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## Review



## Degradation of plastics associated with the COVID-19 pandemic

Carlos Ivan Pizarro-Ortega<sup>a</sup>, Diana Carolina Dioses-Salinas<sup>b</sup>, Melisa D. Fernández Severini<sup>c</sup>, Ana D. Forero López<sup>c</sup>, Guido Noé Rimondino<sup>d</sup>, Nsikak U. Benson<sup>e</sup>, Sina Dobaradaran<sup>f,g,h</sup>, Gabriel Enrique De-la-Torre<sup>b,\*</sup>

<sup>a</sup> Universidad San Ignacio de Loyola, Av. La Fontana 501, Lima 12, Lima, Peru

<sup>b</sup> Grupo de Investigación de Biodiversidad, Medio Ambiente y Sociedad, Universidad San Ignacio de Loyola, Lima, Peru

<sup>c</sup> Instituto Argentino de Oceanografía (IADO), CONICET/UNS, CCT-Bahía Blanca, Camino La Carrindanga, km 7.5, Edificio E1, Bahía Blanca, B8000FWB Buenos Aires, Argentina

<sup>d</sup> Instituto de Investigaciones en Fisicoquímica de Córdoba (INFIQC), Departamento de Fisicoquímica, Facultad de Ciencias Químicas, Universidad Nacional de Córdoba, Ciudad Universitaria (X5000HUA), Córdoba, Argentina

<sup>e</sup> Department of Chemistry, Covenant University, Km 10 Idiroko Road, Ota, Nigeria

<sup>f</sup> Systems Environmental Health and Energy Research Center, The Persian Gulf Biomedical Sciences Research Institute, Bushehr University of Medical Sciences, Bushehr, Iran

<sup>g</sup> Department of Environmental Health Engineering, Faculty of Health and Nutrition, Bushehr University of Medical Sciences, Bushehr, Iran

<sup>h</sup> Instrumental Analytical Chemistry and Centre for Water and Environmental Research (ZWU), Faculty of Chemistry, University of Duisburg-Essen, Universitätsstr. 5, Essen, Germany

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## ABSTRACT

The ongoing COVID-19 pandemic has resulted in an unprecedented form of plastic pollution: personal protective equipment (PPE). Numerous studies have reported the occurrence of PPE in the marine environment. However, their degradation in the environment and consequences are poorly understood. Studies have reported that face masks, the most abundant type of PPE, are significant sources of microplastics due to their fibrous microstructure. The fibrous material (mostly consisting of polypropylene) exhibits physical changes in the environment, leading to its fracture and detachment of microfibers. Most studies have evaluated PPE degradation under controlled laboratory conditions. However, in situ degradation experiments, including the colonization of PPE, are largely lacking. Although ecotoxicological studies are largely lacking, the first attempts to understand the impact of MPs released from face masks showed various types of impacts, such as fertility and reproduction deficiencies in both aquatic and terrestrial organisms.

## 1. Introduction

Since it entered the market in the 50's, plastic has brought many economic and social benefits. However, the excessive use of disposable products has caused an exponential increase in the amount of plastic waste globally (Benson et al., 2021a; Torres and De-la-Torre, 2021a). Therefore, plastics are gradually becoming a global environmental threat. Plastics are one of the most used materials due to their excellent versatility, malleability, and ability to provide solutions to a wide variety of needs in today's society. In 2019, plastic production reached 368 million tons, the most common being polypropylene (PP), followed by polyethylene (PE) in all its versions (PlasticsEurope, 2020). Plastic waste in the environment can be transported by rivers, storms, strong winds, or

dumped directly into terrestrial or aquatic ecosystems. The interactions of these residues with environmental conditions could lead to their physical damage (e.g., fragmentation) and changes in their physicochemical properties (e.g., crystallinity, glass transition temperature (T<sub>g</sub>) due to mechanical abrasion, photolytic, chemistry, or biological degradation (Ganesh Kumar et al., 2020), giving rise to new types of micropollutants, such as microplastics (MPs) (plastics smaller than 5 mm) and nanoplastics (PNPs) (plastics smaller than <1 μm) (Akhbarizadeh et al., 2021a, 2020; Takdastan et al., 2021). MPs are cataloged as primary or secondary. Primary MPs/PNPs are manufactured in micro/nano-size, while secondary ones are derived from the degradation of larger plastics (Cole et al., 2011). They are ubiquitous in all environments of the world (Gela and Aragaw, 2022), causing great concern for

\* Corresponding author.

E-mail address: [gabriel.delatorre@usil.pe](mailto:gabriel.delatorre@usil.pe) (G.E. De-la-Torre).

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the environment (Hajiouni et al., 2022; Wang et al., 2019) and human health due to their small size, large specific surface area, and strong biological penetration (Xu et al., 2019). Research has shown that MPs/PNPs are capable of adsorbing and transporting external contaminants, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, among others (Rahman et al., 2021). The type of polymer, size, and environmental conditions affect the absorption of these pollutants (Torres et al., 2021). In addition, based on the morphology, size, and concentration, MPs can cause ecotoxicological consequences to multiple organisms (Aragaw and Mekonnen, 2021a; Rochman et al., 2019). For instance, ingestion of MPs around 70  $\mu\text{m}$  in size and various polymer types can cause intestinal damage to *Danio rerio* after 10 days of exposure (Lei et al., 2018). In the oyster *Crassostrea gigas*, small polystyrene MPs (2–6  $\mu\text{m}$ ) decreased the oocyte number and sperm velocity in exposed individuals, possibly altering their fecundity (Sussarellu et al., 2016).

The ongoing COVID-19 pandemic has led to the excessive use of personal protective equipment (PPE), such as face masks, gloves, face shields, among others, in order to prevent the transmission of the virus (Arduzzo et al., 2021; Benson et al., 2021a). The most widely used type of PPE is the disposable surgical face masks due to their low cost and effectiveness. In most countries, the use of face masks in public places is mandatory (De-la-Torre et al., 2021a). In the United States, KN95 mask production increased from 45 million to 180 million per month in 2020 (Statista, 2021), adding to global plastic production. Due to inadequate management and disposal, PPE items have already become a new threat to the environment. This new waste category has been evidenced on beaches (De-la-Torre et al., 2021b; Rakib et al., 2021; Arduzzo et al., 2021), rivers (Cordova et al., 2021), and urbanized areas (Ammendolia et al., 2021; Torres and De-la-Torre, 2021b).

