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Release of phthalate esters (PAEs) and microplastics (MPs) from face masks and gloves during the COVID-19 pandemic

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ARTICLE INFO

Keywords:

Phthalate esters
Microplastics
Leachate
Plastic
Fiber
Contaminant

ABSTRACT

Marine pollution with personal protective equipment (PPE) has recently gained major attention. Multiple studies reported the release of microplastics (MPs) and chemical contaminants from face masks, the most used PPE type. However, not much is known concerning the release of phthalate esters (PAEs) in aquatic media, as well as the hazard posed by other types of PPE. In the present study, we investigated the release of MPs and PAEs from face masks and gloves recovered from the environment. The results indicated that both PPEs release MPs comparable to the literature, but higher concentrations were presented by face masks. In turn, the total concentration of six PAEs was higher in gloves than in face masks. The release of these contaminants is exacerbated over time. The present study allows researchers to understand the contribution of PPE to marine pollution while accounting for gloves, a generally overlooked source of contaminants.

1. Introduction

On March 11, 2020, the World Health Organization (WHO) declared the outbreak of the novel coronavirus disease (COVID-19) a global pandemic (Cucinotta and Vanelli, 2020). During this time, multiple preventive measures were employed to control the transmission of the virus, such as social distancing, lockdowns, limiting the capacity of businesses, and using personal protective equipment (PPE) (Abeya et al., 2021; Talic et al., 2021). PPE consists of wearable equipment aimed to minimize exposure to hazardous substances, pathogens, or environments. Face masks and respirators, gloves, and face shields were some of the most popular types of PPE used during the pandemic (WHO, 2020). PPE is regarded as a new widely used type of single-use plastic due to its synthetic polymer composition (Nghiem et al., 2021). Because the

lockdown measures disrupted solid waste management systems and recycling operations across the world, incorrectly discarded PPE started entering the environment, being found in coastal areas and beaches (Ben-Haddad et al., 2021; De-la-Torre et al., 2021, 2022b; Rakib et al., 2021; Ribeiro et al., 2022), inland water bodies (Aragaw et al., 2022; Hatami et al., 2022), terrestrial environments (Kwak and An, 2021), and cities (Ammendolia et al., 2021).

Face masks and gloves pose entanglement, entrapment, and ingestion hazards to aquatic and terrestrial biota. Recent studies reported various organisms, such as birds and fishes, entrapped or entangled in PPE, as well as using them as nesting material (Hiemstra et al., 2021; Mghili et al., 2021). Additionally, ingestion of face masks has been reported in top marine predators, such as the Magellanic penguin (*Spheniscus magellanicus*) and green turtle (*Chelonia mydas*) (Fukuoka et al.,

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<https://doi.org/10.1016/j.envres.2022.114337>

Received 4 May 2022; Received in revised form 6 September 2022; Accepted 9 September 2022

Available online 15 September 2022

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2022; Gallo Neto et al., 2021). The indirect impacts of PPE, such as the allocation of antibiotic resistance genes and the proliferation of potentially invasive species have been reported but further research is needed (De-la-Torre and Aragaw, 2021; Zhou et al., 2021).

Upon entering the environment, PPE is subject to weathering conditions, such as sunlight exposure, abrasion from wave action and collision with natural substrates, and biological interactions, among others. These conditions lead to the chemical and physical degradation of the polymeric material (De-la-Torre et al., 2022b; Pizarro-Ortega et al., 2022). A recent study revealed the occurrence of O-containing groups on the surface of polypropylene (PP) surgical face masks and linear low-density polyethylene (LLDPE) as a result of photooxidation induced by sun exposure, as well as changes in the crystallinity and physical changes (e.g., rupture of fibrous materials, cracks, rough surfaces, and cavities) (De-la-Torre et al., 2022a). These changes may compromise the mechanical characteristics of the material, potentially becoming more brittle, and leading to the release or creation of secondary contaminants.

The release of secondary contaminants, such as chemical additives and microplastics (plastic particles smaller than 5 mm; MPs), have been a subject of concern and PPE is no exception (Aragaw, 2020; De-la-Torre and Aragaw, 2021; Fadare and Okoffo, 2020). Multiple studies have investigated the release of MPs from face masks under diverse experimental conditions, as reviewed by Kutralam-Muniasamy et al. (2022). Face masks are regarded as a significant source of MPs, with estimates surpassing the millions per face mask (Z. Wang et al., 2021). However, the reported number of MPs detached from face masks varies depending on the environmental conditions, source, exposure time, and analytical procedures, among other factors. Face masks are also able to leach chemical contaminants, including heavy metals, dyes (Arduoso et al., 2021; Sullivan et al., 2021), UV-stabilizers (UV329) (Fukuoka et al., 2022), organophosphate esters (Fernández-Arribas et al., 2021), and volatile organic compounds, such as alkanes, polycyclic aromatic hydrocarbons, and phthalate esters (PAEs) (Jin et al., 2021). Particularly, PAEs have gained significant attention in recent studies due to their endocrine-disrupting effects (Abtahi et al., 2019) and likelihood of being emitted from the surface of materials containing them (Arfaeinia et al., 2020; Takdastan et al., 2021), such as face masks (Min et al., 2021). The studies mostly focused on developing methodologies to quantify human exposure to PAEs through inhalation while wearing conventional face masks, including estimated dietary intake values (Massarsky et al., 2022; Vimalkumar et al., 2022; X. Wang et al., 2021; Xie et al., 2022). However, quantifying the release of PAEs from face masks and other types of PPE into aquatic environments has been overlooked. In order to further elucidate the impact that PPE poses on aquatic environments, the present study aimed to quantify the release of two secondary contaminants, MPs and PAEs, from the most commonly used types of PPE in Bushehr city, Iran, under controlled experimental conditions.

