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Abundance and characterization of personal protective equipment (PPE) polluting Kish Island, Persian Gulf

Sedigheh Mohamadi a,b,⁎, Reyhane Madadi a, Md. Refat Jahan Rakib b,⁎, Gabriel E. De-la-Torre c,⁎, Abubakr M. Idris d,e

a Environmental Research Laboratory, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
b Department of Fisheries and Marine Science, Faculty of Science, Noakhali Science and Technology University, Noakhali, Bangladesh
c Grupo de Investigación de Biodiversidad, Medio Ambiente y Sociedad, Universidad San Ignacio de Loyola, Lima, Peru
d Department of Chemistry, College of Science, King Khalid University, Abha 62529, Saudi Arabia
e Research Center for Advanced Materials Science (RCAMS), King Khalid University, Abha 61421, Saudi Arabia

HIGHLIGHTS

• PPE abundance and chemical characterization was conducted in Kish Island.
• FTIR spectra showed signs of chemical degradation on weathered face masks.
• SEM revealed the occurrence of cracks, roughness and ruptures on the fibrous network.
• EDX mapping indicated the allocation of various elements, such as Mg, Cl, Ca, Na.

ABSTRACT

Plastic pollution is one of the major environmental threats the world is facing nowadays, which was exacerbated during the COVID-19 pandemic. In particular, multiple reports of single-use plastics driven by the pandemic, namely personal protective equipment (PPE) (e.g., face masks and gloves), contaminating coastal areas have been published. However, most studies focused solely on counting and visually characterizing this type of litter. In the present study, we complement conventional reports by characterizing this type of litter through chemical-analytical techniques. Standardized sampling procedures were carried out in Kish Island, The Persian Gulf, resulting in an average density of 2.34 × 10⁻⁴ PPE/m². Fourier transformed infrared spectroscopy confirmed the polymeric composition of weathered face masks and showed the occurrence of additional absorption bands associated with the photodegradation of the polymer backbone. On the other hand, the three layers of typical surgical face masks showed different non-woven structures, as well as signs of physical degradation (ruptures, cracks, rough surfaces), possibly leading to the release of microplastics. Furthermore, elemental mapping through energy-dispersive X-ray spectroscopy showed that the middle layer of the masks allocated more elements of external origin (e.g., Na, Cl, Ca, Mg) than the outer and inner layers. This is likely to the overall higher surface area of the middle layer. Furthermore, our evidence indicates that improperly disposed PPE is already having an impact on a number of organisms in the study area.
1. Introduction

The COVID-19 pandemic has not only had an impact on the world's socioeconomic status but is also contributing considerably to unprecedented types of plastic pollution (Aragaw and Mekonnen, 2022). Some of the most recognized sources of plastic waste that increased considerably during the pandemic were food wrappers/plastic films, PCR testing kits, and personal protective equipment (PPE). PPE includes facemasks, gloves, face shields, bouffant caps, hazmat suits, wipes, aprons, and hand sanitizers (Mvovo and Magagula, 2022). Synthetic polymers, such as polypropylene (PP), polyurethane (PU), and polycrystallinite (PAN), are the most commonly used materials for single-use masks, whereas polyethylene (PE), latex, and nitrile are utilized for gloves (Akbarizadeh et al., 2021b; Pizarro-Ortega et al., 2022). According to Peng et al. (2021), more than eight million tons of PPE were produced worldwide during the pandemic, with around 25,000 tons of PPE debris entering the water, causing environmental and aquatic species harm.

Face masks and gloves may entangle, trap, or be eaten by organisms, impairing their performance in their natural environment (Mvovo and Magagula, 2022). A Magellanic penguin was claimed to have died after eating a full face mask (Gallo Neto et al., 2021). Because of their fibrous microstructure, face masks can emit microplastics (MPs) (De-la-Torre et al., 2022b). A mask can release roughly 173,000 microfibers per day in the ambient circumstances of coastal habitat, according to estimates (Salii et al., 2021). MPs have now been found not only in different environmental samples, such as natural water bodies (Abelouah et al., 2022; Al Nahian et al., 2022; Compa et al., 2020; Gago et al., 2015), air (Akbarizadeh et al., 2021a; Allen et al., 2019), sediments (Rakib et al., 2022), wastewater treatment plants (Ramasamy et al., 2022), urban ditch sewages (Gela and Magagula, 2022), and human samples, such as blood and lung samples (Jenner et al., 2021; Leslie et al., 2022). When xenobiotics, like MPs, cause an overproduction of reactive oxygen species in organisms, oxidative stress and cellular damage occur if the antioxidative system is not activated (Esterhuizen et al., 2022). Other contaminants leach from PPEs, including heavy metals (Pb, Cd, and Sb), organic pollutants, and chemical additives (Sullivan et al., 2021).