Face masks and gloves are the most commonly used PPE since the pandemic began. In particular, surgical face masks are manufactured using non-woven fabric forming technology for disposal after use (Aragaw, 2020). The micro- and nanofiber mat is produced through electrospinning, but the specific composition, components, and manufacturing conditions vary from brand to brand (De-la-Torre and Aragaw, 2021; Fadare and Okoffo, 2020). The most used material for its production is polypropylene (PP), but polyurethane (PU), polyacrylonitrile (PAN), polystyrene (PS), polycarbonate (PC), polyethylene (PE), and polyethylene terephthalate (PET) are also used (Chellamani et al., 2013). These fabrics, in contact with ultraviolet light and sand, facilitate the release of micro/nanoparticles (De-la-Torre and Aragaw, 2021; Fadare and Okoffo, 2020; Kutralam-Muniasamy et al., 2022). It is estimated that a mask under ambient conditions of a coastal ecosystem can release around 173,000 microfibers per day (Saliu et al., 2021). Likewise, Sullivan et al. (2021) reported that masks exposed to water released some heavy metals such as lead, cadmium, and antimony. On the other hand, the gloves are manufactured with latex or natural rubber, nitrile, foil, vinyl, neoprene, etc. (Preece et al., 2020). In addition, to improve the physical, mechanical, and chemical properties of this PPE type, substances (e.g., plasticizers, stabilizers) are commonly added during their manufacture which may be easily released from gloves throughout aging and may contaminate the aquatic environment (Jędruchiewicz et al., 2021). Given recent reports and investigations about the prevalence of PPE items polluting the marine environment as an unprecedented form of plastic pollution, and the recognition of face masks as important sources of MPs/PNPs in the marine environment, it is imperative to evaluate the effect of weathering conditions and aging on the structural, physical, and chemical properties of PPE items, as well as their consequences. Thus, the present paper integrates and reviews the current knowledge regarding PPE pollution, degradation of PPE items, and their subproducts, such as MPs/PNPs and chemical compounds.

## 2. PPE pollution, sampling methods, and main challenges

Environmental pollution with PPE has been expected due to their excessive use and weakening of solid waste management systems. It was estimated that  $\sim 3.5$  million metric tons (MT) of face masks ended up in landfills worldwide in the first year of the pandemic (Patrício Silva et al., 2021a). Nevertheless, a significant amount may leak into the oceans and natural environments, which is estimated between 0.15 and 0.39 million MT per year (Chowdhury et al., 2021). The first observations of PPE pollution were presented to the public by news outlets, shared on social media, or displayed by NGOs, such as OceansAsia (Stokes, 2020). However, recent scientific publications provided further detail and analysis of the abundance, distribution, sources, and evolution of PPE pollution in aquatic environments (Table 1). On the other hand, other researchers have begun to use mathematical models to quantify the impact of the pandemic on plastic discharge. In this way, Peng et al. (2021) estimated that more than eight million tons of PPE were generated worldwide during the pandemic, and about 25,000 tons of PPE waste entered the ocean.

Initially, (Okuku et al., 2020) surveyed 24 beaches along the Kenya coast through standing stocks procedure. The surveys were carried out 100 days after the first COVID-19 case was reported in Kenya. COVID-19 related items accounted for about 0.43% of all the litter found, with densities ranging from 0.00 to  $3.8 \times 10^{-2}$  PPE  $\text{m}^{-2}$  in urban beaches and from 0.00 to  $5.6 \times 10^{-2}$  PPE  $\text{m}^{-2}$  in remote beaches. These findings were attributed to the possible lack of compliance with public beach closures in rural or remote areas. A few months later, Cordova et al. (2021) reported the unprecedented occurrence of COVID-19 related items in two river outlets discharging into Jakarta Bay, Indonesia. PPE items (mean of 780 items  $\text{day}^{-1}$ ) represented 15–16% of all the litter items collected and were composed of different types of face masks, respirators, hazmat suits, gloves, and face shields. Riverine litter monitoring was carried out between March and April 2020. Interestingly, in a previous survey (between March and April 2016), no PPE items were found in the two river outlets, which confirms the influence of the pandemic on solid waste generation and pollution. In Brazil, 178 face masks were found between April and October 2020 in several sites as part of several marine wildlife monitoring activities (Gallo Neto et al., 2021). The relevancy of these findings is that one of the necropsied penguins (*Spheniscus magellanicus*) had ingested a face mask, which is assumed as the cause of death. This is not the only case of wildlife interaction with PPE items. Hiemstra et al. (2021) reviewed the reports and photographic evidence of PPE entrapment, ingestion, entanglement, and other sorts of interactions across social media and news outlets. A long list of impacted animals from different taxa is displayed, although many could remain unreported.

Tracking the drivers of PPE pollution in beach areas could be a tough task, although the main source is obvious. Beachgoers and visitors are, without doubt, the ones bringing and improperly discarding the highest amounts of PPE. For instance, this became evident in Morocco, where the occurrence of PPE items was almost null during lockdown (the population was not allowed to enter beach areas) and suddenly increased just after the beaches reopened to the public (Ben-Haddad et al., 2021). Several studies tried to investigate the drivers of PPE pollution by assigning and comparing the main activity (e.g., recreational, aquatic sports, fishing, etc.) carried out in each site. The majority agreed that recreational activities are the ones driving more PPE than others (De-la-Torre et al., 2021b; Rakib et al., 2021), probably attributed to the number of visitors to this type of beach. To this end, we believe that encouraging and/or enforcing the use of reusable PPE items (mainly cloth face masks) in beach areas is imperative to reduce the number of littered PPE items.

The emerging field of PPE monitoring lacked standard sampling procedures that would make studies comparable worldwide. However, later studies followed the transect-based methodology used by De-la-Torre et al. (2021b). This sampling procedure consists of determining a

