3.4 × 10^4 items/L; 1 and 8 days	Physiological deformities, compromised reproduction.	Ziajahromi et al., 2017
Mytilus edulis (Mytilda)	PET (< 5 mm) obtained from pink PET fleece	30 items/ mL; up to 72 h	Compromised filtration rates	Woods et al., 2018
Emerita analoga (Decapoda)	PP (1 mm) obtained from rope	3 items every 4 days; 71 days	Adult mortality and adverse embryonic development	Horn et al., 2020
Calanus helgolandicus (Calanoida)	Nylon and PET (10 × 4 μm; 23 × 100 μm; 17 × 60 μm; 23 × 70 μm) purchased from Goodfellow	100 items/ mL; 24 h	Compromised feeding activity, alteration in sinking rates	Coppock et al., 2019
Aiptasia pallida (Actinaria)	Nylon, polyester and PP (50–1000 × 30 Ø um) obtained from fluorescent ropes	10 mg/L (~121 ± 28 items); 72 h	Alteration in intestinal metabolism and gut microbiota, increased inflammation.	de Orte et al., 2019
Danio rerio (Cypriniformes)	PP (20–100 × 20 Ø um) obtained from containers	20 mg/L; 24 h	Intestine alterations, gut inflammation, and metabolism disruption. Gut microbiota dysbiosis.	Qiao et al., 2019
Palaemonetes pugio (Decapoda)	Polyester (63–150 um) obtained from fabric PP (34–93 um) obtained from weathered marine rope	50,000 items/L; 96 h	No effects on survival and bacterial infection (for polyester). Increased mortality (PP)	Leads et al., 2019
Lumbricus terrestris (Opisthopora)	Polyester (361–387 × 40 Ø um) obtained from cushion	0, 0.1 and 1.0% *w*/w microfibers for 35 days	ALtered burrowing and feeding behaviour, molecular genetic biomarkers.	Prendergast-Miller et al., 2019
Achatina fulica (Stylommatophora)	PET (1257 × 76.3 Ø um)	0.01–0.71 g/kg; 28 days	Reduction in food intake and excretion, damage in the gastrointestinal walls, oxidative stress.	Song et al., 2019
Folsomia candida (Collembola)	PP obtained from PPE microfibres (< 300 μm)	1000 mg/kg dry soil; 28 days	Ingestion/egestion observed, reproduction and growth decreased by 48% and 92%, respectively, no biochemical and behavioural alterations	Jin and Youn-Joo, 2021
Eisenia Andrei (Opisthopora)	PP obtained from PPE microfibres (< 300 μm)	1000 mg/kg dry soil; 21 days	Biochemical alterations (esterase activity dropped 62%; spermatogenesis declined to 0.8). No effects on survival and absence of pathological symptoms	Jin and Youn-Joo, 2021

and hazardous contaminants leachates analysis. Using advanced techniques (Fourier-transform infrared spectroscopy, light microscopy, scanning electron microscopy with energy dispersive X-Ray analysis, Liquid chromatography / Inductively coupled plasma –mass spectrometry), the authors reported the release of micro and nano polymeric fibres (as also observed by Saliu et al., 2021; just characterized by size by SEM, not counted), siliceous fragments, and other irregularly-shaped plastic particles; but also leachable inorganic and organic substances, such as metals (up to 6.79 μg lead/L; 1.92 μg cadmium/L, 393 μg antimony/L, 4.17 μg copper/L) and polar organic species related to plastic additives, surfactant molecules, dye-like molecules, polyamide-66 monomer and oligomers (nylon-66 synthesis), and polyethylene glycol (Sullivan et al., 2021). Anatopoulos and Anastopoulos and Pashalidis (2021) also underline the role of microplastics released from disposable face masks as dye carriers. In addition, Fernández-Arribas et al. (2021) reported the release of organophosphate esters from different surgical (KN95, FFP2, FFP3) and reusable face masks. Chemicals adsorbed to microplastics may leach into body tissues after ingestion/contact, resulting in induced changes or bioaccumulation (Issac and Kandasubramanian, 2021). Some of the mentioned hazardous chemicals (metals, surfactants, plasticisers, additives) and microplastics (fibres) as only stressors induce ecotoxicological effects (Issac and Kandasubramanian, 2021). In addition to chemicals in plastics, microplastics can interact with environmental contaminants. The interaction of microplastics with persistent organic pollutants (POPs) is a complex issue, as it depends on the characteristics of microplastics, contaminants, and environmental conditions, potentially originating additive, synergistic, or antagonistic effects (Rodrigues et al., 2019). Masks can often be incorrectly disposed of in wastewater (Rasmussen, 2020) or in landfills (Prata et al., 2020), where they can release microfibers that will be exposed to high concentrations of contaminants and microorganisms. For instance, microplastics can contribute to spreading antibiotic-resistant genes (Hu et al., 2019) and increased plasmid transfer (Arias-Andres et al., 2018).