The COVID-19 pandemic provides an unprecedented opportunity to track and evaluate environmental spills from a pulse-like event that results in plastic pollution (De-la-Torre and Aragaw, 2021; Rhee, 2020). The most recent PPE surveys focused on aquatic environments, such as river outlets in Indonesia (Cordova et al., 2021); marine coasts in Peru, Argentina, Chile, Bangladesh, Iran, and India (Akhbarizadeh et al., 2021b; Ben-Haddad et al., 2021); Gunasekaran et al., 2022; Rakib et al., 2021b; Thiel et al., 2021); Lakes in Ethiopia and Iran (Aragaw et al., 2022; Hatami et al., 2022); nature protected areas in Peru (Dioses-Salinas et al., 2022); and a Bay in Brazil (Ribeiro et al., 2022). However, the vast majority of the studies are limited to quantifying the abundance and density (items per m²) of PPE, while deep analytical analyses, such as physicochemical degradation of the material and analysis of adhered substances, are generally overlooked. Furthermore, no research has been done on the island environment. Islands are often geographically isolated, and their ecosystems are distinct in terms of biodiversity, physical environment, and threats from natural and anthropogenic forces (Velmurugan, 2008).

Kish Island in Iran has a diverse range of marine life, including corals, crabs, sea urchins, jellyfish, and sea cucumbers. Among the Iranian coasts of the Persian Gulf, Kish Island contains the most diverse hard coral biodiversity, with 28 species including Porites, Acropora spp., and Platygrya sp. (Kabiri et al., 2014; Mousavi et al., 2015). Coral reefs can be found at depths of 2–20 m on this island, with the majority of living corals found on the east and southeast beaches (Bargahi et al., 2020). Reef fishes and invertebrates are more diverse at shallow depths (3–8 m) (Mousavi et al., 2015). Hawksbill turtles lay their eggs on protected lands along the coastlines of this coral island between February and August (Afsari Hesni et al., 2016). Kish Island is also home to 30% of Iran's bird species, such as the cinereous bunting and the Jacobin cuckoo. While several studies have investigated the abundance of PPE in areas of ecological importance during the pandemic, particularly comparing lockdown seasons (Ben-Haddad et al., 2021), the influence of national holidays in touristic regions is yet to be explored. Thus, in the present study PPE density, as well as their characteristics and distribution, were assessed along Kish Island during a season highly influenced by the changing number of visitors driven by the start of holidays and festive seasons. Furthermore, several face masks were selected to be analyzed by Fourier transformed infrared spectrometry (FTIR) in order to identify signs of chemical degradation, such as the occurrence of O-containing functional groups and scanning electron microscopy (SEM) coupled to energy-dispersive X-ray spectroscopy (EDX) in order to identify signs of physical degradation on the surface of face masks, as well as external element accumulation patterns on the three layers of surgical face masks.

2. Materials and methods

2.1. Study area

The Persian Gulf is a one-of-a-kind ecosystem in terms of biodiversity, fishery resources, and particularly rich oil resources. It is surrounded by eight countries: Iran, Iraq, Kuwait, Saudi Arabia, United Arab Emirates, Qatar, Bahrain, and Oman. The Persian Gulf is the world's third-biggest bay, covering an area of around 240,000 km². The Iranian coastline of the Persian Gulf is nearly 1300 km long (Ghayezbadreh et al., 2020; Kabiri et al., 2013). The study area, Kish Island, with an area of 91.5 km² is located in the northeast of the Persian Gulf (Fig. 1). Kish Island, which has a population of 40,000 people and is a free trade zone, is a popular tourist attraction that receives about 1 million tourists each year. Kish Island has 22 water recreation centers and clubs with equipment and facilities for a variety of water sports like swimming, snorkeling, SCUBA diving, cable skiing, jet skiing, submarine scooters, and spear and hook fishing (Shokri and Mohammadi, 2021). Furthermore, Kish Island is home to a wide range of marine diversity, such as crabs of the family of Coenobitidae (suborder: Anomura), Hexapodidae, Ocypodidae rafinesque, Grapsidae macleay, Macrophthalmidae Dana, and Portunidae Rafinesque (Naderloo, 2017), which were observed on the field. Kish Island is an important habitat for >200 bird species. About 70% of them are migratory birds arriving from October to May to take the advantage of distinctive nature of the island (Kish free zone Environmental Protection Organization report).