**Table 1**  
Summary of the studies quantifying PPE in coastal sites.

Country	City	Sampling type	Total area covered per sampling campaign (m <sup>2</sup> )	Number of sampling campaigns	Total PPE	Mean PPE density (PPE m <sup>-2</sup> )	Most abundant PPE	Ref.
Argentina	–	Transects <sup>a</sup>	474,719	1	43	$7.21 \times 10^{-4}$	Face masks (48.8%) Gloves (48.8%)	(De-la-Torre et al., 2022)
Perú	–	Transects <sup>a</sup>	1,179,727	1	489	$6.60 \times 10^{-4}$	Face masks (94.5%)	
Perú	Lima	Transects <sup>a</sup>	110,757	12	138	$6.42 \times 10^{-5}$	Face masks (87.7%)	(De-la-Torre et al., 2021b)
Morocco	Agadir	Transects <sup>a</sup>	282,374	16	689	$1.13 \times 10^{-5}$	Face masks (96.8%)	(Ben-Haddad et al., 2021)
Morocco	Tetouan	Transects <sup>a</sup>	17,789	5	321	$1.20 \times 10^{-3}$	Face masks (100%)	(Mghili et al., 2021)
Iran	Bushehr	Transects <sup>a</sup>	43,577	4	2382	$1.72 \times 10^{-2}$	Face masks (66.2%)	(Akhbarizadeh et al., 2021b)
Bangladesh	Cox's Bazar	Transects <sup>a</sup>	516,683	12	29,254	$3.16 \times 10^{-4}$	Face masks (97.8%)	(Rakib et al., 2021)
Kenya	Kwale and Kilifi	Transects <sup>b</sup>	–	1	–	$0.00\text{--}5.6 \times 10^{-2}$	–	(Okuku et al., 2020)
Ethiopia	Bahir Dar	Transects <sup>a</sup>	119,850	12	221	$1.54 \times 10^{-4}$	Face masks (93.7%)	(Aragaw et al., 2022)
Chile	Nationwide	Quadrants	–	1	17	$6.00 \times 10^{-3c}$	– <sup>c</sup>	(Thiel et al., 2021)
Brazil	Sao Paulo	–	–	–	178	–	Face masks (100%)	(Gallo Neto et al., 2021)

<sup>a</sup> The length and number of transects varied per site, aiming to cover the whole beach area.

<sup>b</sup> Standing stock surveys.

<sup>c</sup> Only face masks were counted.

sampling area within each beach (mostly aiming for the entirety of the beach) and, subsequently, a number of transects parallel to each other (separated by 8–10 m) enough to cover the selected area (Fig. 1). Litter monitoring is carried out by walking along the transects once and visually identifying PPE items. The benefit of this methodology is that the sampled area is well defined and ignores sampling bias due to unevenly distributed litter across the beach. Thus far, this methodology has been applied in Perú, Argentina, Bangladesh, Iran, and Morocco. Their overall results are shown in Table 1. However, after applying this methodology in a nationwide study including 36 sampling sites with covered areas ranging from a few hundred meters squared, a nonlinear inverse correlation (sampled area vs. PPE density) was observed (Fig. 2). This is mainly because a very small covered area with a few PPE items translates into a relatively high PPE density (number of PPE per m<sup>2</sup>), which could bias the interpretation of the results in terms of PPE density

and statistical analysis. In this sense, we suggest the covered areas to range from around 25,000 to 50,000 m<sup>2</sup> per sampling site.

Due to lockdown and travel restrictions (which may vary across countries), complying with scheduled sampling campaigns has become quite difficult. Particularly, obtaining a comprehensive overview of PPE pollution in terms of abundance and distribution is key but challenging at the same time. Many long-term marine litter monitoring projects were compromised or momentarily stopped due to the COVID-19 pandemic (Thiel et al., 2021). Some studies may need specific permission from the local government authorities in order to complete the monitoring schedule (Ben-Haddad et al., 2021) but being granted such permission may not always be successful. Given the current monitoring challenges that researchers may encounter, citizen science projects have been regarded as suitable initiatives for obtaining reliable and well-distributed litter data while engaging with the general public (Oturai



**Fig. 1.** Map of a sand beach displaying the sampling area (yellow area) and appropriate transects parallel to each other (red lines) separated by 10 m, as described by De-la-Torre et al. (2021b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



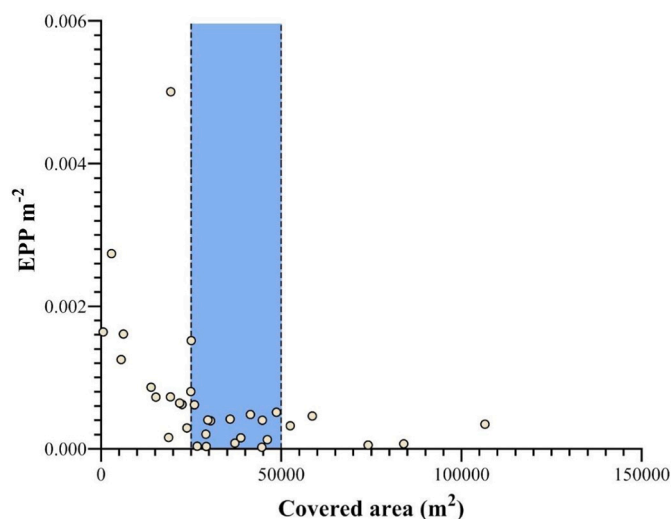


Fig. 2. Scatter plot of sampled area vs. PPE density from 36 sites along the coast of Peru. The Blue region indicates the suggested range of covered area (from 25,000 to 50,000 m<sup>2</sup>) to avoid bias. Spearman correlation:  $p \leq 0.0001$ ,  $r = -0.6698$ . The data was obtained from (De-la-Torre et al., 2022). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2021). This approach may be exceptionally useful in the context of the COVID-19 pandemic (Ammendolia and Walker, 2022). The first demonstration of PPE monitoring using a readily available technological tool was carried out by Ammendolia et al. (2021). In their study, the spatial distribution of different types of PPE items was recorded in the city of Toronto using the georeferencing mobile application “Marine Debris Tracker” (<https://debristracker.org/>). This tool was initially developed as part of a citizen-science initiative. Thus, providing a great opportunity for PPE monitoring under the current scenario (Ammendolia and Walker, 2022).

### 3. Degradation and subproducts

Before the COVID-19 pandemic, the presence of plastic debris in different environmental matrices had become a concern due to their low rate of degradation, ubiquity, and high fragmentation into the smaller particles (meso/micro/nanoplastics) could be potentially dangerous to wildlife and humans (Kumar et al., 2021). Moreover, during aging of this plastic debris and their respective fragmentation due to exposure to the weathering conditions (e.g., UV-light, temperature) can leach other emerging pollutants (e.g., plasticizers, antioxidants, UV stabilizers, lubricants, dyes) and be a vector for other pollutants such as heavy metals, persistent organic pollutants (POPs), pesticides, and polycyclic aromatic hydrocarbons (PAHs) (Agboola and Benson, 2021; Hüffer et al., 2018; Ricardo et al., 2021; Torres et al., 2021). As previously mentioned, there has been a substantial increase in the production and use of PPE for slowing down the transmission rate of the virus SARS-CoV-2 in human beings (Ardusso et al., 2021; Patrício Silva et al., 2021a; Peng et al., 2021). However, due to the improper disposal of this new type of waste, there have been negative implications for the terrestrial and aquatic environments, as well as wildlife, in the short and medium-term, as a result of the increase in pollution triggered by plastic debris (Hiemstra et al., 2021; Patrício Silva et al., 2021b).