The presence of both plastic fragments and chemicals contaminants from disposable face masks in natural environments is, therefore, expected, with the potential for causing ecotoxicological effects on wildlife at different levels of biological organisation (from cell to communities). The release of contaminants can occur from masks directly thrown in the water and soil compartments exposed to weather conditions; or via leachates from landfill leachates facilities or wastewater treatment plants (here considering a more appropriate end-of-life options such as landfilling) as most of such facilities do not possess advanced treatments to eliminate both persistent hazardous chemicals and microplastics of small size (Silva et al., 2021). For example, the combined effect of microplastics and copper (a metal that can leach out from face masks (Sullivan et al., 2021) promoted genotoxicity, neurotoxicity and physiological effects on the neotropical teleost *Prochilodus lineatus*, with greater effects (for some endpoints) that each contaminant alone (Roda et al., 2020). Synergistic effects were also observed for cadmium combined with microplastics in the common carp *Cyprinus carpio*, with greater effects on biochemical and immunological parameters than individual stressors (Banaee et al., 2019). Antagonistic effects (i.e., when the effects of a combination result in lower effects that each stressor) can also occur (as observed in *Danio rerio*, which revealed lower mortality when exposed to cadmium and microplastics mixtures, Zhang et al., 2020), but they do not threaten organisms performance.

Conversely, synergistic effects call for urgent mitigation measures, particularly when they occur at low intensities of each stressor (i.e., above the legal levels). A biomonitoring study carried out in Songkhla Lake, Thailand, during the COVID-19 on fish (*Arius maculatus*) and shrimps (*Parapenaeopsis hardwickii* and *Metapenaeus brevicornis*) reported a higher occurrence of microplastics (particularly PE and polyester fibres, with high numbers on black or blue colour) in the gut of the organisms, along with trace metals (cadmium, lead, arsenic) (Pradit et al., 2021). One can argue that the presence of fibres could be a result of increased laundry activities, while metals are also commonly found in urbanised areas; but it cannot rule out potential contribution (even the slightest) from disposable masks as both fish and shrimps proved to interact with such items (Table 2). Future research must address the fragmentation of face masks, as well as the release of a cocktail of contaminants, including their toxicological effects complemented by biomonitoring studies.

5. Final remarks and future recommendations

COVID-19 has elevated our dependency on plastic products, such as face masks, to ensure safety against infection. However, intense use and mismanagement of COVID-19 waste are imposing a severe environmental challenge. Thousands of tons of disposable face masks are ending up in natural environments worldwide; where they can scale up microfibres and hazardous chemicals contamination, with the potential to induce severe effects on their inhabitants, from invertebrates to vertebrates and at different levels of biological systems. To fully understand the scope of the abundance, source, drivers, and impact of such plastic litter in order to improve current legislation and legal frameworks, it is crucial to: i) increase research on this topic by increasing long-term monitoring programs, including aerial surveys and citizens science initiatives (for collection and reporting); and ii) assess the ecotoxicological impacts on different biota, considering environmental levels found for microplastics (including cocktails of hazardous contaminants that might be present in single-use masks).

New masks are being certified, but the assessment of their environmental performance is still lacking. For instance, some disposable face masks are being optimised for antimicrobial, self-cleaning, and skin protector properties (Chua et al., 2020), which can also leach to the environment. It is known that, for instance, antimicrobial substances are designed to inhibit the growth of microorganism, whereas skin protectors can include nanoparticles. Thus, certification of such masks should be complemented with tests addressing their environmental performance.

Before COVID-19, several strategies and policies were in place to reduce our dependency on plastics. Yet, it seems that the COVID-19 pandemic might have driven us from such a sustainable goal. It appears that global dependence on plastics might even increase from pre-COVID-19 pandemic levels, as epidemics are predicted to increase due to climate change. Thus, it is of utmost importance to determine leakage points and interventions (mitigation measures) so that disposable masks (and other PPE debris) leakage do not pose future environmental problems. In addition, action is urgently needed to promote the correct reuse (after disinfection), disposal and/or treatment (recycling) of plastics, including masks. For instance, a novel plant-based ionizer proved efficiency in eliminating COVID-19 droplets (Suwardi et al., 2021).

Moreover, it is vital to scale up innovation and technology to substitute current disposable masks (petrochemical-based) with bio-based and eco-friendly (potentially biodegradable) alternatives. Among bio-based solutions, polyhydroxyalkanoates (PHA) and poly(lactic)acid (PLA) obtained from microorganisms (including microalgae) have raised scientific attention, as they can be biodegradable (i.e., able to mineralise into water, carbon dioxide, and biomass in the presence of biological activity). However, biodegradable options from PLA or PHA (or other options) should be environmentally friendly, implying not being blended with hazardous chemicals. Biodegradation and ecotoxicological assays performed on PLA and PHA commercial versions (obtained from plant-based biomass that contains additives) highlights for their low biodegradation in aquatic systems (e.g., Emandian et al., 2017) and adverse effects on invertebrate (e.g., Chagas et al., 2021) and vertebrate (e.g., Malafaia et al., 2021) species. Wheat gluten biopolymer (a by-product or co-product of cereal industries) has also been considering a promising solution for biodegradable masks (Das et al., 2020). Such polymer allied with lanosol (a naturally occurring substance that imparts fire and microbe resistance) can be electrospun into nanofibre membranes and subsequently carbonised to form masks. Such polymer has a lower environmental footprint than PLA and PHA (Das et al., 2020), and do not degrade into microplastics but rather into nitrogen-based components that could even work as soil fertilising.

CRediT authorship contribution statement

A.L.P.S.: visualisation, writing - original draft, writing - review and editing. J.C.P.: visualisation, writing - original draft, writing - review and editing. C.M.: conceptualisation, supervision, writing - review and editing. D.B.: conceptualisation, supervision, writing - review and editing. A.C.D.: conceptualisation, supervision, writing - review and editing. T.R.-S.: conceptualisation, supervision, writing - review and editing.

Declaration of competing interest

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

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