The Persian Gulf is a shallow semi-enclosed sea that is one of the world's largest aquatic ecosystems, surrounded primarily by land. As a result, this body of water is extremely vulnerable to both natural and man-made contamination. Because of the discharge of petroleum, industrial pollutants, wastes, crude oil transport, and various oil and gas installations, refineries, and petrochemical plants, the Persian Gulf habitats are currently among the most contaminated aquatic environments. The amount of plastic waste entering the Persian Gulf in 2016 ranged from 155 to 413.4 Kt (Ghayezbadreh et al., 2020). Both land-based (recreational and wastewater treatment) and marine (fishing) activities have been linked to these substances. The Persian Gulf is the prominent oil producer in the world, and as a result, there is a significant degree of plastic solid waste generation associated with the petrochemical industry, oil-rig installations, and marine operations may also be important sources (Stüfen-O'Brien et al., 2022).

2.2. PPE survey strategy

To better understand PPE pollution on Kish Island's coastlines, 12 stations were monitored for 10 weeks from March to May 2022 (Fig. 1). A comparison of the number of incoming passengers to Kish Island during various months of the year reveals that April has the most passengers, followed by March and February (Shokri and Mohammadi, 2021). The sites were well distributed and covered nearly the whole coastline of Kish Island. The principal activities of each location were recognized and classified as swimming, fishing, recreational and tourism activities, and ship traffic. Table S1 shows the sampling station coordinates, the type of coast (rock
and sand), the main activities undertaken at each site, and the estimated area of each sampling site. In summary, for each sampling location, numerous transects parallel to the tideline (spaced by 10 m) were made to provide a thorough survey of the beach (from the low tideline up to the beach limit [road or vegetation]). Depending on the length of the beach and the distance between the tideline and the limit, the number and length of transects varied greatly. Station 7, for example, was 450 m long and 50 m wide; hence, a total of five 450-m transects were determined to cover the entire area. While walking along each transect, PPEs were visually identified and categorized as face masks (surgical masks, dust masks, and reusable masks), gloves, and associated PPEs (e.g., alcohol pad, alcohol packet, bouffant cap, face shield, and alcohol or disinfectant container). In the case of reusable masks, we refer to any type of commercial mask that is apparently composed of cloth or printed textiles, generally consisting of cotton or cotton-synthetic polymer blends. Samples of weathered face masks were collected and placed in aluminum foil and plastic bags individually. In the laboratory, the collected samples were air-dried at room temperature. The samples were then examined with the naked eye and then using binocular microscopes to look for signs of weathering and/or degradation in the environment. Damaged PPE was defined as any sample that showed signs of degradation.

2.3. Analytical characterization

2.3.1. FTIR analysis

A square of three layers of weathered (n = 2) and new (n = 1) surgical face masks were cut and dried at room temperature. Fourier-transform infrared (FTIR) spectroscopy analysis was used to determine the polymer composition and chemical degradation. The experiments were done using a BRUKER TENSOR II FTIR spectrometer with a scanning range of 400–4000 cm\(^{-1}\) and 4 cm\(^{-1}\) resolution. Absorption bands were manually analyzed to identify the presence of chemical functional groups and polymers.

2.3.2. SEM-EDX analysis

A Scanning Electron Microscope (SEM) coupled with an energy dispersive X-ray analyzer (EDX) (TESCAN VEGA 3) was used to investigate the
elemental composition (elemental mapping) and the surface of the three face masks analyzed by FTIR.

2.4. Statistical analysis

PPE density (items m$^{-2}$ ± standard deviation) was used to express the results. Eq. (1) was used to compute the PPE density in each sampling site:

\[ C = \frac{N}{A} \] (1)

where C represents the density of PPE per m$^2$, N is the number of PPE counted, and A is the surveyed area. Each sample campaign was treated as a repeat ($n=10$) to compare PPE density among sampling sites. The Kolmogorov–Smirnov test disproved the dataset’s normality assumption. As a result, the Kruskal-Wallis non-parametric test was used, followed by Dunn’s multiple comparisons test. The significance threshold was set at 0.05. GraphPad Prism (version 8.4.3) was used for all statistical analyses and visualizations, and ArcGIS (version 10.3) was used for the maps.