2. Materials and methods

2.1. Sampling and selection

According to our previous survey, face masks represented about one-third of the total number of PPE litter, and the rest was composed of gloves in the sampling area (Bushehr port, Iran) (Akhbarizadeh et al., 2021b). Furthermore, PP surgical face masks and LLDPE gloves accounted for 57–63% and 92–96% of the total number of face masks and gloves, respectively. Thus, LLDPE gloves and PP surgical face masks were selected for being representative of the types of PPE most commonly found contaminating coastal areas. Sampling procedures were carried out on sandy and rocky beaches, where multiple activities take place (e.g., swimming, fishing, exercising). Each site was surveyed several times in order to visually identify LLDPE gloves (transparent film-like gloves) and PP surgical face masks (3-ply surgical face masks of multiple colors). The recovered PPE was packed in aluminum foil, stored

in plastic bags, and transported to the laboratory until further analysis. The material was air-dried at room temperature and scanned under a binocular microscope for signs of degradation or weathering. PPE with notorious signs of degradation (e.g., damaged structure, broken parts, colored/stained) were excluded from the analysis. The polymeric composition was confirmed by Fourier transformed infrared (FTIR) spectroscopy, as described in our previous study (De-la-Torre et al., 2022a).

2.2. Experimental design

A total of 48 face masks and 48 gloves were selected for the PAEs and MPs release experiment. Eight separate treatments were evaluated per type of PPE, considering four exposure times (1, 10, 30, and 60 days) and two water mediums (pre-filtered seawater [S] or distilled water [D]). Each treatment was repeated six times (three repetitions destined for PAEs and three for MP analysis). Each treatment per PAEs or MPs analysis was conducted per triplicate to obtain the minimum number of repetitions to conduct statistical analyzes for an experimental design under controlled conditions. Exposure days were chosen considering the solid waste management plans and beach cleaning procedures in Bushehr port. We estimated that common marine litter, such as face masks and gloves, could remain up to 2 months abandoned on the beach area. The experiments were performed by placing one face mask or glove in a 500 mL beaker filled with the water medium. The beakers were placed outdoors (laboratory balcony) and subject to natural environmental conditions. Bushehr port experiences sunny days and hot weather without rain. Between August to September, temperatures ranged from around 32 to 40 °C with no precipitation, and sunlight exposure (from sunrise to sunset) lasts for about 14 h. The laboratory balcony was located approximately 8 m high. The experiment was not affected by the wind direction and intensity because the face masks remained inside beakers. Each treatment beaker was covered with well-placed aluminum foil to avoid external contamination. However, since only the opening of the beaker was covered, the samples were exposed to sunlight passing through the glass, ultimately degrading the material. After the desired exposure time, each beaker containing the leachates was immediately transported to the laboratory for further MP and PAEs analyses.

2.3. PAEs analysis

2.3.1. Sample preparation

Samples preparation and analysis were carried out as described by Hajiouni et al. (2022). Leachates were filtered through polytetrafluoroethylene membranes with a pore size of 0.45 µm (Whatman, Maidstone, Kent, UK). Phthalate separation was carried out using 20 mL of dichloromethane and 20 µL of benzyl benzoate (Merck, Germany) as internal standard per 100 mL of leachate in a separation funnel. The solvent was then poured into glass dishes and washed with dichloromethane, acetone, and hexane (Merck, Germany). The resulting extract was sealed and stored at 4 °C until further analysis.

2.3.2. Gas chromatography-mass spectrometry (GC-MS)

A gas chromatography-mass spectrometer (GC-MS) device (Agilent Technologies, Avondale, PA, USA) equipped with a quadrupole mass spectrometer was employed for PAE analysis. Isolation was achieved with a capillary column of polydimethylsiloxane (HP-5 MS (5% phenyl) –95%) made of silica with a film thickness of 0.25 µm. Helium (99.999% purity) was used as a carrier gas with a flow rate of 1 mL/min and selected ion monitoring (SIM) analysis was carried out. The samples were injected in splitless mode at 290 °C. The oven temperature was gradually increased from 70 °C to 300 °C at 10 °C/min and maintained for 7 min. The temperatures of the ion source and quadrupole were 230 °C and 150 °C, respectively. The software of MSD ChemStation E.02.01.1177 was used to record and evaluate the measured data.