Plastics undergo environmental weathering through abiotic and biotic processes. The former refers to the physical and/or chemical changes that occur due to abiotic factors, such as sunlight, temperature, wind, and mechanical forces, while the latter is driven by organisms through physical (chewing, biting, etc.) and biochemical processes (Zhang et al., 2021). The degradation process of plastic debris can last

up to hundreds of years depending on its physicochemical properties and the surrounding environmental condition. During this process, there are changes in their properties, such as crystallinity, hydrophobicity, functional groups, mechanical properties, among others (Ali et al., 2021). In particular, when plastic debris is in contact with the aquatic environment, the hydrophobicity of plastic material begins to change due to the formation of dissolved organic matter layers on their surface, which is essential to the adherence and growth of microbial communities present in the water column (e.g., bacteria, single-celled algae, and fungi), forming the so-called plastisphere (Arias-Andres et al., 2018; De Tender et al., 2017; Rummel et al., 2017). It is well known that this microcosm or plastisphere can influence the aging processes, vertical transport and migration of plastic debris, enrichment or dissemination of harmful microorganisms, and the sorption and release of contaminants by plastic debris (He et al., 2022; Rummel et al., 2017). In the case of PPE (in particular, face masks) in aquatic ecosystems, they can be a potential refuge for pollutants and to facilitate enrichment and spread of antibiotic resistance genes (ARG) in the environment due to lateral gene transfer (LGT) between unilateral and/or multicellular microorganisms, causing antibiotic-sensitive microorganism to evolve resistance (Zhou et al., 2021). According to Zhou et al. (2021), face masks can be a base substrate to ARG processes between aquatic microorganisms and accelerate this transfer. In a previous work, we suggested that the architecture of the face masks (microscopy meshing) could influence the preferential growth of some microorganism communities during the first stages of formation as in the topography or texture of the biofilm.

#### 3.1. Chemical degradation

Weathering of plastics causes irreversible changes in their chemical characteristics. For instance, photodegradation of synthetic polymers exposed to incident UV light induces chain scission reactions (Gewert et al., 2018). The chemical changes occurring in the polymer backbone can be evaluated by FTIR spectroscopy, Raman, and X-ray photoelectron spectroscopy (XPS). In polyolefins (e.g., PE, PP), UV light causes the oxidation of the polymer structure, which appears in the IR regions ranging from 3300 to 3500 cm<sup>-1</sup> and 1610–1800 cm<sup>-1</sup> (Almond et al., 2020; Grigoriadou et al., 2018). For instance, Ainali et al. (2021) reported the occurrence of new peaks around 3300–3500 cm<sup>-1</sup> and 1650–1860 cm<sup>-1</sup> in PP and HDPE, attributed to the occurrence of hydroxyl/hydroxyperoxide and carbonyl groups, respectively, after 45 days of exposure to UV light. These results are consistent with PE and PP exposed to different environments (land, water, and ocean) for 23 weeks (Q. Chen et al., 2021), confirming the formation of ketone and oxygen-containing functional groups due to polyolefin polymer chain scission (Resmeriță et al., 2018). While the studies aforementioned conducted experiments with pristine pieces of plastic, this type of chemical change is also expected in face masks. Saliu et al. (2021) analyzed the surgical face masks exposed to the experimental conditions specified in Table 2 by  $\mu$ FTIR. Unlike pristine face masks, weathered face masks displayed broad peaks around 3400 cm<sup>-1</sup> assigned to hydroxyl groups and various overlapping carbonyl groups around 1720 cm<sup>-1</sup>. Furthermore, a surgical mask picked up from a beach presented very similar additional peaks, suggesting that these experimental conditions may represent chemical degradation in the environment. It should be noted, however, that directly analyzing plastics extracted from the environment without any cleaning treatment could lead to erroneously assigning additional hydroxyl and carbonyl peaks to chemical degradation (Sandt et al., 2021). This is due to the possible contamination of plastics with organic matter rich in oxygen-containing groups (e.g., lipids, polysaccharides). Hence, plastics extracted from the environment must be sufficiently cleaned before being analyzed by spectroscopic techniques.

On the other hand, XPS is an essential technique to identify the changes in the compositions and state chemicals, group functionals, and elements adsorbed on the plastic surface (Kim et al., 2021; Mao et al., 2020). In this way, Mao et al. (2020) studied the aging mechanism of PS

**Table 2**  
Summary of the experimental conditions and MP release from experimental studies.

Type of mask	Experimental conditions	Quantification technique	MP release	Ref.
Disposable surgical	Virgin face mask was placed in an aqueous solution and shaken for 24 h.	Laser in-situ scattering and transmissometry analyzer (particle detection range 1–500 $\mu\text{m}$ )	483,888 MPs per mask	(Z. Wang et al., 2021)
	Virgin face mask was UV-light irradiated, placed in an aqueous solution, and shaken for 24 h.		1,566,560 MPs per mask	
	Virgin face mask was UV-light irradiated, placed in an aqueous solution in the presence of sand, and shaken for 24 h.		16,001,943 MPs per mask	
Disposable surgical	Virgin face mask was placed in an aqueous solution and stirred for 24 h. The face mask was then dried, and the experiment was repeated 2 more times	Metallographic microscopy (40 $\times$ and 100 $\times$ magnification) Scanning electron microscopy (SEM) (1000 $\times$ and 10,000 $\times$ magnification)	116,600 MPs per mask	(Shen et al., 2021)
	Virgin face mask was placed in an aqueous solution in the presence of alcohol and stirred for 24 h. The face mask was then dried, and the experiment was repeated 2 more times		147,000 MPs per mask	
	Virgin face mask was placed in an aqueous solution in the presence of detergent and stirred for 24 h. The face mask was then dried, and the experiment was repeated 2 more times		168,800 MPs per mask	
Disposable surgical (7 types)	Virgin face mask was UV-irradiated (10 h at 65 $^{\circ}\text{C}$ , repeated 15 times), placed in an aqueous solution, and stirred for 24 h.	Stereomicroscope	61 MP per mask (1–5 mm) 117,400 MP per mask (25–500 $\mu\text{m}$ )	(Saliu et al., 2021)
Disposable surgical	Virgin face mask was placed in an aqueous solution and exposed to shear damage using a kitchen chopper (2 min),	Stereomicroscope Flow cytometry	28,000 MP per mask (0.1–5 mm) $2.1 \times 10^{11}$ MP per $\text{m}^2$ of treated fabric (0.1–100 $\mu\text{m}$ ).	(Morgana et al., 2021)
Disposable surgical (3 types) and N95	Virgin face masks were placed in an aqueous solution and stirred for 24 h. Worn (24 h of usage) face masks were placed in an aqueous solution and stirred for 24 h.	Stereomicroscope	183 MPs per mask 1246.6 MPs per mask	(X. Chen et al., 2021)
Disposable surgical (8 brands) and N95 (2 brands)	Virgin face masks were placed in a glass bottle, 100 mL was added and stirred for 3 min, and the leachate was extracted. The procedure was repeated 10 times.	Field-emission SEM Atomic force microscopy (AFM)	$2.23 \times 10^3$ MPs per mask (>1 $\mu\text{m}$ ) $2.43 \times 10^9$ MPs per mask (<1 $\mu\text{m}$ )	(Ma et al., 2021)
Disposable surgical	Virgin face masks were placed in soil and exposed to the environment (sun and rain) for 30 days. The masks were then rubbed 120 times inside a closed chamber lined with filter paper.	Digital microscope	$1.01 \times 10^5$ MPs per mask	(Rathinamoorthy and Balasaraswathi, 2021)
	Virgin face masks were placed in soil and exposed to the environment (sun and rain) for 30 days. Then, masks were placed in water (freshwater or marine) and rubbed continuously for 15 min.		$1.64 \times 10^4$ – $6.61 \times 10^4$ MPs per mask	