3. Results and discussions

3.1. PPE abundance and characteristics

A great variety of PPE types were found during the sampling procedures (e.g., Fig. S1). Out of the accumulated total number of PPE, 79.5% were regarded as masks, 10.8% as gloves, and 9.7% were other types of materials associated with the pandemic (Fig. S2a). The proportion of subtypes is displayed in Fig. 2. The majority of face masks were surgical. On the other hand, wastes related to any form of disinfectant alcohol products (e.g., wipes/pads) dominated other types of waste. The dominance of surgical face masks followed by gloves has been observed worldwide with very few exceptions (De-la-Torre et al., 2021b; Hatami et al., 2022; Rakib et al., 2021b; Ribeiro et al., 2022). This is likely due to the low-cost and accessibility to conventional surgical face masks, as well as face mask use mandates. Also, polyethylene film gloves have been reported as a very popular alternative in Iran (Akhbarizadeh et al., 2021b; De-la-Torre et al., 2022a), which are similar to those found in the present study. However, further polymer identification techniques are required to assure the composition of the gloves found. Regardless, PPE preferences are region-specific.

### Table 1
Summary of worldwide PPE monitoring.

| Area                          | Number of sampling campaigns | Area covered (m$^2$) | PPE abundance (items) | PPE density (item/m$^2$) |
|-------------------------------|------------------------------|----------------------|-----------------------|--------------------------|
|                               |                              |                      |                       |                          |
| Lake Tana, Ethiopia           | 12                           | 119,850              | 221                   | $1.22 \times 10^{-5}$-$2.88 \times 10^{-4}$ | $1.54 \times 10^{-4}$ (Aragaw et al., 2022) |
| Santos Bay, Brazil            | 6                            | –                    | 131                   | $0.389 \times 10^{-4}$    | $7.46 \times 10^{-5}$ (Ribeiro et al., 2022) |
| Coasts of Tetouan, Morocco    | 5                            | 17,789               | 321                   | $0.367 \times 10^{-3}$    | $1.20 \times 10^{-3}$ (Mghili et al., 2021) |
| Coasts of Agadir, Morocco     | 16                           | 282,374              | 689                   | $0.121 \times 10^{-4}$-$2.80 \times 10^{-3}$ | $1.13 \times 10^{-5}$ (Ben-Haddad et al., 2021) |
| Coasts of Tamil Nadu, India   | –                            | 143,080              | 496                   | $2.80 \times 10^{-4}$-$2.80 \times 10^{-3}$ | $1.08 \times 10^{-3}$ (Gunasekaran et al., 2022) |
| Coasts of Argentina           | 1                            | 474,719              | 43                    | $0.560 \times 10^{-3}$    | $7.21 \times 10^{-4}$ (De-la-Torre et al., 2022c) |
| Coasts of Peru                | 1                            | 1,179,727            | 462                   | $0.501 \times 10^{-3}$    | $6.60 \times 10^{-4}$ (De-la-Torre et al., 2022) |
| Coasts of Lima, Peru          | 12                           | 110,757              | 138                   | $0.744 \times 10^{-4}$    | $6.42 \times 10^{-5}$ (De-la-Torre et al., 2021b) |
| Coasts of Cox’s Bazar, Bangladesh | 12                        | 516,683              | 29,254                | $3.16 \times 10^{-5}$-$2.18 \times 10^{-2}$ | $6.29 \times 10^{-3}$ (Rakib et al., 2021b) |
| Bushehr Port, Iran            | 4                            | 43,577               | 2382                  | $7.71 \times 10^{-5}$-$2.70 \times 10^{-2}$ | $1.72 \times 10^{-2}$ (Akhbarizadeh et al., 2021b) |
| Caspian Sea, Iran             | 12                           | 293,825              | 360                   | $0.716 \times 10^{-4}$    | $1.02 \times 10^{-4}$ (Hatami et al., 2022) |
| Kish Island, Iran             | 10                           | 351,463              | 840                   | $0.1-1.18 \times 10^{-5}$ | $2.34 \times 10^{-4}$ Present study |
Fig. 3. a) Boxplot diagram and individual values of PPE density in each sampling site. Letters indicate significant differences according to Dunn's multiple comparisons test ($p < 0.05$). b) Heat map of PPE density in each site for 10 weeks. W: week.

Fig. 4. a) Alcohol wipe with an entangled juvenile crab. b) A surgical face mask torn apart by a marine bird. c) A surgical face mask with entangled seaweed.
should be noted that other types of wastes driven by the pandemic, such as disinfectant residues and wet wipes are generally not counted. In the present study, the contribution of these types of items was minimal, but their occurrence cannot be neglected.