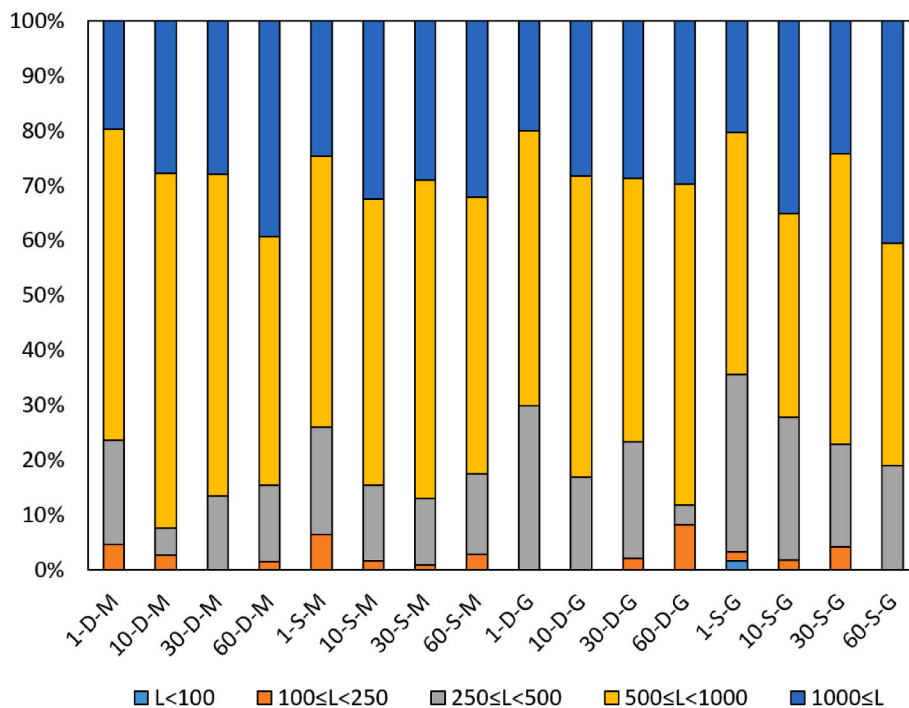


Fig. 1. Percentages of MPs of different sizes under different exposure times, mediums, and types of PPE. #: Exposure days. D: Distilled water. S: Seawater. M: Masks. G: Gloves. L: Length (μm).

2.4. MP analysis

PPE was carefully taken out of the beakers and rinsed with prefiltered water. The leachates were vacuum filtrated through a grade 42 (Whatman, Maidstone, Kent, UK) filter with a $2.5 \mu\text{m}$ pore size. The inner walls of the beaker were rinsed several times with prefiltered water to make sure detached MPs were recovered as efficiently as possible. The filters were then stored in sealed glass petri dishes under further analysis. Then, each filter was visually scanned with a KRÜSS binocular microscope (A. KRÜSS optronic, Germany) under $100\times$ magnification (Akhbarizadeh et al., 2020). Suspected MP particles were selected based on their physical characteristics, such as opacity, hardness, color, and structure (Bellas et al., 2016; Hidalgo-Ruz et al., 2012). Additionally, a hot needle was used to test if the suspected particle curled or melted. MP morphotypes were classified into fragments, fibers, and films (Hartmann et al., 2019).

2.5. Quality control (QC)/quality assurance (QA)

For MP analysis, recommended QC/QA measures were taken into account as indicated by Dehaut et al. (2019). In brief, all the containers and materials used during the experiments and MP extraction were made of glass or metal to avoid cross-contamination. The samples were covered with aluminum foil when not in use. All the equipment and containers were previously rinsed with ultrapure water and solutions were pre-filtered through a grade 42 (Whatman, Maidstone, Kent, UK) filter. Cotton laboratory coats and nitrile gloves were worn at all times. Procedural blanks for each treatment were carried out by conducting the exact experiment with both distilled and seawater at different exposure times but without including a PPE sample in the medium. The blanks were then analyzed for PAEs and MPs to account for external contamination. The instruments used in the PAEs analyses were calibrated with standards. Calibration curves indicated good linearity ($R^2 > 0.99$) for all the evaluated PAEs. The limit of detection (LOD), limit of quantification (LOQ), and recovery of individual PAEs are presented in Table S1. Additionally, solvent and procedural blanks were prepared for each batch of samples. The concentration of the different PAEs was presented

and subtracted from the results.

2.6. Statistical analyzes

The data were expressed in terms of MPs per PPE (MP/PPE \pm standard deviation) and ng of Σ_7 PAEs per mL of water medium (ng/mL \pm standard deviation) for MPs and PAEs, respectively. PAE and MP data were grouped by exposure time (1–60 days) and separated by different types of PPE (face mask or glove) and medium (distilled or seawater). Significant differences among exposure times were determined through Kruskal-Wallis tests followed by Dunn's multiple comparisons test. Additionally, in order to visually interpret the influence of the independent variables, multidimensional scaling (MDS) graphs were plotted based on the mean MP and Σ_7 PAEs considering the medium, PPE type, and exposure time variables. Considering the variability of the datasets, the variables were log-transformed and normalized before constructing resemblance matrices and subsequent MDS graphs. Statistical significance was set to 0.05. The analyzes were carried out with GraphPad Prism (version 8.4.3 for Windows) and the MDS graphs were constructed with PRIMER 6 (version 6.1.16).

3. Results

3.1. MP release

MPs were identified in all sample treatments with an overall mean value of 32.6 ± 13.4 MPs/PPE (ranging from 16.7 to 57 MPs/PPE; median: 29.6 MPs/PPE), with a mean of 4.25 MPs in the blanks. Grouped by type of medium and PPE, mean MPs abundance was ranked as D-M (46.3 ± 10.5 MPs/PPE; median: 43.6 MPs/PPE) > S-M (38.8 ± 11.6 MPs/PPE; median: 36.2 MPs/PPE) > D-G (23.4 ± 6.37 MPs/PPE; median: 22.8 MPs/PPE) > S-G (21.8 ± 3.23 MPs/PPE; median: 21.5 MPs/PPE). MPs in the range of $500\text{--}1000 \mu\text{m}$ were the most abundant (52.0%), followed by $> 1000 \mu\text{m}$ (29.8%), and $250\text{--}500 \mu\text{m}$ (15.7%), while those in the range of $100\text{--}250 \mu\text{m}$ and $< 100 \mu\text{m}$ were the least represented (2.49%, and 0.06%, respectively). The size range percentages for each treatment are displayed in Fig. 1. Concerning shape, fibers