with UV irradiation under different conditions (air, pure water, and seawater) and the effect of aging on heavy metal adsorption. In the case of plastic particles, this technique shows the changes in the binding energy (BE) of the different atomic orbitals from the chemical elements that comprise the surface of plastic particles, which are influenced by their chemical structure, changes in the surface oxidation due to aging processes of MPs/PNPs, and adsorption and/or interactions with other compounds, like heavy metals such as Cd (A. Yu et al., 2021), Pb (Fu et al., 2021), and Cu (Qiongjie et al., 2022), among others. Yan et al. (2021) studied the changes in the surface chemistry of face masks (i.e., N95, 3 M) upon the heat treatment for their reusing. These authors informed no change in the surface chemistry of the different types of face masks by dry or steam heat treatment.

The wettability of a liquid indicates its ability to interact with another liquid or solid. This property is evaluated by measuring the contact angle. A lower contact angle ( $\leq 90^{\circ}$ ) indicates greater wettability and vice versa (Sarkar et al., 2020). Environmentally degraded polyolefins in contact with water generally exhibit greater wettability than pristine ones, probably due to the formation of polar groups on their surface (Waldman and Rillig, 2020). Previous studies have demonstrated a notorious increase in the wettability of PP plastics after several weeks exposed to different environments (Q. Chen et al., 2021), likely due to the formation of oxygen-containing groups. To the best of our knowledge, no previous study has evaluated the wettability of PPE samples from the environment or after experimental treatments. This property is relevant to understanding the ability of littered plastics,

particularly PPE, of interacting with external environmental contaminants and serving as suitable substrates for biofilm formation (Bhagwat et al., 2021; Torres et al., 2021). These characteristics of PPE are still poorly understood and have been suggested as a research priority in this field of research (De-la-Torre and Aragaw, 2021). The degree of crystallinity refers to the number of aligned polymer chains that make up a polymer matrix. The parts where polymer chains are aligned with one another are called crystalline regions (lamellae), and the remaining parts lacking a specific ordering (mostly entangled polymer chains) are called amorphous regions (Drioli and Giorno, 2016). This property highly influences the chemical, optical, thermal, and mechanical properties of plastic materials, including its fracture mechanism (Crawford and Quinn, 2017; Julienne et al., 2019). This property has been investigated in plastics exposed to weathering conditions, generally showing a time-dependent behavior. For instance, LDPE and HDPE plastics (degree of crystallinity of 34% and 45.4%, respectively) exposed to UV light displayed an increase in the degree of crystallinity after the first 10–20 days of exposure but decreased back to near the initial values (33.2% and 46.6%, respectively) after 60 days (Ainali et al., 2021). This behavior is attributed to the chain scission in PE molecules and later crystallization of unchained segments within the polymer matrix. Q. Chen et al. (2021) and X. Chen et al. (2021) demonstrated the influence of the different types of aquatic environments (freshwater, estuary, and ocean) on the changes in the degree of crystallinity after exposure time. They reported that PE plastics exposed to either of the aquatic environments (+UV light) results in an increased degree of crystallinity

(after 11 weeks), which continued increasing until 23 weeks of exposure. Conversely, PP plastics showed a slight increase after 11 weeks but later decreased below the degree of crystallinity at time 0. For PE, it was observed that the degree of crystallinity was positively correlated to the salinity of the medium (freshwater < estuary < ocean), suggesting that salinity could promote the crystallization of segmented chains. In our previous study (De-la-Torre et al., 2022), we reported a notorious decrease in the crystallinity of PP-based face masks recovered from the environment compared to pristine ones through X-ray diffraction (XRD). However, cotton-polyester face masks displayed little variation in the intensity of their XRD patterns. Although the time the analyzed face masks were exposed to natural environmental conditions is unknown, our results provided preliminary evidence of the changes in crystallinity in PPE exposed to the environment. Hence, further research is needed concerning the degree of crystallinity and thermal stability of different PPE items under controlled environmental conditions.

Figs. 3 and 4 showed an example of the characterization techniques used for identifying PPE commonly employed during the current COVID-19 pandemic. The photographs of pristine and sample surgical face masks were exhibited (Fig. 3a). It can be seen in (Fig. 3b) that intensities of peaks characteristic of PP in  $2\theta$  angles of  $14^\circ$  (110),  $17^\circ$  (040), and  $18.6^\circ$  (130) and minor signals at  $21\text{--}22^\circ$  and  $25.6^\circ$  (Li et al., 2019). The intensities of diffraction peaks of 110, 040, and 130 segments of crystal planes of polymers decreased in the outer layer from the sample compared to pristine material. On the other hand, the XRD pattern of the inner layer from the sample face mask did show a slight difference in the intensity of peaks than the pristine face mask. ATR-FTIR spectrums of layers and cord composed of the sample face mask were presented in Fig. 3c. FTIR spectra from three layers of the sample showed characteristic bands of PP, and the FTIR spectrum from the cord sample exhibited signals typically representative of Polyamide 6 and Polyamide 6,6 mixes.