The abundance of PPE represents a mean density of 2.34 × 10⁻⁴ PPE/m² (ranging from 0 to 1.18 × 10⁻³ PPE/m²) considering the sampled areas. These magnitudes are comparable to those found along the Iraqi coast of the Caspian sea (Hatami et al., 2022), and in other parts of the world (Table 1). The Kruskal-Wallis followed by Dunn’s multiple comparisons tests indicated that PPE density only S3 differed significantly (p < 0.05) from S10 (Fig. 3a). Overall, it is apparent that the abundance of PPE decreases over time (Fig. S2b). Following the heat map displayed in Fig. 3b, the sampling campaigns with the highest PPE densities were recorded in the first 5 weeks. A similar temporal trend has been observed in the Caspian Sea, Iran, and Lake Tana, Ethiopia (Aragaw et al., 2022; Hatami et al., 2022). In this case, the reduction of the number of PPE found is likely associated with social events, such as holidays, and with the school year, suggesting a pronounced influence of socio-cultural activities. Specifically, municipal workers clean beach areas every day in the morning. However, the waste management strategies during the holidays (W4 and W5) were different. The number of municipal workers increased in the stations with a high rate of visitors (including S3, S4, S5, S8, S9, and S10). The working time of municipal workers changed to three shifts (8 h per shift, covering 24 h). The overall number of samples was highest in the first week. (Akkbarizadeh et al., 2021b) also observed the same trend during their sampling. The number of tourists reached a peak in the fourth week due to the Noruz holidays. A considerable number of PPEs were recorded in week 4 (Fig. 3b). Actually, no comprehensive data was available about the visitors entering the Island. Kish Island welcomed a record of 81 thousand tourists on the 24th of March according to local news outlets. It has also been reported that over 200 thousand visitors traveled to Kish Island from 16th March to 2nd April (W2 to W4). The full waste management schedule in W4 and W5 kept the number of PPEs to 147, which could be much higher regarding the significant increase in the number of visitors. There was a decline in the number of PPEs in W6. From the beginning of W6, the number of visitors suddenly decreased to 5000 people per week (based on unpublished data from Kish airport) that was coincided with the beginning of Ramadan (an Islamic fasting month) and the reopening of the schools. The Eid al-Fitr festival was during the last week of sampling and the waste management was same as the normal days (only an 8-h shift a day in the morning). During this festival, a growth in the visitors was observed, which caused an increase on the PPEs (S3, S4, S7, S8, S9, and S10). For instance, in S8 and S10, PPE density increased from 6.67 × 10⁻⁵ PPE/m² (W9) to 4.67 × 10⁻⁴ PPE/m² (W10) and from 6.16 × 10⁻⁷ PPE/m² (W9) to 3.39 × 10⁻⁴ PPE/m² (W10), respectively. This suggests that waste management during this week was not enough for controlling PPEs accumulation.

Similar to the studies by Mghili et al. (2020) and Hiemstra et al. (2021), several PPE-marine biota interactions were recorded. This type of material represents entanglement and ingestion hazards for top predators, such as marine birds and mammals (Gallo Neto et al., 2021). The southern-east intertidal zone of the island is home to various kinds of crab species. Interestingly, a juvenile rock crab (Infrorder: Brachyura, Macroarthridae Dana) was found dead in an alcohol wipe in S2, W1 (Fig. 4a). This crab has toothed margins on his walking legs; thus, they can be easily trapped in the unwoven fibrous materials. We suspect that due to the physical characteristics of the crab’s legs, it could have become entangled in the alcohol wipe, where it remained until its death. Two cases of shrimps (Carcinus maenas) entanglement in face masks were also recorded in France (Hiemstra et al., 2021). During the sampling time, 12 bird species were observed including Curlew, Larus cachinnans, Eretta gularis, Corvus splendens, Burhinus oedicnemus, Acridotheres tristis, Golerida cristata, Pittaculax krameri, Cinnyris asiaticus, and Sterna hirundo. During sampling in S2 (W7), we saw a bird (Sterna hirundo) that was tearing a surgical face mask with its beak on the rocky shore (Fig. 4b). However, the bird took flight upon trying to approach it. Several reports have shown that seabirds mistakenly suppose face masks as food or use them for nest construction (Dharmaraj et al., 2021; Mghili et al., 2021). Gallo Neto et al. (2021) attributed the death of a Magellanic penguin to the ingestion of a whole face mask. On the other hand, it has been suggested that face masks may serve as a suitable substrate for colonization and dispersal of sessile macroinvertebrates, such as bivalves, barnacles, and seaweed (De-la-Torre and Aragaw, 2021). On some occasions, stranded face masks were found entangled with seaweed on them (Fig. 4c). Invasive species, including multiple types of seaweeds, are some of the most notable threats to marine ecosystems and native communities (Pinteus et al., 2018). Since plastics tend to float on seawater, this type of observation suggests the possibility of seaweed species dispersal to foreign ecosystems (Kiessling et al., 2015; Póvoa et al., 2021; Thiel et al., 2018). Other studies have experimentally shown that face masks shelter and enrich microbial communities, including antibiotic-resistant pathogens (Zhou et al., 2021), ultimately serving as vectors of pathogens and potentially invasive species. However, fouling microbiota has not been evaluated in the present study. Without a doubt, PPE and associated contaminants are interacting with marine biota in multiple ways. Some variables that may influence the type of interaction are the state of degradation and exposure time to the environment. Yet, this evidence is not sufficient to estimate the overall impact generated by the type of litter on the ecosystems of Kish Island. Another threat posed by this material is the release of secondary contaminants, such as MPs and chemical contaminants, which have been evidenced in previous studies evaluating face mask leachates under simulated weathering conditions (Chen et al., 2021; Fernández-Arribas et al., 2021; Sullivan et al., 2021).