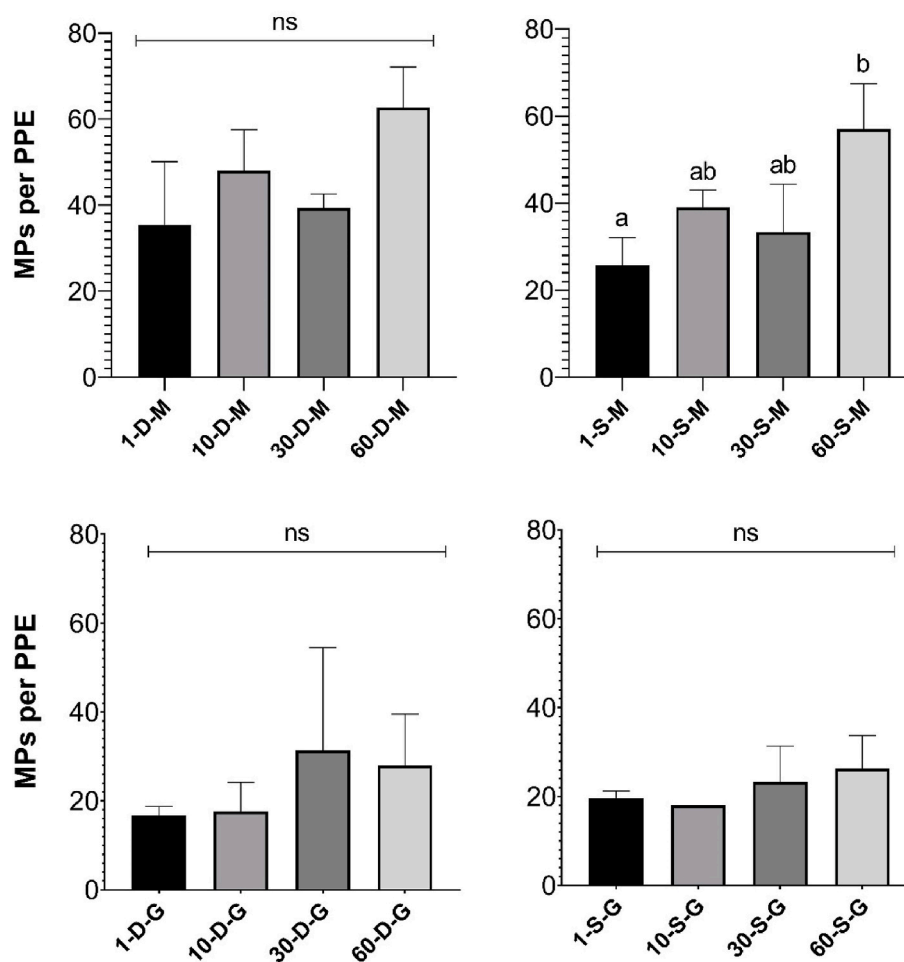


Fig. 2. Mean MPs/PPE at different exposure times and experimental conditions. Error bars indicate standard deviation. Letters indicate significant differences. ns: No significant differences (Kruskal-Wallis: $p > 0.05$).

Table 1

Overall descriptive statistics of the seven detected PAEs. %FO: frequency of occurrence.

PAE	Abbreviation	Mean \pm SD (ng/mL)	Median (ng/mL)	Range (ng/mL)	%FO
Dimethyl phthalate	DMP	1250.6 \pm 5813.7	0	0–36964	25%
Diethyl phthalate	DEP	50.0 \pm 59.9	32	4–337	100%
Diisobutyl phthalate	DIBP	325.1 \pm 816.7	100	7–3822	100%
Dibutyl phthalate	DBP	108.5 \pm 238.6	39	15–1324	100%
Butyl benzyl phthalate	BBP	1.7 \pm 7.7	0	0–49	10.4%
Diethylhexyl phthalate	DEHP	558.1 \pm 886.8	225	4–3890	100%
Diocetyl phthalate	DOP	22.3 \pm 54.1	5	0–322	54.2%

dominated in the case of both face masks (96.6%) and gloves (96.3%), while the color “white/transparent” was the most abundant in both cases (82.1–85.7%). The proportion of each color evaluated is presented in Fig. S1. The Kruskal-Wallis tests indicated no significant differences (ns) in most cases (Fig. 2), except for the face masks under seawater medium (Kruskal-Wallis, $p = 0.0191$), where the group 60-S-M differed significantly from 1-S-M.

3.2. PAEs release

The mean Σ_7 PAEs concentration was 2316.4 ± 5463 ng/mL (ranging from 178.8 to 23162.5 ng/mL; median: 38 ng/mL), while an average of 26 ng/mL was found in the blanks. Grouped by type of medium and PPE, the mean Σ_7 PAEs concentration was ranked as S-G (6292.6 ± 9749.3 ng/mL; median 684 ng/mL) > S-M (1325.5 ± 1475.1 ng/mL; median: 638 ng/mL) > D-M (942.5 ± 744.9 ng/mL; median: 670 ng/mL) > D-G (704.8 ± 578.9 ng/mL; median 454 ng/mL). The overall mean, range, and frequency of occurrence of each PAE type are displayed in Table 1. The proportion of each PAE per sample treatment is displayed in Fig. 3.

The concentration of Σ_7 PAEs presented no significant differences across exposure times for gloves (Fig. 4). Face masks under distilled water medium showed significant differences ($p = 0.0328$), as well as under seawater medium ($p = 0.0137$). In the former, only the 60-D-M treatment differed significantly from the 1-D-M treatment, while in the latter the 30-S-M treatment differed significantly from 1-S-M.