On the other hand, the photograph of a glove found in the coastal

area was presented in Fig. 4a. The XRD pattern of pristine and sample gloves was exhibited in Fig. 4b. Both spectra exhibited a broad amorphous region of natural rubber that is visible at  $2\theta = 18.13$  (Parvathi et al., 2021), and characteristic peaks of  $\text{CaCO}_3$  were also identified in both spectra (Lee et al., 2012). The intensity of the amorphous region decreased in the sample compared to pristine material. Finally, SEM images of gloves show small micro-voids, cavities, and particles (crystals) adhered to their surface.

### 3.2. Physical degradation

Chemically degraded plastics display downgraded physical properties, which may result in changes in their mechanical properties (Speight, 2011) or structure, commonly observed as cracking or embrittlement of the material (Chamas et al., 2020). The mechanical properties of plastics refer to their reaction (behavior) to an applied force. For instance, Rajakumar et al. (2009) reported a dramatic decrease in the elongation at break (maximum stretch before breaking) and tensile strength (maximum load supported before breaking) of PP film after 70 days of natural weathering regardless of the season. With reduced mechanical properties and embrittlement of the plastic material, fragmentation will likely occur under natural conditions. The fragmentation mechanism of degraded plastics is dependent on their chemical properties. Julienne et al. (2019) demonstrated that LDPE and PP plastics experimentally exposed to UV irradiation displayed differentiated crack propagation. The distinctive crack propagation pathways of each type of plastic were associated with their crystalline morphology rather than the degree of crystallinity, thus providing insights concerning the formation of secondary MPs. SEM micrographs of experimentally degraded surgical face masks showed the breakage of loosely attached fibers and rough surfaces that exacerbated at longer exposure time (Saliu et al., 2021; Z. Wang et al., 2021). Similarly, face masks and gloves recovered from the urban and marine environment displayed

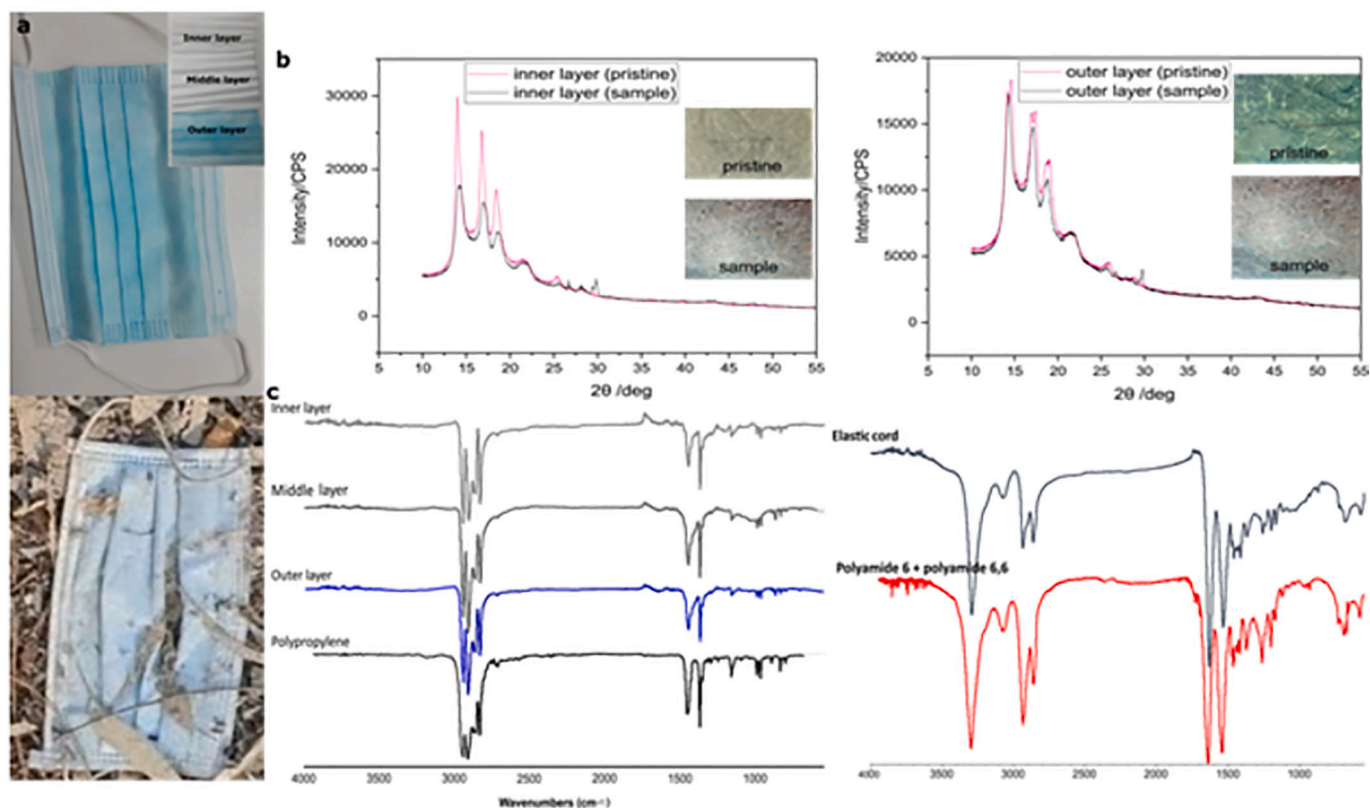


Fig. 3. (a) Photograph of pristine and sample surgical face masks. (b) XRD spectra of pristine and sample surgical face masks, and (c) ATR-FTIR spectra of layers and cord compound the sample surgical face mask.