3.2. FTIR

Three surgical face masks extracted from the environment were analyzed by FTIR and compared to a brand-new one. As expected, the FTIR analysis confirmed PP as the main polymeric composition of the three layers of surgical face masks. This coincides with multiple reports that analyze one or multiple layers of surgical face masks found on beaches or urban environments (Aragaw, 2020; Aragaw et al., 2022; Fadare and Okoffo, 2020). However, other types of face masks have been reported to be made of cotton-polyester fabric (De-la-Torre et al., 2022c). Regardless, it is safe to say that PPE waste is mainly dominated by PP plastic, as surgical face masks are the most dominant types of PPE in the majority of studies (e.g., Ben-Haddad et al., 2021; De-la-Torre et al., 2021a, 2021b; Mghili et al., 2021) and the present one. FTIR spectra were compared to that of a brand-new surgical face mask, as displayed in Fig. 5 for the three layers. Three notable new absorption bands are observed around 3360, 1785, and 1650 cm⁻¹ as indicated by arrows in Fig. 5, corresponding to hydroxyl/hydroperoxycarbonyl, carbonyl, and vinyl groups, respectively (Ainali et al., 2021; Almond et al., 2020; Grigoriadou et al., 2018), which are signs of degradation of the polymeric material. For instance, exposure to UV light-induced the occurrence of hydroxyl and carbonyl groups on PP-based face masks under experimental conditions as indicated by the broad and sharp peaks at around 3400 and 1720 cm⁻¹, respectively (Sallu et al., 2021). The degradation experiment carried out by De-la-Torre et al. (2022a) with littered face masks showed the occurrence of a broad peak between 300 and 3700 cm⁻¹ and a sharper peak between 1600 and 1700 cm⁻¹, similar to Fig. 5. The occurrence of O-containing functional groups on the polymer backbone upon exposure to the environment is most likely due to the chain scission and oxidation induced by UV light (Pizarro-Ortega et al., 2022). This behavior follows the Norris type
I or II pathways associated with the appearance of carbonyl and vinyl and hydroxyl/hydroperoxide groups, respectively (Grigoriadou et al., 2018). Both degradation pathways are demonstrated by the spectra in Fig. 5 (notice arrows), but it is apparent that Norrish type II is the dominant pathway. Despite being covered between the two external layers, degradation is more pronounced in the middle layer (Fig. 5b) as it presents stronger peaks. We are unsure why this is the case. Some possible factors that could influence sun-induced degradation, apart from direct exposure to sunlight, could be the surface area of the material (further explained in the following section) and the presence of UV stabilizers on the inner and outer layers. For instance, Fukuoka et al. (2022) detected the presence of benzotriazole-type UV stabilizers, such as UV329, in commercial PP face masks. Nevertheless, this requires further investigation. Also, Jemec Kokalj et al. (2022) reported that the concentration of multiple plastic additives was significantly different among face mask layers. On the other hand, due to logistical constraints and inaccessibility to analytical techniques, gloves were not analyzed in the present study. This is an important limitation of the present study. However, the majority of gloves were made of transparent film, which has been characterized as LDPE in previous studies carried out in Bushehr port, Iran (Akhbarizadeh et al., 2021b; De-la-Torre et al., 2022a). Nevertheless, the contribution of gloves to the total amount of PPE cannot be neglected in this region.