4. Discussions

Surgical face masks are particularly prone to release MPs due to their nonwoven microfibrillar structure, which has been observed by SEM in multiple studies (Akarsu et al., 2021; De-la-Torre et al., 2022b; Saliu et al., 2021). The release of MPs from face masks under simulated environmental conditions has shown great variability across studies. This may be attributed to the heterogeneous quantification methodologies and techniques applied. For instance, Shen et al. (2021) combined

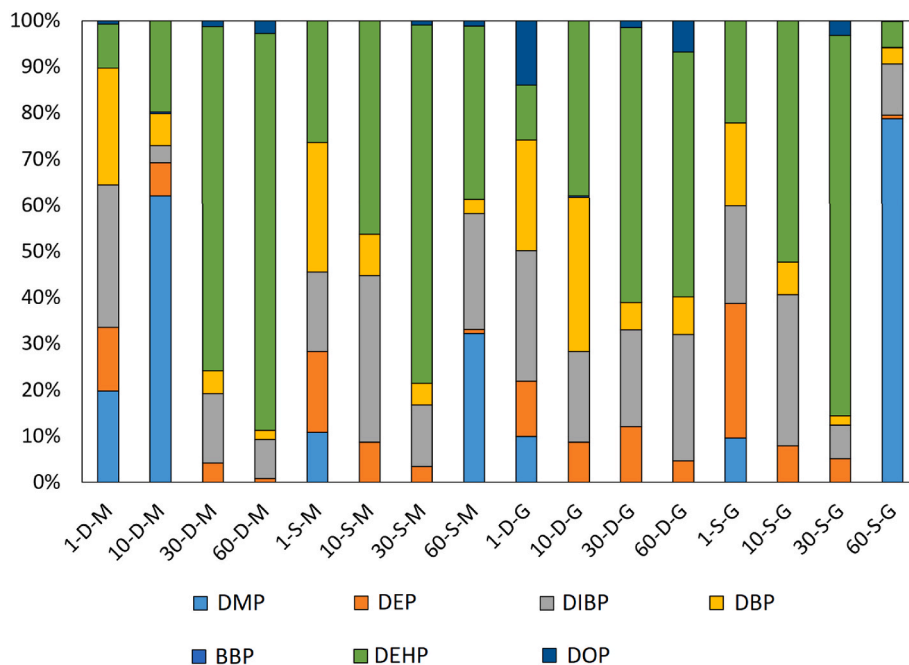


Fig. 3. Percentages of independent PAEs under different exposure times, mediums, and types of PPE.

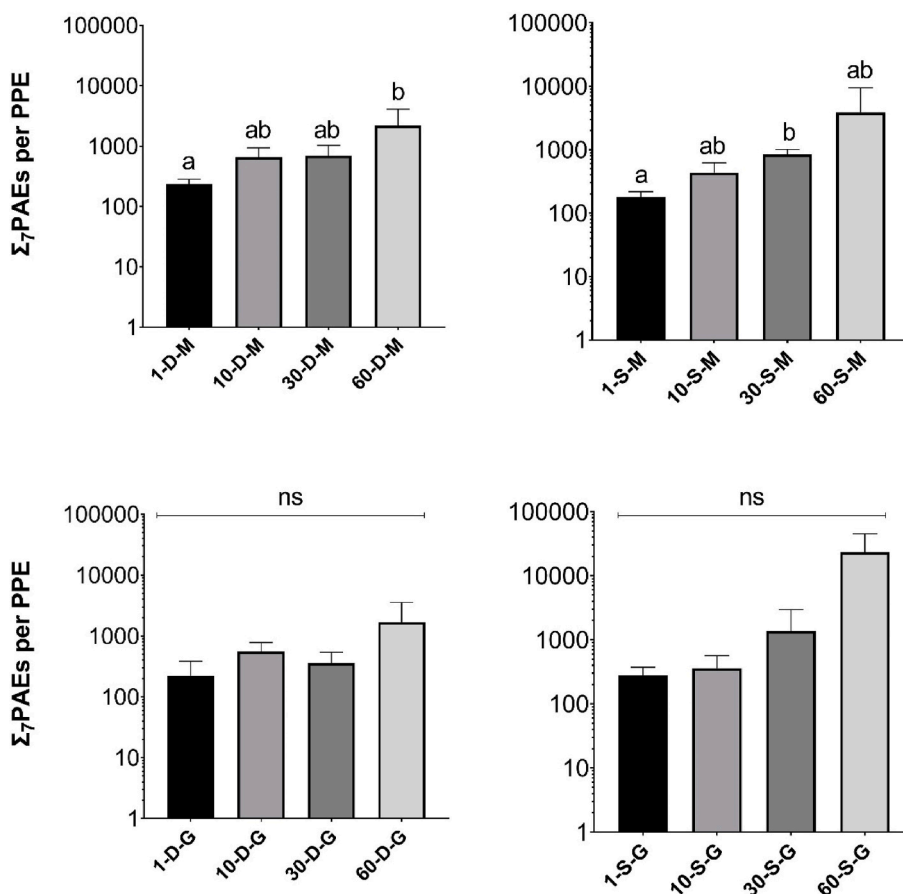


Fig. 4. Mean Σ_7 PAEs at different exposure times and experimental conditions. Error bars indicate standard deviation. Letters indicate significant differences. ns: No significant differences (Kruskal-Wallis: $p > 0.05$).

the use of a metallographic microscope and scanning electron microscope (SEM) to quantify the release of MPs from surgical face masks after several washes, which ranged from 116,600 to 147,000 MPs/mask

depending on the type of washing. Ma et al. (2021) counted MPs in face mask leachates with atomic force microscopy (AFM) and field-emission SEM. Released MPs ranged from 1.7×10^3 to 4.4×10^3 MPs/mask and

Table 2

Summary of the experimental conditions and MP release from studies applying an optical microscope or stereomicroscope as a counting technique.

Type of PPE	Medium	Stirring	Exposure time	Face mask source	Size range (μm)	Mean MP release (MPs/PPE)	Reference
Surgical face mask	Deionized water	120 rpm	24 h	New Used	<100 – >2000	183 1246	Chen et al. (2021)
Surgical face mask	MilliQ water	Shear damage ^a	1 s 120 s	New	>100	0.3×10^5 ^b 2.8×10^5 ^b	Morgana et al. (2021)
Surgical face mask	Distilled water Seawater	–	1–60 days	Old	<100–5000	46.3 38.8	Present study
Gloves	Distilled water Seawater					23.4 21.8	

^a Kitchen cutter.^b Concentration expressed in items per m^2 of face mask fabric.