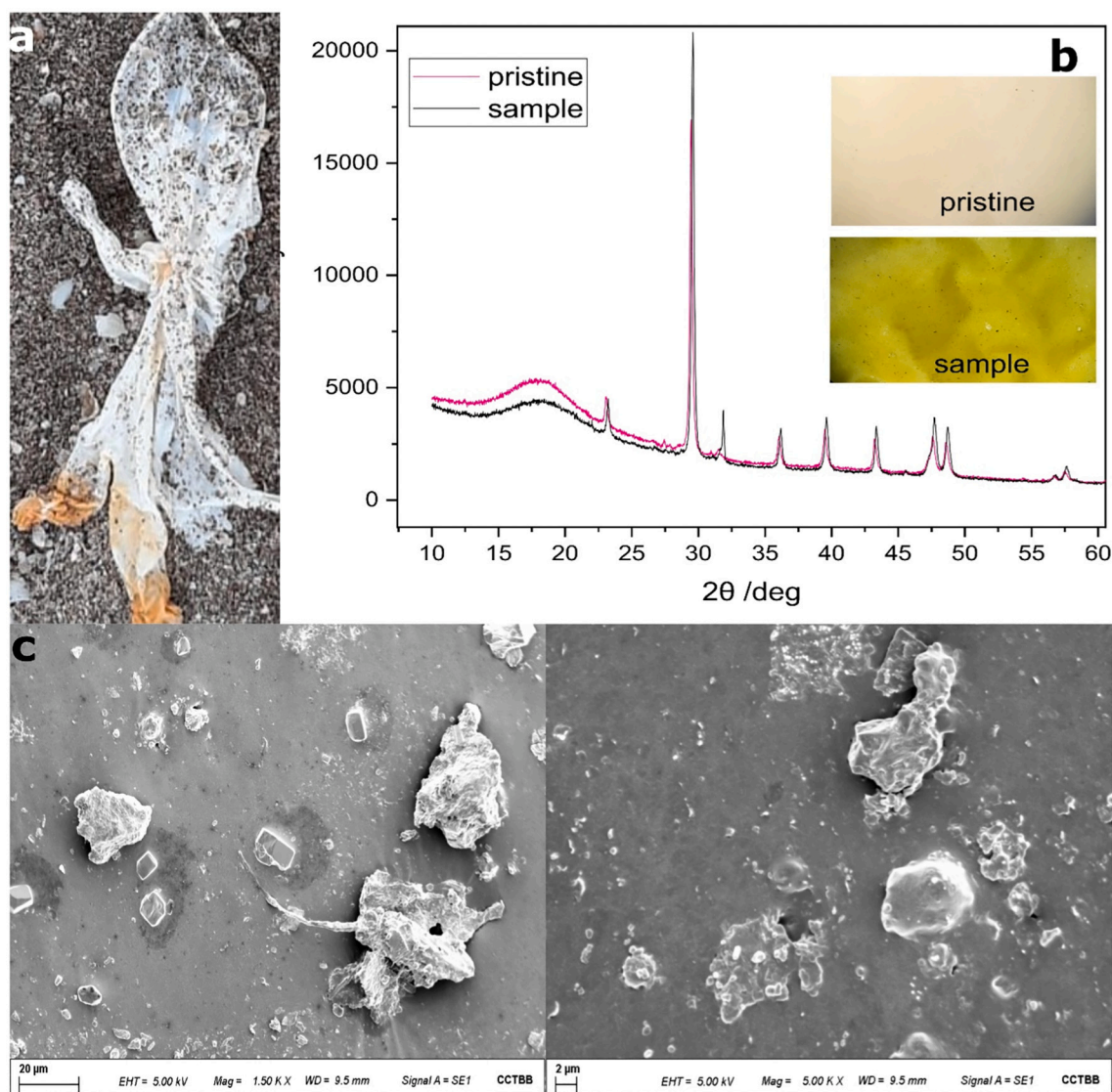


Fig. 4. (a) Photograph of a glove found in coastal areas. (b) XRD spectra of pristine and sample gloves, and (c) SEM micrograph at 1500 and 5000 $\times$  of sample gloves.

microfiber fragmentation and the formation of cracks and micro-voids, respectively (Akarsu et al., 2021; De-la-Torre et al., 2022). This suggests that PPE, especially face masks, are highly susceptible to fragmentation and may act as a source of MPs into the environment. The studies investigating this behavior under controlled conditions are reviewed in Section 3.3.

Finally, Yan et al. (2021) studied the impact of heat and steam treatment on the protection surgical masks (N95, WDR, and 3 M) using a group of characterization techniques such as XRD, XPS, Raman, SEM, and near-edge X-ray absorption fine structure spectroscopy (NEFAXS). Moreover, these authors also evaluated the angle of contact of mask materials after and before each treatment. According to the results of these authors, they suggested that applied steam treatment in surgical face masks may generate an increase of crystallinity, a decrease of elasticity, a change of surface adsorption to the fibers, and higher structural damage to sample polymers.

### 3.3. Release of contaminants

We previously discussed the knowledge gaps concerning PPE pollution in the marine environment and proposed several research questions (De-la-Torre and Aragaw, 2021), many of which have been partially addressed in recent studies. One of the main concerns is the release of

MPs (mostly in the form of microfibers) from face masks and PPE items in general. Under different experimental setups and evaluated variables, this issue has been investigated with great interest. Table 2 summarizes the main methodology and quantification techniques carried out in the recent literature, as well as the concentration of MPs released per face mask. These studies combine simple and low-cost techniques, such as the use of a stereomicroscope, and advanced equipment, such as scanning electron microscopy (SEM) and/or atomic force microscopy (AFM), to quantify MPs. In general terms, optic microscopy is used to visually identify MPs of larger fractions, and more sophisticated techniques are applied for smaller MPs (e.g., <100  $\mu\text{m}$ ) or even nanoplastics (PNPs) (<1  $\mu\text{m}$ ). Combining both quantification methods is pivotal to understanding the MPs particle size distribution leached by face masks. Also, all of the consulted studies reporting differentiated size ranges agree that the smaller MPs fractions are the most abundant by several orders of magnitude (Ma et al., 2021; Morgana et al., 2021; Saliu et al., 2021). Interestingly, Ma et al. (2021) went a step forward and evaluated the bioaccumulation potential of MPs released by disposable face masks. This experiment was carried out by exposing face mask MP leachates to multiple organisms (rotifer *Brachionus rotundiformis*, copepod *Parvocalanus crassirostris*, shrimp *Penaeus vannamei*, scallop *Chlamys nobilis*, and juvenile grouper *Epinephelus lanceolatus*), all of which effectively ingested MPs. While this study provides an interesting overview of the



interaction between face mask-associated MPs and aquatic organisms, ecotoxicological studies are largely lacking. However, recently, Sun et al. (2021) studied the chronic toxicity of MPs released from PP-face masks on marine copepod *Tigriopus japonicus*. These authors reported that copepods ingested the MPs release from the PP-face mask generating an important decline in the fecundity of this marine species (Sun et al., 2021). In terrestrial organisms, this type of study has only been carried out on earthworms and springtails, resulting in the inhibition of organism reproduction and other impacts (Kwak and An, 2021). Furthermore, the human health effects of PPE-associated MPs are still largely unexplored (De-la-Torre et al., 2021a; Kutralam-Muniasamy et al., 2022).