3.3. SEM-EDX

The microstructure of new and weathered surgical face masks was evaluated by SEM. SEM micrographs showed a typical non-woven fibrous structure displayed by electrospun materials. The structure of the outer and middle layers of new and weathered surgical face masks at ×200 and ×2700 magnification is displayed in Fig. 6. The width of the fibers in the outer, middle, and inner layers ranged from 28–30, 1.6–6.2, to 30–32 μm, respectively. Inner and outer layers presented a similar structure, while the middle layer was notoriously thinner and greater number of fibers, possibly displaying a larger surface area. This is because the middle layer, which acts as a filter, generally consists of melt-blown PP fabric. Interestingly, at ×2700 magnification, the fibers in the outer and inner layer showed some pieces exfoliating from their surface and rough surfaces, while the middle layer present smoother fibers (Fig. 6a). Regardless, surfaces became rougher after exposure to the environment. Exposed fibers also presented mineral inclusions and fractures/cracks. The changes and inclusion displayed by SEM micrographs are in agreement with previous reports (De-la-Torre et al., 2022c). The affection of the fibrous structure is the main driver of MP pollution in face masks. Numerous studies have evidenced the release of MPs and nanoplastics (PNPs) from face masks, with estimates surpassing the millions of particles per face mask depending on the experimental conditions and quantification techniques. (Kutralam...
Muniasamy et al., 2022; Morgana et al., 2021; Rathinamoorthy and Balasaraswathi, 2021; Saliu et al., 2021; Shen et al., 2021; Wang et al., 2021). Further, face mask degradation products, including MPs/PNPs, may cause sublethal ecotoxicological effects on aquatic and terrestrial organisms (Kwak and An, 2021; Sun et al., 2021) and could potentially be breathed in by wearers (De-la-Torre et al., 2021a; Han and He, 2021). However, the actual impact that PPE has caused on the already existing plastic issue at an ecological level and human health are unknown. In the particular case of Kish Island, PPE are unlikely to remain long periods of time abandoned on the beach area due to the continuous and systematic collection procedures. This may suggest that the number of released particles and chemical contaminants is limited to the first days or hours of weathering conditions, which is normally exacerbated over time and with increased plastic degradation (Andrady, 2022).

In addition to SEM imaging, EDS elemental mapping was conducted on the evaluated face masks. Selected elements comprising the microstructures are displayed in Fig. 6. Similar to the experimental results by De-la-Torre et al. (2022a), only elements commonly found in seawater and sand (e.g., Ca, Na, Cl, Mg, Si) were found through EDX elemental mapping. It is widely known that MPs/PNPs are capable of adsorbing organic and inorganic contaminants, such as heavy metals (Benson et al., 2022; Torres et al., 2021). In fact, the occurrence of Pb-containing particles adhered to face masks and Cd, Cu, Pb, and Sb leachates have been reported by Sullivan et al. (2021). Similarly, De-la-Torre et al. (2022b) reported Ag signals from the surface of a reusable face mask found on Argentinian beaches.

This find was attributed to the use of face masks impregnated with metallic nanoparticles (NPs), such as AgNPs and CuNPs (antiviral components) (Ardusso et al., 2021). It has been suggested that NP-containing face masks may represent a higher environmental risk than conventional ones, although these have been poorly investigated in the literature (Kahru, 2022).

In addition to EDX punctual analyzes, carrying out elemental mapping provides a better overview of the accumulation areas of certain elements. For instance, in Fig. 7 (middle layer – weathered blue mask) can be observed that Na and Cl are allocated in the same regions, suggesting that the two elements come from a single compound, most likely NaCl salt from its contact with seawater. Furthermore, the elemental signals are more pronounced and distributed in the middle layer than in the outer layer, suggesting that this layer accumulates more external matter, such as minerals and organics. We hypothesize that this is attributed to the higher surface area of the middle layer in contrast to the outer and inner layers. Also, its thinner and more compact fibrous microstructure (Fig. 6, middle layer) make extraneous particles a few micrograms in diameter more likely to be attached and retained. While SEM-EDX analyzes of this type of material have been carried out previously in the literature (De-la-Torre et al., 2022c; Sullivan et al., 2021; Wang et al., 2022), this is the first time an in-depth analysis of the microstructure of the multiple layers comprising conventional face masks is made. This could provide insights regarding the interaction between face masks and extraneous materials and contaminants.
4. Local solutions and outlook

The wave behavior of the ongoing COVID-19 pandemic and the occurrence of multiple variants raised concerns to national authorities. Despite the increasing vaccination rates, the WHO highly recommends wearing masks and practicing other safety options, even after vaccination, to tackle the spread of disease. For this reason, the island tourism chiefs still encourage and enforce the use of face masks. Under the current scenario, it is important to provide local solutions and recommendations to prevent this issue from exacerbating. Concerning local infrastructure, advertisements in various public places (e.g., airports, malls, beaches) encourage tourists to use a facemask. However, there are no signposts indicating the importance of correctly discarding PPE materials, nor educating on the consequences of contaminating the marine environment with PPE. Using special signs or advertisements, and installing educational posters and banners are among the recommended actions that can guide the public. On the other hand, waste management agencies must increase their personnel to keep beaches clean throughout the holidays. Installing bins specialized for face masks and PPE in general on beaches might capture the attention of tourists and meliorate the PPEs disposal management (Thiel et al., 2021).