1.6×10^9 to 3.8×10^9 MPs/mask in the case of particles $>1 \mu\text{m}$ and $<1 \mu\text{m}$ in size, respectively. However, other studies opted for a stereomicroscope to count MPs or combined it with more advanced methods (Chen et al., 2021; Morgana et al., 2021), as summarized in Table 2. The present study reported the lowest number of MPs released per PPE despite having a prolonged exposure time. This may be due to the lack of movement or agitation during the experiment. Chen et al. (2021), for instance, quantified 183 and 1246 MPs per face mask (for new and used face masks, respectively) under continuous stirring at 120 rpm. It is apparent that agitation plays an important role in the release of MPs. Additionally, other studies reported that agitation in the presence of an abrasive component (such as beach sand) could further induce the release of MPs (Z. Wang et al., 2021). However, limited movement of the PPE in the water medium could be representative of environments with fairly limited hydrodynamics, such as wetlands and ponds. These environments may be particularly subject to the ecological implications of external contaminants due to a significantly lower dilution factor.

This is the first study to evaluate the release of MPs from gloves under the COVID-19 pandemic scenario. Unlike face masks, gloves exhibit a smooth surface instead of a microfibrinous material. However, degradation experiments showed that after prolonged exposure time LLDPE gloves lose their smoothness and display cracks, rough surfaces, and cavities (De-la-Torre et al., 2022a). PE-based gloves are regarded for their poor physical and mechanical properties (Jędruchiewicz et al., 2021), which could exacerbate after exposure to environmental conditions.

The presence of MPs in the marine environment has been a subject of concern in the last decade due to their widespread abundance and inherent characteristics (Abelouah et al., 2022; Saldana-Serrano et al., 2022). The occurrence of MPs has been evidenced in any possible environmental compartment, including surface waters, sediments, soils, atmosphere, and elsewhere (Akhbarizadeh et al., 2021a; Dioses-Salinas et al., 2020; Dobaradaran et al., 2018a; Forero López et al., 2021; Hajjoui et al., 2022; Kashfi et al., 2022; Takdastan et al., 2021; Torres and De-la-Torre, 2021). Organisms are prone to ingest or inhale MPs through multiple pathways, with potential ecotoxicological effects (Dioses-Salinas et al., 2022). For instance, exposure to polystyrene (PS) MPs induced moderate and severe histological lesions (leukocyte infiltration, hyperemia, crypt cell loss, and villi cell loss) in the intertidal fish *Girella laevis* (Ahrendt et al., 2020). Other observed effects in various fish and aquatic invertebrates are behavioral alterations, decreased reproduction, oxidative stress, and damage, and decreased antioxidant prevention system and neurotransmission (Han et al., 2022). Ma et al. (2021) exposed various aquatic organisms to face mask leachates to assess the bioaccumulation potential of released MPs. Their observations indicated that all the test organisms (rotifer *Brachionus rotundiformis*, copepod *Parvocalanus crassirostris*, shrimp *Penaeus vannamei*, scallop *Chlamys nobilis*, and juvenile grouper *Epinephelus lanceolatus*) had ingested face mask-derived MPs. Furthermore, face mask MPs induced a significant decline in the fecundity of the marine copepod *Tigriopus japonicus* (Sun et al., 2021). In terrestrial organisms, face mask-derived MPs inhibited reproduction and spermatogenesis in springtails and

earthworms, respectively (Kwak and An, 2021). While ecotoxicological studies are fairly limited, this first evidence confirms the detrimental effects caused by MPs derived from face masks. However, the concentrations evaluated in the most recent investigations are much higher than those expelled by face masks in the present study. Future research is needed to understand the ecological impacts caused by the increasing number of face masks entering the environment.

Another concern associated with MPs is the release of chemical contaminants (e.g., flame retardants, plasticizers, dyes, etc.) and adsorption of external organic and inorganic compounds (De-la-Torre et al., 2020; Dobaradaran et al., 2018b; Torres et al., 2021). PAEs are esters of 1,2-dibenzene dicarboxylic acid widely used as plasticizers to improve the flexibility of high molecular weight synthetic polymers (Peijnenburg, 2008) and are able to leach into aquatic media. Cao et al. (2022) investigated the release of PAEs from various commercial plastic products (prepared as MPs) incubated in water for 14 days. Their results indicated that PVC, PA, and rubber materials presented the highest PAEs release (6660, 1830, and 1390 ng g^{-1} , respectively), while PP and PET were among the lowest. In the present study, PAEs concentrations in leachates presented comparable concentrations after prolonged exposure time (60 days), as displayed in Fig. 4. By observing the direction of the MP and PAEs vectors, the constructed MDS graphs (Fig. 5) show that mean MP and Σ_7 PAEs concentrations tend to increase at higher exposure time, as highlighted in the first graph. On the other hand, the second graph highlights the type of PPE, which denotes that face masks are prone to release a higher number of MPs, while LLDPE gloves have higher concentrations of PAEs. Recent studies proposed face mask-wearing as a potential pathway for PAEs intake (Massarsky et al., 2022; Vimalkumar et al., 2022; X. Wang et al., 2021; Xie et al., 2022). However, considering the higher migration potential of PAEs in gloves commonly found during the COVID-19 pandemic, their contribution to human exposure cannot be neglected. For instance, food handling gloves are treated as a potential source of PAEs in food and foodstuffs (Edwards et al., 2021).