Similar to commercial plastic products, face masks include a number of additives and chemicals that could potentially leach into the environment. However, this has been poorly investigated in contrast with MP release and the number of studies is fairly limited. For instance, Sullivan et al. (2021) determined that the leachates of several disposable face masks contained organic chemicals, surfactants, dyes, and plastic oligomers, as well as potentially harmful heavy metals (Cd and Pb). More recently, X. Wang et al. (2021) determined the presence of phthalate esters plasticizers (most commonly di-methyl phthalate, di-n-butyl phthalate, di-ethyl phthalate, di-isobutyl phthalate, and di(2-ethylhexyl) phthalate) in disposable face masks and estimated daily intake values from face mask usage that exceed tolerable concentrations (Jin et al., 2021). Bussan et al. (2021) determined the levels of heavy metals present in 24 surgical and KN95 face masks using ICP-MS. These authors informed that the concentrations for six elements (Cr, Ni, As, Cd, Hg, and Tl) were below the detection limit; in contrast, detectable concentration levels were observed for Cu, Sb, and Pb. Moreover, the same authors also informed the potential leaching of Pb and Sb from face masks and how heavy metals may interact with humans through their saliva and depending on the time of use of face masks that contained these metals. In specific cases, like Argentina, where antiviral face masks impregnated with Ag and Cu nanoparticles were popularized, the environmental threat posed by their incorrect disposal is more pronounced (Ardusso et al., 2021). The main concern is the possible leaching of metal nanoparticles from commercial products (e.g., face mask and antiviral textiles) since they could negatively impact aquatic environments due to their high reactivity and a possible alteration of the ecotoxicological profile of MPs/PNPs on organism aquatics (Forero-López et al., 2022). Regardless, significantly more research is needed in this sense, which must be accompanied by ecotoxicological studies to better understand the environmental implications of incorrect PPE disposal. Furthermore, studies concerning the adsorption of external contaminants on MPs/PNPs derived from weathered PPE items are necessary to be conducted and compared with conventional MPs/PNPs (Torres et al., 2021).

#### 4. Strategies to decrease PPE pollution

Since the outbreak of COVID-19, improper disposal of PPE waste has resulted in an unprecedented glut of plastic waste into the aquatic and terrestrial environments, prompting concerns that this could potentially aggravate MPs/PNPs pollution globally (Benson et al., 2021a; Fadare and Okoffo, 2020). As previously mentioned, the introduction of face masks into the aquatic environment can result in the release of millions of MPs/PNPs, pollutants (e.g., toxic metals, phthalates), or can serve as a base for deposition and growth of microorganisms or algae. Hence, it is necessary to implement environmental management strategies in order to safeguard the stability of marine ecosystems and human health. L. Li et al. (2021) and S. Li et al. (2021) suggest the implementation of specific garbage containers for PPE, as well as providing guidance for tourists to properly dispose of their wastes, and beach disinfection procedures. These strategies must be accompanied by continuous waste generation monitoring and control (Hatami et al., 2022). Further, authorities should work on public awareness concerning the negative

impact of PPE in the environment and provide guidelines for their correct disposal, as well as promote reusable alternatives (Aragaw, 2021a). These strategies aim to prevent PPE and other types of wastes from entering the marine environment, as well as limit the amount of waste generated (Aragaw, 2021b). However, other conservation actions, such as beach clean-ups, may also contribute to preserving coastal environments free from marine litter (Battisti et al., 2020).

On the other hand, some authors have implemented different technological strategies to mitigate the plastic pollution generated by PPE waste (in particular, face masks), such as employing a Ni(OH)<sub>2</sub>/NiCl<sub>2</sub> hybrid catalyst to catalytic carbonization of face mask waste (R. Yu et al., 2021) or through a method co-hydrothermal liquefaction (Co-HTL) with *Spirulina platensis* grown in wastewater (L. Li et al., 2021). Other authors have developed antiviral/antibacterial biodegradable cellulose textiles for manufacturing face masks with the aim of making woven environmentally friendly and bioprotective materials with the potential to minimize MPs pollution (Deng et al., 2022). Alshabanah et al. (2021) have synthesized thermoplastic polyurethane (TPU) nanofibers impregnated with ZnO and CuO nanoparticles or personal protection applications to supply or improve the antiviral properties of the textiles polymer. However, the problem is also short-term due to the concern about the indiscriminate disposal of PPE (mainly face masks). For this reason, some researchers have proposed the conversion of disposable face masks as carbon powders that can be applied as an anode in sodium-ion batteries (Lee et al., 2022), which is an exciting and innovative development to mitigate plastic pollution from PPE. However, other researchers have proposed implementing a process system to produce renewable fuels from PPE waste (Zhao et al., 2022). Different processes have been employed to treat PPE waste, such as incineration, which is economically feasible but can emit large amounts of greenhouse gases (GHGs) and toxic substances, contributing to climate change (Fang et al., 2020; Klemeš et al., 2020; Zhao et al., 2022). Another process is optimized pyrolysis for mixed medical waste (Aragaw and Mekonnen, 2021b; Fang et al., 2020), a technique with high economic viability and technical feasibility but unknown environmental performance (Zhao et al., 2022).

All strategies have been attractive due to innovation and advances in new materials and processes designed to decrease the plastic pollution from PPE in the environment. However, the possible negative repercussions in the environment in the long-term must be taken into account from these materials waste during their development. For example, the excessive use of additives during the synthesis or modification in the cellulosic materials to confer physicochemical and antiviral properties may change their biodegradability or release chemical compounds in the environment from cellulosic debris (Forero-López et al., 2022; Truchet et al., 2021). Moreover, in developing countries, deficits in final PPE waste disposition and Municipal Solid Waste (MSW) management have been accentuated during this pandemic. The volume of plastic waste generated during the COVID-19 pandemic considerably outweighs the capacity of waste management facilities, particularly in most developing countries (Benson et al., 2021b). The poor waste management infrastructures and other flaws prove that plastic recycling processes (both mechanical and chemical pathways) are challenging to implement in these countries, further complicating the plastic pollutant landscape.

#### 5. Conclusions

The widespread abundance of PPE items has put into perspective the impact of the COVID-19 on marine plastic pollution. This unprecedented type of pollution has raised concerns due to its impact on marine biota and the release of MPs/PNPs and chemical pollutants. To this date, several studies have quantified PPE pollution in the marine environment, their impact on biota (e.g., ingestion and entanglement), and experimentally evaluated the release of MPs/PNPs. However, not much is discussed concerning the degradation of PPE items upon entering the

marine environment. In the present paper, we have reviewed and discussed the studies investigating PPE pollution and degradation of synthetic polymers commonly found in PPE items, as well as the MPs/PNPs release mechanisms. We have provided methodological recommendations for further monitoring programs to take into account, as well as identifying research gaps, and possible strategies to mitigate PPE pollution.

## 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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