Finally, reusable masks are a better choice rather than surgical masks since they can be used repeatedly. The WHO suggests using non-medical grade masks for daily life and medical masks for medical purposes (Hou et al., 2022). However, on Kish Island, only 25% of the face masks in the market are reusable and their prices are five times higher than the other available masks. Local authorities must create policies to make reusable masks more available to the population and inform the population about their advantages.

The possible recycling routes for the vast amount of PP-based material generated during the pandemic have been previously discussed (Torres and De-la-Torre, 2021). The valorization of PPE waste followed multiple innovative pathways in recent years. For instance, the conversion of surgical face mask waste into liquid fuel through pyrolysis has been demonstrated (Aragaw and Mekonnen, 2021), and the environmental benefits of this process were verified with a life cycle assessment approach (Li et al., 2022a). In the field of civil engineering, surgical face mask microfibers were investigated as a suitable additive to cementitious materials with improved mechanical properties (Castellote et al., 2022; Li et al., 2022b) and concrete aggregate for road base and subbase applications (Saberian et al., 2021). Other investigations reported the production of face mask PP-based carbon materials used as advanced materials in electrochemical applications (Hu and Lin, 2021) and absorbers (Maderuelo-Sanz et al., 2021). Inevitably, several innovative repurposing and recycling routes have been investigated driven by the alarming reality of PPE contamination. In light of the environmental consequences accelerated by the pandemic, the scientific community found an opportunity to investigate new repurposing routes and innovative ways to generate advanced nanomaterials. Interestingly, this research output may serve as a framework to prospectively apply these new technologies to other types of plastics that remain a serious environmental issue worldwide, possibly approaching sustainable solutions. While scaling these technologies to account for the amount of waste generated in different locations requires further industrial and scientific efforts, this may be the first step to minimizing the impact of PPE and other types of waste. Local governments and decision makers should take the current context as an opportunity to identify the main flaws in solid waste management systems and plans, seek innovative solutions, and evaluate the application of new technologies for benefit of the environmental health and population.

5. Conclusions

Kish Island is a particularly popular destination for its unique wildlife and landscapes in the Persian Gulf. However, plastic waste driven by the COVID-19 pandemic could represent a biological threat. In the present study, PPE and associated waste contamination was quantified along the northern and eastern coast of Kish Island and analyzed through various chemical-analytical techniques in order to elucidate the degradation behavior of these materials, as well as their interaction with extraneous particles and contaminants. As expected, PPE pollution is mainly dominated by surgical face masks, followed by film gloves. PPE densities are in accordance with previous reports. The polymer backbone of weathered face masks showed signs of chemical degradation induced by its contact with sunlight, such as the occurrence of additional absorption bands indicating O-containing functional groups. On the other hand, the fibrous microstructure showed rougher surfaces and cracks/ruptures after being recovered from the environment, potentially leading to the release of MPs/PNPs. Furthermore, EDX elemental mapping revealed a preference for external particles (e.g., salts and mineral particles) to allocate in the middle layer of conventional surgical face masks. This has been attributed to the higher surface area and structure of the middle layer in contrast with the outer and inner layers, as revealed by SEM micrographs. The present study contributes to the field through a deeper chemical-analytical analysis of weathered face masks, the most abundant type of PPE worldwide, and their interaction with external material. Further research must focus on the absorption behavior and release rates of multiple contaminants present in PPE, as well as their interaction with aquatic micro- and macrobiota.

CRediT authorship contribution statement

Sedigheh Mohamadi: Methodology, Investigation, Data curation.

Reyhane Madadi: Conceptualization, Data curation, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.

Md. Refat Jahan Rakib: Project administration, Visualization, Formal analysis, Resources, Software, Data curation, Investigation, Conceptualization, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

Gabriel E. De-la-Torre: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Abubakr M. Idris: Writing – review & editing.

Data availability

Data will be made available on request.

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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Appendix A. Supplementary data

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