PAEs migration to aqueous media is dependent on several factors. Paluselli et al. (2018) indicated that light and bacterial exposure to PVC cables increased the amount of PAEs released. This was attributed to the changes in the surface of PVC due to photo-chemical oxidation reactions. Additives allocate in the polymeric porous structure, which displays physical characteristics (e.g., pore size) that alter the release of additives depending on their molecular weight (Teuten et al., 2009). PAEs with low molecular weight, such as DMP, are more hydrophilic and prone to be released from the polymeric matrix. On the contrary, high molecular weight PAEs, such as DEHP, are hydrophobic and more resistant to migration. Interestingly, DMP was found with an overall higher concentration in the present study, probably attributed to its low molecular weight. However, the number and concentration of plasticizers included in the polymer matrix depend on the purpose of the plastic product, as well as the manufacturer. Since the PPEs used in the present study were collected from a local beach, these may vary considerably in terms of sun exposure, manufacturing processes, and PAEs content. This experimental design allows evaluating realistic PPEs

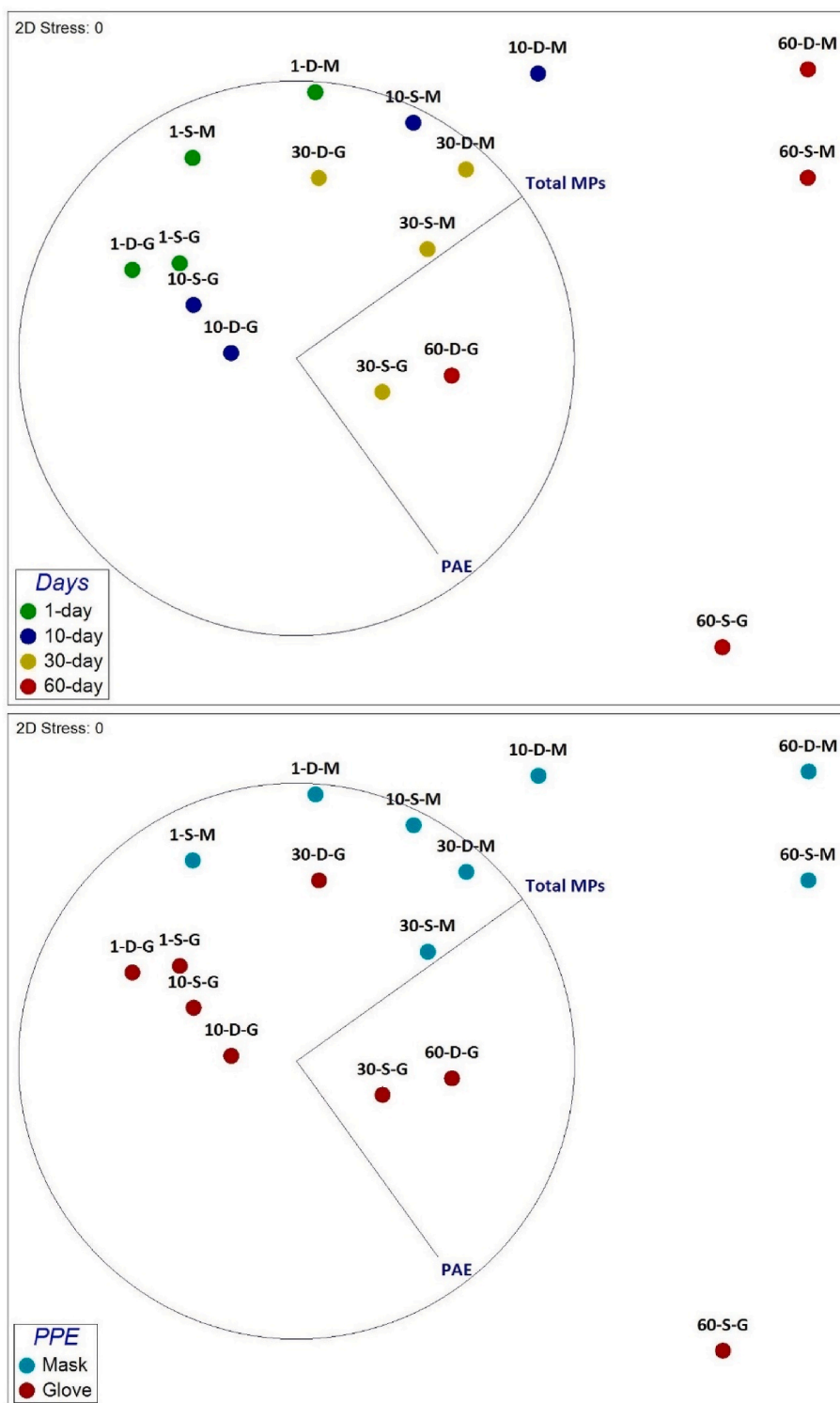


Fig. 5. Multidimensional scaling (MDS) graphs displaying the mean Σ_7 PAEs and MPs abundance in each treatment. The first graph (top) highlights the exposure time variable in days, while the second graph (bottom) highlights the type of PPE.

from a consumer perspective, instead of arbitrarily choosing a possibly unpopular brand of face masks and gloves. A major limitation, however, is the uncertainties regarding the manufacturing characteristics of the products.

Among the PAEs with 100% of FO, DEHP presented the highest concentration (558.1 ± 886.8 ng/mL), while DMP presented the overall highest mean concentration (1250.6 ± 5813.7 ng/mL) but lower FO (25%) and higher variability. DEHP has been found to induce

cytochrome P450 homeostasis disruption, causing immunosuppression in the common carp (*Cyprinus common carpio* L.) at 40 and 200 $\mu\text{mol/L}$ (Wang et al., 2020), increase of the mRNA expression of *TNF* and *IL 8*, and inhibited the mRNA expression of *IFN* in Larval juvenile yellow catfish (*Pelteobagrus fulvidraco*) (Zhang et al., 2019), as well as decreased egg production and fertilization rate of oocytes spawned by female Marine medaka (*Oryzias melastigma*) at 0.1 and 0.5 mg/L (Ye et al., 2014). In general, the most common PAEs may induce detrimental

Table 3

Summary of the abundance of PPE (most face masks and gloves) in aquatic environments worldwide.

Country	Number of PPE	Mean PPE density (PPE/m ²)	Most abundant type of PPE	Reference
Iran	2382	1.72×10^{-2}	Face masks (66.2%)	Akhbarizadeh et al. (2021b)
Iran	360	1.02×10^{-4}	Face masks (95.3%)	Hatami et al. (2022)
Morocco	689	1.13×10^{-5}	Face masks (96.8%)	Ben-Haddad et al. (2021)
Morocco	321	1.20×10^{-3}	Face masks (100%)	Mghili et al. (2021)
Ethiopia	221	1.54×10^{-4}	Face masks (93.7%)	Aragaw et al. (2022)
Peru	489	6.60×10^{-4}	Face masks (94.5%)	De-la-Torre et al. (2022b)
Peru	138	6.42×10^{-5}	Face masks (87.7%)	De-la-Torre et al. (2021)
Argentina	43	7.21×10^{-4}	Face masks (48.8%) Gloves (48.8%)	De-la-Torre et al. (2022b)

effects on the antioxidant system, genotoxicity, immunotoxicity, endocrine toxicity, and metabolism of aquatic animals (Zhang et al., 2021). However, the concentrations at which a significant toxic effect is observed are generally much higher than those determined in the present experiment. Furthermore, in environments with a high dilution factor, like the ocean, high concentrations are likely to dissipate rapidly. Thus, special attention should be given to water bodies with low hydrodynamics.

The approach carried out in the present study, particularly concerning the source of PPE used in the experiments, presents several strengths and weaknesses. Firstly, while the recovered PPE was previously inspected for signs of degradation, the exact number of days the items remained in the environment is unknown. This could provide some degree of uncertainty regarding the time-based analysis of the contaminant release concentrations. Further, the brand or source of the PPE was indistinguishable. Specific manufacturers use different plastic additives and production processes, possibly altering the resulting PAEs content and microstructure in each PPE independently. Regardless, we have previously discussed that arbitrarily choosing a brand for contaminant release experiments may not appropriately portray the most common PPE used by the population (De-la-Torre et al., 2022a). Thus, more realistic results can be obtained, from a consumer behavior point of view, by selecting PPE that are already found littered on coastal sites. On the other hand, incorporating PPE other than face masks into the analysis is relevant to account for the impact generated by this type of single-use plastic during the COVID-19 pandemic. PPE monitoring studies mostly report a dominant number of face masks. However, other studies indicate an equal or higher number of gloves in several sites, like the metropolitan city of Toronto, Canada, or the coast of Argentina (Ammendolia et al., 2021; De-la-Torre et al., 2022b). In this sense, the contribution of the whole set of PPE items used worldwide during the COVID-19 pandemic should be considered. In Bushehr port, the mean PPE density in coastal sites is relatively higher than in the rest of the world (1.72×10^{-2} PPE/m²). Chowdhury et al. (2021) estimated that between 0.15 and 0.39 million tons of COVID-19-derived plastic debris would enter the global oceans within a year. Regardless, there is great variability regarding the abundance and types of PPE among sites (Table 3). Like most types of plastic litter, PPE pollution is primarily attributed to poor municipal solid waste management. It has been recognized that waste management and recycling streams were severely impacted by the COVID-19 measures, such as extensive lockdowns and social distancing (Roy et al., 2021). However, as the world recovered from the pandemic and the measures became more flexible, insufficient waste management plans and infrastructure in developing countries

prevailed. Thus, it should be emphasized that solving waste management shortcomings is a primordial first step to preventing marine pollution with MPs and their associated contaminants.

5. Conclusions

The proliferation of PPE contaminating aquatic environments worldwide has raised environmental concerns in recent years. Apart from direct physical effects, such as entanglement and ingestion, the release of secondary contaminants poses a significant threat to aquatic organisms. In the present study, the release of MPs and PAEs from face masks and gloves commonly found abandoned in coastal sites was evaluated. The results indicated a relatively low number of MPs released per face mask, which was attributed to the lack of an agitation process. These conditions could simulate aquatic environments with limited hydrodynamics. On the other hand, the concentration in PAEs (DMP, DEP, DIBP, DBP, BBP, DEHP, and DOP) in PPE leachates presented high variability. Overall, it was observed that both MPs and PAEs concentrations increased in a time-dependent manner, while face masks and gloves were prone to release higher amounts of MPs and PAEs, respectively. The incorporation of these contaminants into the aquatic environment could pose ecotoxicological threats to biota. However, further research is needed in this sense. While the vast majority of studies focused on studying the multiple variables associated with the environmental and health hazards posed by face mask littering and wearing, other types of PPE, such as gloves, cannot be overlooked.

Author contribution

Gabriel Enrique De-la-Torre: Writing – original draft, Methodology, Writing – review & editing. Diana Carolina Dioses-Salinas: Writing – original draft, Writing – review & editing. Sina Dobaradaran: Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. Jörg Spitz: Writing – review & editing, funding acquisition. Iraj Nabipour: Writing - Review & Editing. Mozghan Keshtkar: Investigation. Razegheh Akhbarizadeh: Writing – review & editing. Mahbubeh Tangestani: Investigation. Delaram Abedi: Investigation. Fatemeh Javanfekr: Investigation.

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.

Data availability

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

Acknowledgments

This study was financially supported by Akademie für menschliche Medizin GmbH.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2022.114337>.

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